status report

UNIVERSITY OF PITTSBURGH
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Carbon Capture and Sequestration: Exploring a Southwestern Pennsylvania Geologic Demonstration Project

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EXECUTIVE SUMMARY

Voices from Al Gore to the United Nations have made global warming the great fear of the 21st century. The polar bear, whose livelihood is threatened by the melting of Arctic ice, has become an icon for worldwide efforts to combat the effects of the burning of fossil fuels and the resulting emission of carbon dioxide and other greenhouse gases.

Large, fixed sources of emissions, like coal-fired electric power plants, are the easiest targets for those seeking to change how the world generates its energy. In the United States alone, opposition on environmental grounds has contributed to the shelving of nearly 60 proposals for new coal-fired power plants.

But about half of the country's power comes from coal-fired generation, and every cancellation of a proposed new plant increases the probability of outages in the future, as demand for more power continues to climb. The use of renewable energy sources, such as solar and wind power, is growing rapidly, but these sources represent such a small percentage of available power that they may not even be able to cover the growth in demand, much less replace existing coal-fired sources. Nuclear power offers a more viable alternative, but an expensive one. Moreover, nuclear plants take a long time to build, and the high cost of natural gas means that nuclear energy is more likely to take market share from gas than from coal.

The bottom line is that coal will continue to power America and much of the world for decades into the future. Because we cannot stop burning coal, in order to make progress on global warming we must do something to capture and get rid of the carbon dioxide that coal plants produce. Planting trees cannot begin to solve the problem—not when 600 U.S. coal-fired plants are each generating enough carbon dioxide to fill the Empire State Building twice a year. Among the possible options, the most promising is **carbon capture and sequestration**—that is, collecting the carbon dioxide and injecting it deep below the earth into a place from which it cannot escape.

Demonstration projects seeking to determine the viability of carbon sequestration are in progress at various locations in the United States. But the challenges are intimidating. They include:

- **Technological challenges.** Although the technology for compressing, transporting, and storing gases like carbon dioxide (CO_2) is well established, large-scale CO_2 capture from smokestacks is still under development. And the implications of long-term underground storage of CO_2 are unknown.
- **Legislative and regulatory challenges.** Although underground injection of CO_2 has been used to enhance oil and gas recovery for decades and some states have developed regulations and legislation governing this process, only a few states have considered the regulatory framework required to govern long-term, large-scale CO_2 storage. Who will carry

the legal liability in perpetuity? Who owns the pore space in the underground rock formations into which the CO_2 would be injected? What state agency will be responsible for oversight? What is the role of the agency that oversees water quality, considering that the greatest (albeit slight) risk in these underground operations appears to be water contamination? Does the operation qualify as mining if it is injecting material? Could there be an impact on air quality? Each state will have to wrestle with these decisions.

- **Community challenges.** NUMBY—"not under my backyard"—issues are arising as residents express concern about CO_2 being injected underneath them or migrating under their property. Community leaders and the general public fear the potential impact of global warming but have minimal understanding of the concept of carbon sequestration and its associated risks and benefits.

Pennsylvania produces 5 percent of U.S. carbon dioxide emissions and 1 percent of the worldwide total. Nearly 45 percent of Pennsylvania's CO_2 comes from the generation of electricity at coal-fired plants, much of it in Southwestern Pennsylvania. Thus, the state and the region can expect growing pressure to manage and reduce these emissions. Geologic storage may be the only way to manage this enormous volume of CO_2 over the next few decades.

To prepare for this situation, Pennsylvania can take several actions:

- Build the requisite legislative and regulatory framework in anticipation of the need to capture and sequester CO_2.
- Educate citizens about the issues and opportunities related to carbon capture and sequestration.
- Start to put in place the "carbon infrastructure"—the pipelines and storage repositories—that will be needed to move and then permanently store the carbon dioxide.
- Test these concepts with a pilot-scale sequestration project in a geologically well explored location in the state.

The nation's CO_2 challenge can be Pennsylvania's opportunity. Pennsylvania, particularly Southwestern Pennsylvania, offers an excellent collection of assets related to fossil fuels and power generation. The region has the only fossil fuel-related national laboratory, the National Energy Technology Laboratory; the research strengths of Carnegie Mellon University, the University of Pittsburgh, and West Virginia University; major coal producers such as CONSOL Energy and Foundation Coal; industry-leading companies that produce, transport, and store natural gas; companies that provide goods and services to the fossil fuel industry; and an underground geology that is well explored and ideal for sequestration. By coalescing these resources into a carbon sequestration industry sector, the region could become a domestic and international center for "clean coal" technology, goods, and services.

Southwestern Pennsylvania is arguably the U.S. region best positioned to develop and refine the technologies for carbon sequestration, to provide the storage space to make it a reality, and then to market clean coal products and services around the globe. The opportunity certainly deserves serious attention.

1. INTRODUCTION: THE CALL FOR CARBON CAPTURE AND SEQUESTRATION

Al Gore's *An Inconvenient Truth* (Gore 2006), various international studies, and a series of scientific reports have heightened concerns that global warming, fueled by increasing worldwide emissions of carbon dioxide, poses a severe threat to our planet. As a result, the human race is searching for solutions.

Some of the proposed solutions, unfortunately, are not viable in the foreseeable future. Worldwide energy demand is not likely to subside, and renewable energy sources can handle only a small portion of this demand. But if we can't stop producing carbon dioxide, perhaps we can keep it from endangering the atmosphere if we bury it underground.

This concept, known by the more technical name of **carbon capture and sequestration**, has generated considerable interest. It is not yet ready for large-scale implementation, but pilot projects across the country are showing promise.

Could Southwestern Pennsylvania become a world leader in carbon sequestration and achieve significant economic benefit by hosting such a pilot project? Several factors, including Southwestern Pennsylvania's scientific expertise and its still-productive coal industry, make this region a potential candidate. But various obstacles, including high costs, regulatory concerns, and the possibility of local opposition, could stand in the way.

This Institute of Politics publication assesses the status of carbon sequestration project development and its potential for Southwestern Pennsylvania. Chapter 2 looks more closely at the factors causing the carbon sequestration solution to gain momentum; it also discusses the concept's technical progress and its implications for Southwestern Pennsylvania. Chapter 3 examines the technology of carbon sequestration in greater detail. Chapter 4 discusses the legislative and regulatory issues that would have to be resolved before a pilot project could take place. Chapter 5 estimates the costs of a carbon sequestration project and suggests where the money could be found. Chapter 6 addresses how a pilot project might incorporate public education, which undoubtedly will be necessary to address concerns regarding the permanent burial of tons of carbon dioxide near populated areas. Chapter 7 considers how a pilot project might offer an attractive opportunity for the region, and Chapter 8 concludes by identifying necessary steps if such a project is to move forward.

2. THE NEED: ENERGY DEMAND AND CLIMATE CHANGE

The United States has a voracious appetite for electricity, and the U.S. Department of Energy expects that demand to grow by 25 percent between now and 2030. The federal Energy Information Administration (2007) estimates that coal-fired power generation is meeting nearly half of the total current demand (see Figure 1) and natural gas is responsible for another 20 percent, so a total of 70 percent of all electricity generation in the United States comes from fossil fuels. Nuclear generation, at 19.4 percent, is the next most popular source, with renewable energy sources trailing far behind.

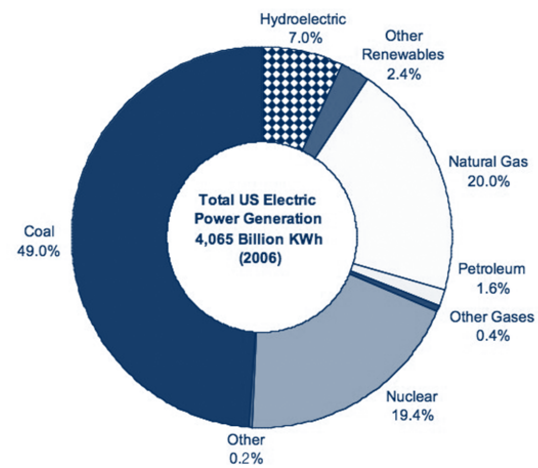

Figure 1: Sources of Electricity to Meet U.S. Demand

This heavy reliance on coal and nuclear power is not likely to change any time soon. Nuclear power is undergoing a resurgence and will help coal in meeting the growing demand. Georgia Power recently signed purchase agreements with Westinghouse Electric Corp., based in Southwestern Pennsylvania, to build the first new nuclear generation plant in the United States in 30 years. Another two dozen U.S. nuclear plants are in the planning stage, with many more under consideration internationally. The percentage of power generated by nuclear plants is expected to grow, capturing market share from natural gas-fired generation as gas prices escalate and supplies grow short.

Power generation from wind turbines, solar panels, and fuel cells is growing rapidly. But these renewable energy sources meet only a very small percentage of total demand. Moreover, the current renewable generation technologies, with the exception of hydropower, are not able to provide the consistent, predictable power that homes and businesses need. Unless we see significant breakthroughs in renewable energy technologies or enormous investment in nuclear power generation facilities, coal will continue to power the country.

Global Warming Becomes a Hot Topic

Nevertheless, coal is facing big challenges on the environmental front. Scores of proposed coal-fired generating plants have been shelved or postponed, primarily due to public pressure related to how these plants' production of greenhouse gases would contribute to global warming.

Greenhouses are warm because light passes through them and the heat becomes trapped under the glass. Greenhouse gases—carbon dioxide, methane, and others—act like the glass in a greenhouse, allowing light to pass through but trapping heat. These gases play a crucial role in warming the earth and allowing life to exist. But too much warmth could become a very bad thing. Most scientists believe the earth is gradually warming because of the increased presence of greenhouse gases, particularly carbon dioxide, coming primarily from the burning of fossil fuels. The Intergovernmental Panel on Climate Change (2007) concluded in its *Fourth Assessment Report* that serious and potentially catastrophic societal and ecological impacts could result.

In response to this threat, many states have taken steps to mitigate the release of carbon dioxide. Voluntary "cap and trade" programs, which set total emission caps and require corporations to purchase extra allowances if they do not curb excess emissions, are organizing across the country. Two dozen states, including Pennsylvania, have legislated renewable portfolio standards that require gradual increases in the use of renewable energy sources such as wind, solar, and biomass energies. Other states have enacted voluntary standards. Some states are encouraging energy efficiency and conservation through financial incentives and technological approaches. Others are using their purchasing and investment power to drive the development of nonfossil power generation.

The U.S. Congress also has taken up the issue of reducing carbon dioxide emissions. In 2007, seven bills carrying mandatory emission targets were proposed. Two of them are summarized below.

- The Bingaman-Specter Low Carbon Economy Act (S. 1766)
  - Would reduce U.S. greenhouse gas emissions (GHG) by about 25 percent in 2030 and by about 40 percent in 2050.
  - Resulting emissions would be approximately equal to 2000 levels in 2030, and 10 percent lower than 2000 levels in 2050.
- The Lieberman-Warner Climate Security Act (S. 2191)
  - Would reduce U.S. emissions by about 40 percent in 2030 and by about 56 percent in 2050.
  - Resulting emissions would be approximately 1 percent lower than 1990 levels in 2030 and 25 percent lower than 1990 levels in 2050.

If federal legislation limiting carbon dioxide emissions does pass, coal-fired power generation will be the primary target for two reasons: Fixed sources are far easier to regulate than mobile sources (i.e., vehicles), and carbon emissions from burning coal are greater than those from natural gas or oil.

The Most Promising Short-term Solution to Global Warming

The U.S. Department of Energy has identified three primary approaches to reducing greenhouse gas emissions; however, as we have seen, two of these appear to have limited short-term potential. Conservation and more efficient energy use could reduce growth in demand, but individuals and corporations are not yet feeling the cost pain that could lead to wider use of these strategies. Renewables may offer long-term solutions, but in the near term they can make only a limited contribution toward supplying the overall power need. The third approach, carbon capture and sequestration, likely will be the most important tool in the carbon reduction arsenal for many years to come.

Carbon capture and sequestration (CCS) is the process of capturing and permanently sequestering, or storing, carbon dioxide (CO_2). Carbon sequestration can take various forms:

- **Biological/terrestrial sequestration:** enhancement of biological systems (e.g., soil tilling practices, reforestation, new forest development)
- **Chemical sequestration:** conversion into a chemical feedstock such as methanol or other useful material such as chalk (calcium carbonate)
- **Geological sequestration:** storage in underground formations (in deep saline deposits, unminable coal seams, depleted oil and natural gas fields, and other compatible systems)
- **Deep sea sequestration:** storage in pools at the bottom of the deepest parts of the ocean

Geological sequestration is currently considered to be the most promising of these options, with a worldwide storage capacity estimated at more than 2 trillion tons of CO_2. As about 30 billion tons of CO_2 emissions can be attributed to human activity each year, geologic sequestration alone can offer decades of capacity. Pennsylvania is fortunate in having ideal geological structures for sequestration as well as the ability to use vast land holdings and agricultural assets for terrestrial sequestration. Scientists believe that CCS technology could reduce the amount of CO_2 released to the air from a coal-fired plant by as much as 80–90 percent (Intergovernmental Panel on Climate Change 2007).

CCS implementation would require capturing the carbon dioxide, conveying it to the underground burial location, and injecting it into the ground permanently. The first two of these steps are already in use. Technology for large-scale capture and conveyance of CO_2 has been deployed for decades in a process known as enhanced oil and gas recovery, in which CO_2 is injected into oil and gas wells to improve output. For example, the Great Plains Synfuels Plant in North Dakota, built in the 1970s, produces natural gas from lignite, also known as "brown coal." The carbon dioxide captured during the process is sent to Canada via a 200-mile-long pipeline. Upon its arrival there, it is used for enhanced oil recovery. As of 2007, the North Dakota plant had captured more than 10 million tons of CO_2 and pumped more than 7.2 million tons into oil wells. The CO_2 injected into the wells is not permanently sequestered but emerges with the oil, at which time it is again separated and reinjected to push out more oil.

On the other hand, long-term geologic storage (i.e., sequestration) of CO_2 is relatively untested. Permanently sequestering CO_2 requires its injection into a well thousands of feet deep, under such high pressure that the gas starts to act like a liquid. The CO_2 diffuses into the pore spaces in the rock, displacing water, oil, and natural gas. It is believed that, over time, the CO_2 changes chemically to become part of the rock. The impacts of long-term CO_2 storage are still unknown.

Although no full-size (i.e., 3 million tons or greater) power plant is presently operating a carbon capture and storage system, four smaller projects of about 700,000–1 million tons are functioning. They include the Sleipner project in the North Sea (developed in 1996); the Weyburn Project in Saskatchewan, Canada (2000); the In Salah Project in Algeria (2004); and the Snøhvit Project in the Barents Sea (Benson 2007).

The U.S. Department of Energy is helping to underwrite the development of seven carbon sequestration projects, each with intended capacity of 1 million tons, through its Regional Carbon Sequestration Partnerships. These government-industry collaborations are intended to enhance the viability of large-scale carbon capture and sequestration through geologic studies and demonstration projects.

Pennsylvania's Interest in CCS

Global warming has aroused renewed opposition to the use of coal. Environmental groups have called for a moratorium on new coal-burning plants until better means of managing the greenhouse gas emissions become available or even for the shutdown of existing plants. This policy movement poses a significant challenge to the coal industry and to the power generation industries that rely on coal.

The coal industry remains a fundamental element of Pennsylvania's economy, directly employing approximately 7,500 people and sustaining thousands more jobs through the revenue it brings into the state.

If carbon capture and sequestration technologies are not sufficiently advanced, or if Pennsylvania is not positioned to implement them, the state and the region's coal-fired generation and mining industries could be placed at a significant disadvantage.

On the other hand, a successful local pilot project in carbon management could become a powerful economic development engine. Southwestern Pennsylvania could bring a wealth of natural and intellectual resources to the task: a vast resource of geologic sinks, local coal companies, researchers at the National Energy Technology Laboratory and area universities, a strong manufacturing and service platform, and international economic development connections. By leveraging these resources through a carbon capture pilot project, the region could conceivably become a domestic and international center for "clean coal" technology, goods, and services.

Pennsylvania's state government is open to the possibility of a CCS pilot. The Pennsylvania Department of Conservation and Natural Resources (DCNR) has been investigating carbon sequestration with the goals of enhancing the value of open space preservation and private land stewardship while at the same time offsetting the state's greenhouse gas load. In 2006, the DCNR and the Pennsylvania Environmental Council convened the Carbon Management Advisory Group (CMAG), through which more than 60 experts and stakeholders from across the state have provided input on strategies and policies that could promote carbon sequestration in Pennsylvania. In 2008, the CMAG produced an important study that strongly recommended a pilot geological carbon sequestration project in Southwestern Pennsylvania.

Just as Governor Edward G. Rendell's alternative energy policies have attracted investment and jobs to Pennsylvania, similar economic opportunities could result if the region could take a lead role in controlling greenhouse gas emissions from coal. There will be significant opportunities to manufacture the specialized carbon capture and sequestration equipment that will be needed both for the retrofitting of existing coal-fired plants and in new construction. If those technologies can be developed in the commonwealth, substantial exports should follow, including sales to the giant economies of China and India, which also will face international pressure to reduce greenhouse gas emissions.

Southwestern Pennsylvania has a major interest in carbon sequestration, not only to preserve the integrity of the coal industry and the quality of our environment, but because this region could become the center of research in carbon emission mitigation and the leading exporter of associated technology, services, and technical expertise. We will return to this potential economic development opportunity in Chapter 7, after we examine the technological, legislative, regulatory, financial, and community components of a possible carbon sequestration pilot project.

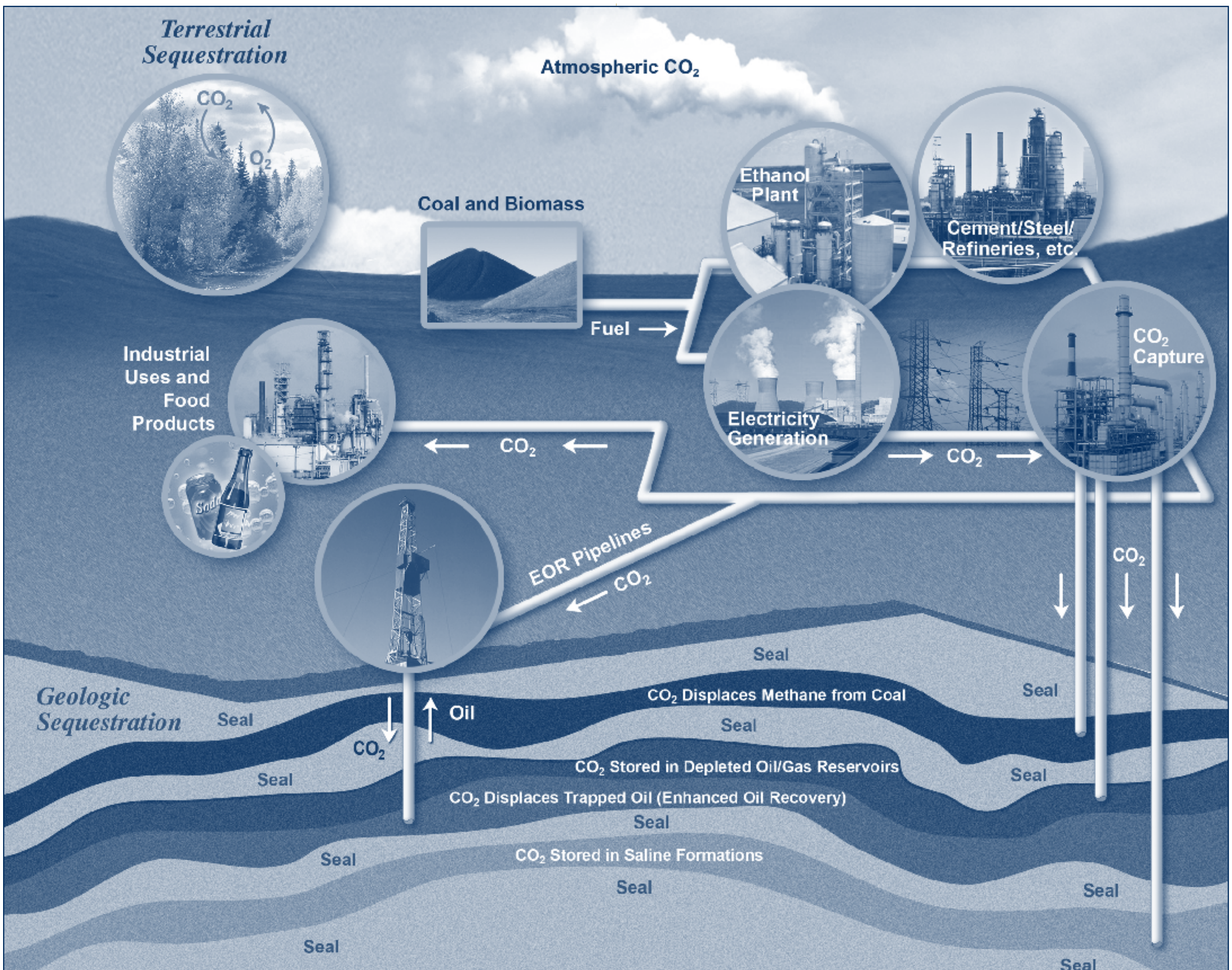

Figure 2: Sources and Uses for CO_2

3. TECHNOLOGY OF CARBON CAPTURE AND SEQUESTRATION

A midsize coal-fired power plant emits enough carbon dioxide in one year to fill the Empire State Building if the gas were converted to dry ice, or twice as much if it were compressed to a fluid-like state, which is the form in which it would be injected into the ground for geological storage. Multiply this volume by about 600, and you get a sense of how much carbon dioxide from coal-fired power generation alone would have to be sequestered in the United States every year. Aboveground storage doesn't make sense, because the volumes are too great. At some future time, conversion of carbon dioxide to a chemical feedstock or some other useful material might be feasible, but until then, geologic sequestration is the most reasonable answer.

The basic steps of geologic carbon capture and sequestration include:

- **Capture:** Carbon dioxide is captured from an emission source, compressed, and injected into a pipeline. The CO_2 is compressed to its "supercritical point," which is a combination of temperature and pressure conditions that enable the CO_2 to diffuse into materials (such as rock) like a gas but also to flow through a pipe and be pumped like a fluid. These properties help to maximize penetration and handling characteristics during injection into the well.
- **Transport:** The CO_2 is transported to the sequestration site using standard transport pipelines and equipment.
- **Well injection:** The CO_2 is injected through a well into a deep geologic rock layer (greater than 2,500 feet deep for permanent storage, where the pressure is sufficient to keep the fluid in a supercritical state). When the reservoir is filled, the well bore is permanently sealed.

- **Sequestration:** The CO_2 is held in place by an impermeable rock seal above it.
- **Monitoring:** The reservoir is monitored for leakage to the surface and for migration through the ground.

Figure 2, developed by the National Energy Technology Laboratory, illustrates the carbon capture and sequestration process from the production of CO_2 to its storage (U.S. Department of Energy, "Carbon Sequestration Atlas" 2007).

Capture Technologies

Power plants or other industrial processes that emit large volumes of CO_2 usually generate an emissions stream that is heavily diluted with other flue or process gases. As a result, CO_2 capture generally requires separation of CO_2 from other gases through one of three approaches: postcombustion capture, precombustion capture, or oxy-fuel combustion (California Department of Conservation 2008).

Postcombustion capture typically absorbs the CO_2 by using chemicals related to ammonia known as amines. The amine molecules are then regenerated by reversing the reaction. The reversal requires large amounts of heat, so an additional power requirement is placed on the plant. About 10 such capture systems using amines are in place around the world, although they are relatively small in scale. The primary advantage of this type of system is that it can be added to virtually any flue gas stream, making it well suited for retrofitting existing facilities.

In March 2008, a We Energies power plant in Wisconsin became the first to utilize a new chilled ammonia technology developed by the French company Alstom. The Wisconsin plant also became the first to capture carbon dioxide solely for the purpose of permanent sequestration. Should this carbon capture pilot prove successful, it will be installed at a 20-megawatt power plant in West Virginia, with the goal of geologically sequestering about 165 metric tons of CO_2 per year into a deep saline aquifer layer, starting in mid-2009.

Pre-combustion capture of CO_2 is more complex, involving three steps. First, the fuel is converted into a mixture of carbon monoxide and hydrogen. Second, this synthetic gas is converted to hydrogen and CO_2. Finally, the CO_2 is separated from the hydrogen. This capture technology is the most developed, with nearly 40 commercial-scale operations in existence.

In **oxy-fuel combustion,** combustion air is replaced with oxygen and recirculated flue gas, resulting in a flue gas that is composed mostly of CO_2 and water vapor. This process is only now in development, but it holds promise in that it is less energy-intensive and less chemically complex than the other approaches.

Many research programs are seeking to develop other technologies that can be retrofitted onto existing facilities effectively and inexpensively. For example, in February 2008 scientists at the University of California, Los Angeles, reported creation of a new material called zeolitic imidazolate frameworks, or ZIFs. These ring-like structures are porous, with large surface areas, and quite robust. The UCLA scientists claim that ZIFs can selectively capture and store carbon dioxide from flue gas more effectively than any other substance.

The National Energy Technology Laboratory (NETL) has set a goal for carbon capture technology of controlling 90 percent of the carbon dioxide emitted by existing plants without raising the cost of electricity by more than 20 percent. NETL hopes that, through the use of new amine capture technologies under development and new materials like ZIFs, this goal might be met as early as 2011.

Transport Technologies

Large-scale implementation of carbon sequestration will require a system for transporting CO_2 from the capture site to the permanent storage site. The only practical way to move enormous quantities of CO_2 will be a dedicated interstate pipeline network, which may have to be as large as the current 1.7 million-mile natural gas pipeline network.

CO_2 pipeline transportation technology in the United States is well developed after several decades of use and the construction of 1,500 miles of pipeline (see Figure 3) (Folger and Parfomak 2007). CO_2 pipelines, like natural gas pipelines, operate at ambient temperature and high pressure. Compressor stations are located at the points where CO_2 is injected into the pipeline, and booster stations provide additional power along the way.

The oldest long-distance CO_2 pipeline in the United States, the 140-mile Canyon Reef Carriers Pipeline in Texas, was built in 1972 to support enhanced oil recovery. Thirteen more large pipelines have since been constructed in western states for the same purpose. There are no CO_2 pipelines in Pennsylvania.

The steel pipeline technology used to transport CO_2 is identical to that used by the natural gas industry. Although carbon dioxide does have the potential to make water acidic, conventional carbon-manganese steel pipelines can be used with little risk as long as the CO_2 is dried before injection into the pipeline so as to minimize the potential for corrosion.

CO_2 pipelines have an excellent safety record. A report issued in *Energy* (Gale and Davison 2004) found no injuries or fatalities associated with CO_2 pipelines in the United States during the previous 13 years. The same precautions used by the natural gas industry, such as siting the pipelines away from populated areas, installing monitors and emergency shutoff valves, and maintaining regular inspection protocols, should ensure ongoing safety. Most natural gas injuries are the result of fires and explosions, and carbon dioxide is not flammable.

Small leaks in a pipeline or capture system would likely be dissipated by air movement and would have little effect on the atmo-

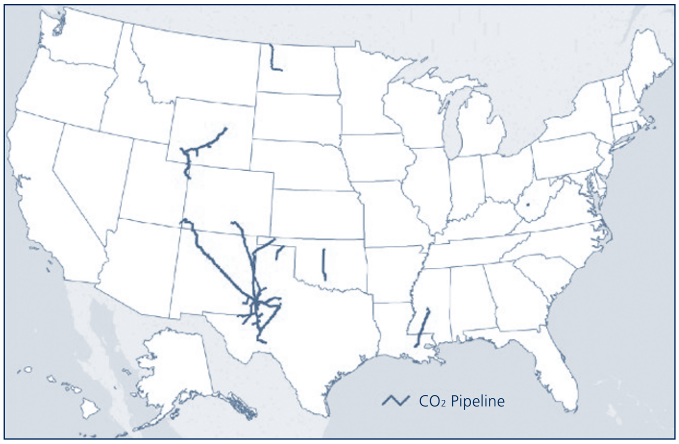

Figure 3: U.S. CO_2 Pipeline System

sphere (which already contains 0.038 percent carbon dioxide) or local water. Sudden leaks due to a rupture or other failure would trigger safety valves and monitors to control the release.

Well Injection Technologies

A typical CO_2 injection well is illustrated in Figure 4 (U.S. Department of Energy, "Carbon Sequestration Technology Roadmap" 2006). The technology related to a well of this type is mature and well proven after decades of use in enhanced oil and gas recovery. Some issues specific to CO_2 must be taken into account. For example, CO_2, when mixed with water, forms carbonic acid, so the CO_2 must be thoroughly dried before injection to minimize acid formation and corrosion of metal surfaces. Also, CO_2 injection pressure must be maintained to ensure that the CO_2 remains in the supercritical state in the well bore. Finally, the traditional Portland cement normally used to build a well is susceptible to corrosion by the acid produced when the CO_2 encounters the brine (water with dissolved mineral salts) in this type of cement. Instead, an acid-resistant calcium phosphate-based cement is used.

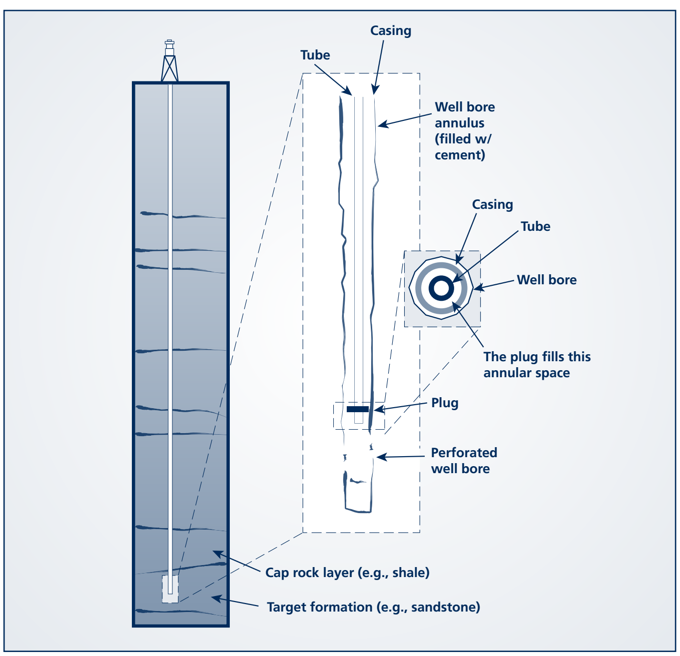

Figure 4: A Typical CO_2 Injection Well Design

Sequestration Technology

Naturally formed geologic carbon dioxide reservoirs have existed for millions of years, just as have natural gas reservoirs. In other words, nature already does what carbon sequestration technology is proposing to do. This underground carbon dioxide has been mined for decades, primarily for use in the food and chemical industries and for enhanced oil and gas recovery. The existence of these large, stable reservoirs gives credibility to the concept of long-term, stable carbon dioxide storage. Further, the natural gas industry has used gas injection for many years to fill reservoirs near major northern cities so that adequate supply will be available for wintertime use.

The optimum depth for carbon sequestration is below 2,500 feet. At this depth, the carbon dioxide is stable in a supercritical form; that is, the carbon dioxide gas is compressed to a point where it has unusual characteristics, like the density of a liquid and the mobility of a gas, that make it easier to handle and sequester.

The rock layer selected for long-term storage must be porous and must have an overlying umbrella-like layer of impermeable rock to ensure that the CO_2 does not migrate upwards. The CO_2 would not be pumped into a large open underground cavity; rather, it would diffuse into microscopic spaces within layers of sponge-like rock, such as sandstone, or between tightly fitting layers of high-carbon shales from which natural gas or oil may already have been removed. Most likely these pores and spaces now contain a brine water solution that would be displaced when the CO_2 is injected under pressure. The CO_2 is less dense than other liquids contained within the rock, so it will tend to float up to the bottom of the impermeable rock layer that forms the upper cap on the reservoir.

Carbon sequestration within rock layers should be permanent, as long as the CO_2 injected does not exceed the capacity of the reservoir and a good seal is put in place. However, carbon storage has a much less extensive history of successful application than do carbon capture, transport, and injection. Some questions remain, such as how much CO_2 can be pushed down the well, how far the CO_2 plume will travel through the ground, and whether it will have any impact on nearby oil and gas fields.

Pennsylvania's Carbon Management Advisory Group (CMAG) identified possible risks associated with the long-term sequestration of CO_2 in geological reservoirs and discussed ways to mitigate each risk:

- **Leakage** of CO_2 can occur through faults and fractures that pass through the impermeable rock layers within the CO_2 reservoir. To avert this problem, seismic testing can identify large breaches in the rock seals. Careful investigation of oil and gas drilling records (so that known wells can be sealed) and site inspections to identify unmapped wells would also help to minimize the risk of leakage.
- **Seismic events** like earthquakes result from the stresses on subsurface rock. The injection of large volumes of CO_2 could conceivably create such stresses. Although the resulting earthquakes would be localized and small, they could still cause damage. A seismic assessment could help to minimize this risk.
- **Ground movement**, such as the sinking or rising of the surface above the injected CO_2, could result from overpressurizing the storage reservoir. Careful monitoring could help to manage this risk.
- When CO_2 is mixed with water, carbonic acid is created, which could possibly **contaminate underground water supplies**. As the CMAG report stated, "Even small amounts of CO_2 in groundwater can cause significant deterioration in local water quality by decreasing pH, which in turn will dissolve calcium, increase water hardness, and potentially change trace element concentrations to levels that exceed drinking water standards" (Carbon Management Advisory Group 2008). The Bureau of Economic Geology at the University of Texas at Austin has been studying the impacts on groundwater of decades of CO_2 injection related to enhanced oil and gas recovery operations in thousands of wells. Although researchers have found very localized elevations in acidity, efforts so far to find water-related indicators, such as elevated trace elements, that would allow them to assess migration of CO_2 have been inconclusive. Research into any possible impact on human health is ongoing.

Monitoring and Verification Technologies

Future CCS projects should provide better answers as to whether underground carbon storage poses any of these risks. Regardless, public concerns about unforeseen consequences of sequestration will require some type of monitoring to verify that the buried CO_2 is not escaping. Potential techniques for long-term monitoring of CO2 reservoirs are described by Heidug (2006). Examples include:

- Sensors, to detect levels of CO_2 in the surrounding air;
- Geochemical downhole sampling, which uses monitoring wells to obtain information on CO_2 movement;
- Acoustic waves propagated in or around the well boreholes, to assess specific characteristics of the surrounding geology;
- Gamma ray logging, which uses natural gamma radiation to characterize the rock or sediment in monitoring wells;
- Cross-hole electrical resistivity tomography, which provides imaging of the volume of CO_2 in the reservoir by using electrodes placed in different monitoring wells;
- Seismic reflection, which uses energy from a seismic source (generally mounted on a truck) to detect changes in the geologic layers within the earth;
- Electromagnetic transmission, where data on the propagation time and attenuation of electromagnetic energy through the rocks surrounding the borehole can be used to assess their properties; and
- Gravimetry, which monitors CO_2 migration through changes in pressure that result from the daily movements of the bodies in the solar system.

Most of these monitoring methodologies have been solidly established through long use in the oil and gas industry, so we can reasonably presume that any pilot projects in carbon sequestration can be carefully and accurately monitored.

4. LEGISLATIVE AND REGULATORY ISSUES RELATED TO A CARBON SEQUESTRATION PILOT PROJECT

Geological carbon sequestration represents a new frontier, not only for scientists but also for policymakers. The public policy challenge can be divided into four major areas, each of which would have to be addressed through legislation and regulation to allow a geological sequestration project to move forward.

Those areas include:

- Property rights (including eminent domain), access, and siting;
- Compliance;
- Transport; and
- Liability and long-term stewardship.

A few states (notably Wyoming) and countries (e.g., Australia) have addressed particular aspects of sequestration policy, but none has developed a comprehensive legislative and regulatory framework. The U.S. Department of Energy (USDOE) recognizes both the difficulty of the challenge and the many similarities between the issues related to carbon dioxide management and those already faced by the oil and gas industry. Accordingly, in 2002, USDOE contracted, through its National Energy Technology Laboratory, with the Interstate Oil and Gas Compact Commission (IOGCC) to examine the technical, policy, and regulatory issues related to the safe and effective long-term geological storage of CO_2 and to develop a detailed policy guidance document for states that want to implement carbon-related legislation and regulations. The resulting document, *Storage of Carbon Dioxide in Geologic Structures, a Legal and Regulatory Guide for States and Provinces* (IOGCC 2007), includes a model ordinance and model rules and regulations; it should be highly useful for any state considering public policy related to carbon sequestration.

Carnegie Mellon University has recently undertaken a three-year, $2 million project to design and facilitate the rapid adoption of a U.S. regulatory environment for the capture, transport, and deep geological sequestration of carbon dioxide. The project team also includes experts from the University of Minnesota, Vermont Law School, and Van Ness Feldman law firm (CCSReg 2008).

Property Rights, Access, and Siting

Before a geologic sequestration project can begin, the project developer lawfully must be able to inject carbon dioxide into a particular layer related to a particular surface boundary.

Property rights: The right to use underground pore space and reservoirs is a private property right, and the right to this property must be acquired in order to use the geological strata for carbon sequestration. Acquisition of the rights also is a condition of the storage site licenses granted for natural gas storage.

Land ownership in Pennsylvania is complex, primarily as the result of the state's significant mineral wealth. Over time, many landowners have sold or leased resource or mineral rights (coal, oil, timber, etc.) to others, to the extent that, in many parts of the state, severance of rights is the rule rather than the exception. All of Southwestern Pennsylvania's counties are among the 29 in the state where mineral or resource rights are severed from surface property rights. To complicate matters further, in some cases the rights have been fractionated, with multiple parties each owning some percentage share of the rights related to a particular property.

Access: Utilities pump natural gas from wells and terminals across the country to fill empty natural gas reservoirs near major population centers in anticipation of high cold-weather demand. Pennsylvania stores as much as 1.2 trillion cubic feet of natural gas in such reservoirs (Pennsylvania DCNR 2007). Experts at the Pennsylvania Department of Conservation and Natural Resources (DCNR) believe that a much larger volume of unutilized reservoir space may well be available for sequestration. Ownership of this pore space is a complicated matter and can vary from contract to contract. But the owner or leaseholder of the underground rights would likely expect to receive rental payments for the space in perpetuity unless the entity responsible for sequestration can purchase them outright. Perhaps the state will have to use eminent domain in order to assemble suitable reservoirs for sequestration.

DCNR suggests that a better possibility, especially for early demonstration projects in carbon sequestration, would be to make use of the 85 percent of state-owned lands where the state has full ownership of all associated rights. The state would then also be able to limit surface uses of the land so as to avert activities, such as drilling, that might result in a release of the CO_2.

Siting: DCNR's Carbon Sequestration Management Advisory Group recommends that the state develop protocols for siting sequestration projects. It proposes the creation of a Geographic Information System (GIS)-based database, built on the framework in place at the Bureau of Topographic and Geologic Survey, that would list the location of potential storage sites, the capacity of each site, and potential pipeline or other transportation structures that could support each site. Southwestern Pennsylvania has generated considerable information on potential sites through prior oil and gas exploration and has extensive pipeline mileage and rights of way that could become the backbone of a carbon infrastructure system.

Compliance

Carbon sequestration well and reservoir operators must comply with both federal and state regulations. The U.S. Environmental Protection Agency (EPA)'s Underground Injection Control (UIC) program currently has authority to control the injection of CO_2 under the federal Safe Drinking Water Act. The injection of carbon dioxide that is currently used for enhanced oil recovery falls under the regulatory control associated with Class II wells, as can be seen in the table (Figure 5) of UIC well types and uses (U.S. EPA 2006). EPA does not currently have a designation for wells used for carbon sequestration, but a classification scheme and a corresponding set of guidelines and regulations are scheduled for release in 2008.

Research-related and demonstration wells have been included under Class V well regulations, where EPA has regulatory primacy. In some states, such as Illinois, where the state holds primacy, demonstration wells have been subject to more rigorous classification. For example, a new sequestration project associated with an Archer Daniels Midland ethanol plant is being permitted as a Class I well.

Class	Material Injected
Class I	Hazardous wastes, industrial nonhazardous liquids, or municipal wastewater
Class II	Brines and other fluids associated with oil and gas production and hydrocarbons for storage
Class III	Fluids associated with solution mining of minerals
Class IV	Hazardous or radioactive wastes
Class V	All injection wells not included in Classes I–IV

Figure 5: UIC Well Classifications and Uses

In order to construct and operate an injection well in Pennsylvania, one also must obtain a permit from the Pennsylvania Department of Environmental Protection's Bureau of Oil and Gas Management. As most proposed geologic sequestration regulations are based on oil and gas rules, IOGCC recommends that the lead regulatory agency in a given state should be the same agency that oversees the oil and gas industry. IOGCC also notes that, unlike pollutants such as nitrogen oxide and sulfur dioxide that are regulated for public health and safety, CO_2 is regarded as nontoxic and is not now classified as hazardous or a waste product. IOGCC strongly recommends maintenance of this classification, so that CO_2 can continue to be used for beneficial purposes such as enhanced oil and gas recovery. Whether or not state regulators choose to designate CO_2 as a waste or as a hazardous substance would also impact the well type used and the corresponding controls and regulations that would accompany it.

Transport

Although Southwestern Pennsylvania is well suited geologically for long-term CO_2 storage, it is unlikely that a given source of CO_2 will sit directly over an ideal storage site. Therefore, the CO_2 will have to be transported.

The federal Office of Pipeline Safety (OPS), an agency of the U.S. Department of Transportation's Pipeline and Hazardous Materials Safety Administration, oversees the country's pipeline networks. Many states, including Pennsylvania, have established partnerships with OPS under which oversight authority is delegated to the state. Pennsylvania does not have a partnership with OPS with regard to CO_2, so at this point OPS would retain oversight of any pipeline constructed in the region.

Liability and Long-term Stewardship

In order for carbon sequestration to be an effective tool against global warming, CO_2 storage must be permanent. All scientific experts believe this goal is achievable. Nevertheless, a large-scale accidental release is always possible, so questions related to liability—who would be held responsible, standards of proof, and compensation—must be addressed.

Once the CO_2 is injected into the reservoir, it must be monitored in perpetuity to ensure that it is not escaping or causing undesired impacts such as groundwater contamination. IOGCC suggests a two-stage approach to determining what entity should be responsible for long-term monitoring and liable for any damages. The first stage, the "closure" period, would constitute a defined amount of time after the closure of the injection well (IOGCC suggests 10 years), during which time the operator would maintain suitable bonds to cover possible costs. After the expiration of the closure period, the state would assume control and liability, with any associated costs to be covered by a state-administered trust fund.

In 2006, Texas took steps to address the issue of liability. The Texas oil and gas industry has injected CO_2 into the ground for decades to enhance oil and gas recovery, so laws and regulations governing those activities have been in place for some time. However, this use does not constitute long-term storage. The Texas law transferred ownership and responsibility for stored CO_2 to a state authority. By contrast, Wyoming recently passed a law specifically excluding the state from liability, and a recent statute passed in Washington presumes that the state does not carry liability.

DCNR Secretary Michael DeBerardinis has suggested that Pennsylvania explore assuming liability for geological carbon sequestration in order to encourage development of projects within the state. An interesting precedent under which government managed the liability associated with commercial activity is the federal Price-Anderson Act.

Just as is the case today with carbon sequestration, the unresolved potential for liability was a major deterrent to the development of the nuclear energy generation industry 50 years ago. To address this issue, Congress passed the Price-Anderson Act in 1957. This law enabled private-sector participation in nuclear energy project development by creating a federal insurance fund into which the commercial sector paid prescribed amounts. The law placed a cap on overall liability while providing a source of funds to pay claims.

Licensees must carry the maximum level of primary insurance available from private sources and also must contribute to a secondary insurance pool. The coverage available now totals over $10 billion for the industry. Over the last 40 years, the nuclear insurance pools have paid a total of about $150 million in claims (American Nuclear Society 2005).

As the American Nuclear Society notes, "The federal government provides similar insurance mechanisms for other types of disasters, such as floods; agricultural disasters; bank and savings and loan company failures; home mortgages; and maritime accidents. Liability limits also exist for oil spills; bankruptcy; worker's compensation; and medical malpractice."

Benchmarking

Several states have begun to form a legal framework for carbon sequestration. Wyoming has come the closest to passing comprehensive legislation governing geologic carbon storage (House Bills 89 and 90, 2007). Its laws took effect on July 1, 2008, and established the following regulatory framework:

- Wyoming currently has primacy over wells.
- The Department of Environmental Quality oversees permitting and regulation, while the Oil and Gas Conservation Commission oversees any subsequent extraction of sequestered carbon.
- The state carries no liability.
- Ownership of pore space resides with the surface owner.

The **Kansas** Carbon Dioxide Reduction Act of 2007 required that CO_2 injection rules and regulations be established by July 1, 2008. It also exempts CCS property and any electric generation unit utilizing CCS from all property taxes for five years following completion of construction or installation of CCS equipment.

In 2007, **New Mexico** created the first tax credit in the nation to cover carbon capture technology. The credit will apply to 6 percent of a plant's expenditures for development and construction, up to $60 million.

Montana adopted a carbon dioxide emissions performance standard (50 percent capture) for coal-fired electric generating units constructed after January 1, 2007. The state also decreased taxes by 75 percent for pipelines that carry carbon emissions captured at clean energy facilities.

In contrast to the above states, **California**'s legislature has recently deleted a provision that would have recognized carbon sequestration as a viable environmental strategy.

As no state has yet put in place a comprehensive legal framework addressing carbon capture and sequestration, there is room for Pennsylvania or any other state to become nationally prominent through thoughtful legislative development.

5. CARBON CAPTURE AND SEQUESTRATION PROJECT COSTS AND FINANCIAL VIABILITY

Even if carbon sequestration is an environmentally safe, technically feasible solution to greenhouse gas proliferation, is the added cost justifiable? This question is hard to answer in advance. Most likely, a carbon exchange will develop, within which companies will trade carbon emission rights much as they have done with nitrogen oxide and sulfur dioxide emissions since the 1990s. As shown in Figure 6 below, predictions as to the value of one ton of carbon emissions on the open market vary widely (Synapse Energy Economics 2008).

The cost of carbon capture for a given plant is estimated at $1,000–$1,500 per kilowatt of power generation capacity. It is thus possible that the cost of building a midsize (500-megawatt)

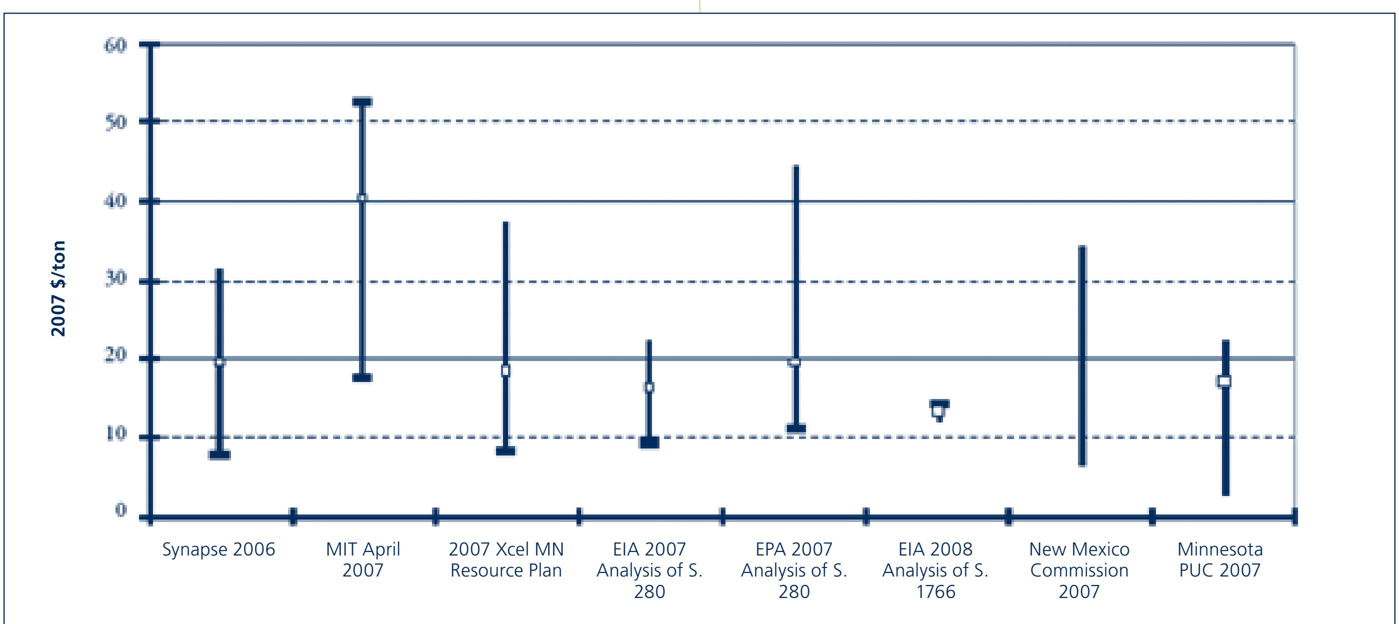

Figure 6: Levelized CO_2 Costs (2010-2030)

coal-fired plant will increase by $500–750 million, or 50–75 percent, due to the inclusion of carbon capture capacity. That sounds like an enormous jump, but without carbon capture, the plant might generate 5 million tons of CO_2 per year for 50 years. At a carbon market price of just $30 per ton, the emission credits would cost $150 million per year, making the investment in carbon capture and sequestration quite attractive.

The costs and risks associated with the mitigation of carbon emissions at both new and existing coal-fired generation plants should become more predictable once Congress establishes a trading scheme and a ceiling for carbon emissions and once demonstration projects determine if carbon capture and sequestration will solve the carbon emission problem safely and at what price. Federal and state governments could support the deployment of CCS technology through rational rule making and financial incentives, as well as by offering liability protection as discussed in the previous chapter.

Pilot Project Costs and Financing

Pennsylvania DCNR has estimated that a pilot carbon sequestration project might cost $15 million, not including transport and long-term monitoring expenses. This cost does not cover capturing the CO_2, an expensive step in retrofitting projects (perhaps 80 percent of total costs) but a less important factor if a relatively pure CO_2 source is available for the pilot.

DCNR's Carbon Management Advisory Group identified various components of a project and, where possible, estimated the costs of each component. Figure 7 draws on the advisory group's work. Once a prospective project source and sink have been identified, the costs described here as uncertain can be better addressed.

Sources of support for the various project aspects might include the following:

- State government programs (e.g., Energy Harvest, Pennsylvania Energy Development Authority)
- U.S. Department of Energy's National Energy Technology Laboratory
- U.S. Department of Defense
- Corporations (possibly providing land, equipment, consultation, or site preparation assistance as well as financing)
- In-kind services from the Department of Conservation and Natural Resources, Department of Environmental Protection, Midwest Regional Carbon Sequestration Partnership, National Energy Technology Laboratory, and local organizations such as Sustainable Pittsburgh
- Private investors
- Foundations

Project Element	Task	Rough Cost
Administration	Project management Assembly of the partnership, staffing, grant writing, etc.	$100,000
	Public outreach and education	$100,000 (including web-site, printed materials, etc.)
	Technical assistance - legal, financial, etc.	TBD
Capture		TBD*
Transport	Pipeline	$800,000 - $1M/mile
Sequestration	Literature/file search	$5000
	Geological assessment (seismic, etc.)	$1,500,000
	Preliminary engineering	$350,000
	Well drilling	$300,000
	Bore hole testing	$100,000
	CO_2 injection	TBD
Monitoring		TBD

Figure 7: Representative Cost Elements for a Pilot Geologic CO_2 Sequestration Project

*Identifying a relatively pure stream of CO_2 that is already a by-product of an industrial process would be an important cost-controlling measure.

6. PUBLIC OUTREACH AND EDUCATION

In *An Inconvenient Truth,* Al Gore brought worldwide attention to the problem of climate change, instilling fear about the increasing presence of carbon dioxide. Gore identified fossil fuel-powered electricity generation as a primary source of carbon dioxide and renewable sources of power as the primary solution. The reader or viewer of *An Inconvenient Truth* is not reminded that renewables still occupy a small fraction of the power generation market, that fossil-fueled generation will remain necessary for many decades or longer, and that it is therefore prudent to invest in technologies and projects that could capture and sequester carbon dioxide.

Watch out, Coke and Pepsi: People increasingly believe that carbon dioxide is dangerous. The public appetite for carbon sequestration was tested in 2007 during hearings concerning geologic sequestration in California. The California Global Warming Solutions Act, passed in 2006, had called on the state legislature to identify opportunities to reduce emissions through a variety of approaches, including carbon sequestration. But in 2007, public pressure caused legislators to back off from a proposed measure that would have authorized sequestration activity. The notion of NUMBY—"not under my backyard"—prevailed.

Outreach and Education as Keys to Success

Clearly, public outreach and education will be an essential part of any successful CCS initiative. Resistance is likely to arise in at least two forms:

- **NUMBY.** Carbon dioxide would be injected into the ground, where it might conceivably creep through layers of rock over many years, possibly impacting water supplies and causing other environmental effects. The nontechnical public will not take the time to explore or assess the risks; rather, people will recall the recent home explosions resulting from the buildup of methane gas—also a substance stored and transported underground—and fear the worst, even though carbon dioxide is neither explosive nor toxic. Despite the fact that we inhale carbon dioxide in every breath and consume it in carbonated beverages, resistance to burying massive amounts of it underground can be anticipated.
- **Opposition to the use of public funds and public land to support development.** This issue already has been raised by state environmental groups with regard to the use of fossil fuels. Environmental groups have expressed similar objections to the use of state-owned land as the site for carbon sequestration wells.

To win sufficient public support for a CCS pilot project, DCNR and other organizations will need to construct a solid public education and outreach plan, including polling, focus groups, and public meetings, with a particular focus on the stakeholder groups most affected by the project. Partnerships with schools and the media could help to educate the public about CCS and displace ignorance and fear through understanding. Educational initiatives could emphasize the benefits of carbon sequestration and the excellent safety history that has accompanied the use of carbon dioxide in oil and gas recovery.

7. IS THERE A REGIONAL OPPORTUNITY?

Pennsylvania produces 5 percent of U.S. carbon dioxide emissions and 1 percent of the worldwide total. The state ranks third behind Texas and California in total CO_2 emissions and fourth in CO_2 emissions related to power generation behind Texas, Ohio, and Florida. Nearly 45 percent of Pennsylvania's CO_2 comes from the generation of electricity at coal-fired plants, with much of that generation in Southwestern Pennsylvania. The state can expect growing pressure to manage and reduce these emissions. Now is the time to develop alternatives so as to minimize the impact on electricity generators and ratepayers as well as to maximize the positive environmental outcomes.

The federal government, through its carbon sequestration partnerships, is investing tens of millions of dollars in fledgling pilot carbon sequestration projects across the country but not in Pennsylvania. Other states are using these projects to drive legislative and regulatory development; Pennsylvania has made little headway. Utilities have expressed some interest in investing in sequestration projects, but with no guidelines in place, the idea is too risky.

Southwestern Pennsylvania has the greatest need of any part of the state, the greatest potential opportunity, and the right assets (geologic, intellectual, and corporate) to build on. Much of the technology required for CCS is in place, and the remaining pieces are taking shape rapidly. Other states are positioning themselves for the likely onset of federally mandated carbon controls.

The most viable way to galvanize the necessary leadership and stakeholders around this opportunity is a small-scale, low-cost pilot project with low commercial risk. Such a project could accelerate legislative development, build public awareness, contribute to technical knowledge, and demonstrate capacity to reduce carbon dioxide emissions.

Maximizing the Chances for Success

The success of such a pilot project in Southwestern Pennsylvania would require the convergence of several factors:

- The right geological sink
- An appropriate source of carbon dioxide
- An accepting public
- An enabling regulatory and legislative framework
- Innovative and strategic leadership
- Financial resources

Critical groundwork already laid by the National Energy Technology Laboratory, Midwest Regional Carbon Sequestration Partnership, and Pennsylvania Department of Conservation and Natural Resources (DCNR) provide a strong foundation for a potential CCS pilot. The work of these three entities underlies the following discussion of these factors.

The Right Geological Sink

Underground pore space is a new natural resource, and Pennsylvania has a wealth of it.

Geological assessments have shown that Pennsylvania has huge sequestration potential. Even when initial estimates were reduced by as much as 90 percent to ensure that they were conservative, they indicated that geologic structures in Southwestern Pennsylvania alone could store 250 years of

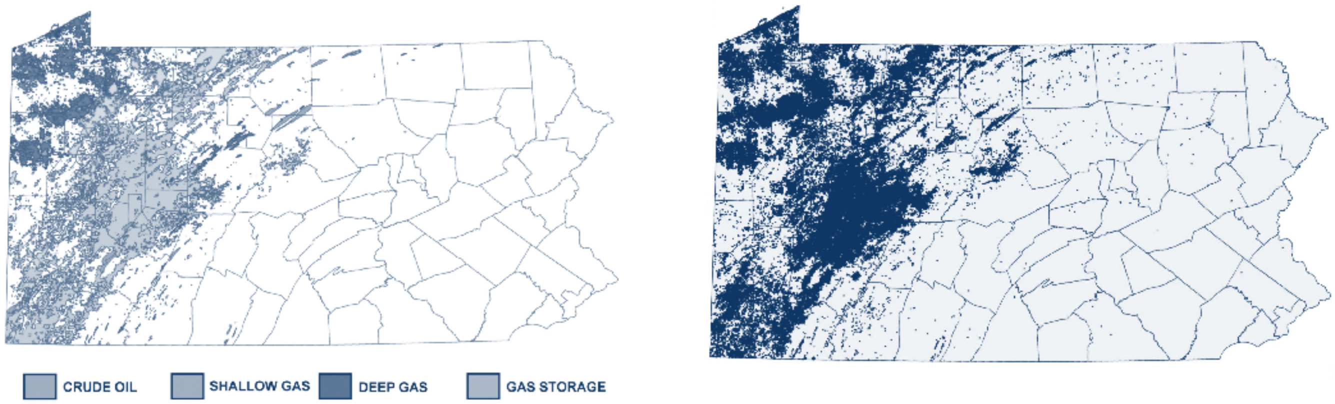

Figure 8: Pennsylvania Oil and Gas Wells and Fields (Carbon Management Advisory Group)

Pennsylvania's carbon emissions at the present rate of 317 million tons per year, and that figure of 317 million tons represents the total Pennsylvania CO_2 output, including both mobile and fixed sources. These capacity estimates are largely based on the extensive geologic data collected in the course of oil and gas exploration over the last century, so the western third of the state, where the greatest oil and gas exploration has occurred, offers the best data.

Deep saline formations offer an estimated 85 percent of Pennsylvania's sequestration potential. In addition, Figure 9 shows the vast extent of oil and gas wells and natural gas fields in Western Pennsylvania, illustrating the considerable opportunities for carbon sequestration in this region.

Not only does Western Pennsylvania contain numerous candidates for geological carbon sinks, but the region's underground strata also appear suitable for stable, long-term sequestration because of their formation. The layers were not deposited in long, continuous, blanket-like layers but in the shape of long lenses, with beginning and end points, sealed with tight shales and clays in between. These seals have kept the rich oil and gas deposits in the region stable for millions of years. They should also be able to hold CO_2 deposits. However, the thousands of wells used to access underground oil and gas resources over the past century will have to be accurately located and capped to ensure long-term security of the CO_2.

The coal industry's presence should not impact sequestration adversely. The most desirable and minable coal, the Pittsburgh Seam, is located at a depth of about 700–1,000 feet, or 2,000 feet above the minimum safe depth for sequestration. Virtually every rock layer in Pennsylvania that has produced oil or gas—rock layers that would be under consideration for carbon storage—is below the level of the Pittsburgh Coal Seam.

Two other important issues when considering an area's sequestration potential are low seismic activity and ample water. An area prone to seismic activity would present an increased risk of a rupture of the rock layers that seal the CO_2 reservoir; Southwestern Pennsylvania does not have this problem. With regard to water, the risk of negative impact on drinking water supplies is greatest where aquifers are depleted or where water supplies are in decline due to overuse, as is the case in many parts of the country. In contrast, the U.S. Army Corps of Engineers has designated Southwestern Pennsylvania as the most reliable watershed in the country. These factors help to make the region a very attractive carbon sink.

Suitable geology alone is not enough; the geology also must be under friendly ownership. Pennsylvania is unique in its property ownership in that the state government owns about 16 million of the nearly 30 million acres in Pennsylvania. These land holdings consist primarily of state parks, state forests, and state game lands. DCNR owns the mineral rights and the associated pore space on about 85 percent of these public lands. Such property would be ideal for early sequestration trials, as the state's partnership would eliminate the complexities of dealing with private land and mineral rights owners. In addition, because the state's land holdings are so vast, pilot sites could be placed far away from any private landowner's property.

An Appropriate Source

Identifying a carbon source of the right magnitude and purity for the pilot will require careful consideration. Because the pipeline would cost about $1 million per mile, the carbon source also should be located as close as possible to a suitable storage site.

The carbon dioxide emitted from smokestacks at power plants or major industries is heavily diluted with other gases, such as nitrogen, and would not offer the best source. Two better candidate sources, Integrated Gasification Combined Cycle power generation plants and ethanol plants, do not exist in

Southwestern Pennsylvania. Tankers deliver pure, commercially refined CO_2 for use by the food industry, but this source would be expensive.

On the other hand, Southwestern Pennsylvania's mining industry offers an excellent option. In order to keep mines safe for breathing, big fans push air in and ventilate the methane that accumulates. The vented air is scrubbed to strip out the methane, the methane (a greenhouse gas 21 times more potent than CO_2) is converted to CO_2, and the CO_2 is then released to the atmosphere. This CO_2 is relatively pure and of a volume amenable to a pilot sequestration project.

An even better source might be a coal bed methane gas recovery plant. Once a deadly threat to coal miners, methane gas has become a valuable natural resource for companies like CONSOL Energy, which extracts and sells it for transmission through the natural gas distribution system. Before its sale, the natural gas is processed through a recovery plant that strips out the water vapor and the CO_2, as the methane must meet high quality standards before it can be injected into the distribution system. The CO_2 generated by such a facility is relatively pure, already captured in a pipeline, and adequate in quantity.

An Accepting Public

Scores of coal-fired power generation facilities have been shelved or postponed in recent years, largely because the public believes that global warming is primarily attributable to carbon dioxide emissions from fossil fuel combustion. However, as we have already seen, our society has no viable near-term alternative to the use of coal to generate electricity, so we will continue to emit great amounts of CO_2 for decades or longer. Geologic carbon capture and sequestration is the only strategy currently available that can contain even a significant percentage of the volume of carbon generated. As Southwestern Pennsylvania has many major carbon-generating facilities, the region most likely also will become, sooner or later, the home of carbon sequestration projects of equivalent scale.

A good outreach and education strategy could help Southwestern Pennsylvania's citizenry to understand these issues, to recognize that the United States must move forward on developing its carbon sequestration assets, and to perceive this need as an economic development opportunity for the region.

An Enabling Legislative and Regulatory Framework

Carbon sequestration brings with it challenges and questions that will have to be addressed through legislation and regulation, such as the following:

- Who carries the liability associated with the behavior of the carbon dioxide underground?
- Does the ownership of the pore spaces in the rocks into which the CO_2 is injected convey with the mineral rights?
- What state agency (or agencies) will assume regulatory authority for the sequestered CO_2?

By acting soon, Pennsylvania could become the national leader in establishing an intelligent legislative and regulatory framework for CCS projects.

Innovative and Strategic Leadership

A pilot carbon sequestration project requires innovative, risk-taking leaders who understand the project's great potential value and are dedicated to bringing it to fruition. Leaders from various sectors could contribute toward the pilot's success:

- **Elected officials and regulators** could be asked to pass new legislation and prepare regulations that will facilitate implementation of new technologies while ensuring public safety and protecting the rights of property owners and citizens. As no state has passed comprehensive model legislation, Pennsylvania would be breaking new ground. Legislators also could help to fund the project.
- **Corporations** could provide resources, equipment, or services that would advance the project, showcase the assisting corporation, and open the door to the development of a new industry in the region.
- **Foundations** could provide early stage funding for planning, engineering, and public outreach, along with matching funds to secure state and federal program dollars.
- **Community leaders** could promote reasonable public discussion, move stakeholders away from highly polarized positions, and broker the compromises necessary for a project of this magnitude and potentially controversial nature to move forward.
- **Research leaders** could volunteer to help with project design, implementation, and oversight.

A core leadership team, with membership from all the sectors just enumerated, should be formed to move the project forward.

Financial Resources

Chapter 5 outlined the likely costs of a pilot project, to the extent that they can be reasonably assessed before selection of a carbon dioxide source or sequestration site. Identification of a relatively pure CO_2 source could greatly reduce costs at the pilot stage. The opportunity to be a national or even international leader in the emerging carbon sequestration sector would seem to justify a $15 million initial investment.

8. NEXT STEPS

Should state and regional leadership agree to move forward with a carbon sequestration pilot project, the first step would be to assemble a project team including elected officials, corporate leaders, agency heads, regulators, engineers, and representatives of foundations and community organizations. This team's first task would be to identify one or more options for a CO_2 source and sink. Key factors in this selection would include:

- The location of a suitable source, with the right purity and volume;
- The suitability of the nearby geologic substrate for use for CO_2 storage;
- Property rights ownership; and
- Quality of available geological and engineering data for the target formation.

Development of a public outreach plan also should begin immediately. Broad-based public education before the announcement of a proposed location could increase the effectiveness of subsequent outreach in the vicinity of a prospective project site.

Other planning-stage actions following selection of a source and sink would include:

- Completion of a preliminary cost analysis and a preliminary project plan,
- Meeting with the governor and appropriate executive agency heads,
- Working with state and regional elected officials to outline a plan for enacting the necessary legislative and regulatory framework, and
- Identifying potential sources of funding and initiating grant applications.

After the enactment of suitable legislation and the acquisition of sufficient funds, the project could then move into implementation, beginning with construction of the pipeline and injection well, followed by the beginning of CO_2 injection.

The time required from project launch to initial injection would be at least two years; it could be longer if efforts to pass legislation, write regulations, and assemble adequate funding cause delays.

Capturing greenhouse gases and figuring out how to store them forever is a big challenge, and the solutions will be expensive. But this challenge also presents an economic development opportunity. Southwestern Pennsylvania is arguably the U.S. region best positioned to develop and refine the technologies, to provide its ample pore space for a pilot project, and then to market clean coal products and services across the world. The opportunity certainly deserves serious attention.

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