PERSPECTIVE

Preparing to Capture Carbon

Daniel P. Schrag

Carbon sequestration from large sources of fossil fuel combustion, particularly coal, is an essential component of any serious plan to avoid catastrophic impacts of human-induced climate change. Scientific and economic challenges still exist, but none are serious enough to suggest that carbon capture and storage will not work at the scale required to offset trillions of tons of carbon dioxide emissions over the next century. The challenge is whether the technology will be ready when society decides that it is time to get going.

Strategies to lower carbon dioxide (CO_2) emissions to mitigate climate change come in three flavors: reducing the amount of energy the world uses, either through more efficient technology or through changes in lifestyles and behaviors; expanding the use of energy sources that do not add CO_2 to the atmosphere; and capturing the CO_2 from places where we do use fossil fuels and then storing it in geologic repositories, a process known as carbon sequestration. A survey of energy options makes clear that none of these is a silver bullet. The world's energy system is too immense, the thirst for more and more energy around the world too deep, and our dependence on fossil fuels too strong. All three strategies are essential, but the one we are furthest from realizing is carbon sequestration.

The crucial need for carbon sequestration can be explained with one word: coal. 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 cheap relative to almost every other source of energy (Table 1). Today, coal and petroleum each account for roughly 40% of global CO_2 emissions. But by the end of the century, coal could account for more than 80%. Even with huge improvements in efficiency and phenomenal rates of growth in nuclear, solar, wind, and biomass energy sources, the world will still rely heavily on coal, especially the five countries that hold 75% of world reserves: the United States, Russia, China, India, and Australia (*1*).

As a technological strategy, carbon sequestration need not apply only to coal plants; indeed, any point source of CO_2 can be sequestered, including biomass combustion, which would result in negative emissions. Carbon sequestration also refers to enhanced biological uptake through reforestation or fertilization of marine phytoplankton. But the potential to enhance biological uptake of carbon pales in comparison to coal emissions, ever more so as India, China, and the United States expand their stock of coal-fired power plants. So developing and deploying the technologies to use coal without releasing CO_2 to the atmosphere may well be the most critical challenge we face, at least for the next 100 years, until the possibility of an affordable and completely nonfossil energy system can be realized.

If carbon sequestration from coal combustion is essential to mitigate the worst impacts of global warming, what stands in the way of its broad implementation, both in the United States and around the world? With limited coal reserves, countries in the European Union have chosen to emphasize climate mitigation strategies that focus on energy efficiency, renewable sources, and nuclear power. Of the major coal producers, Russia, China, and India have been unwilling to sacrifice short-term economic growth, although Chinese coal gasification efforts, which many see as a step toward sequestration capacity, are more advanced than current U.S. policies. In the United States, there are scientific and economic questions that must be answered before large-scale deployment can be achieved. But none of these is critical enough to suggest that carbon sequestration cannot be done. The real obstacle is political will, which may require more dramatic public reaction to climate change impacts before carbon sequestration becomes a requirement for burning coal. In the meantime, there are critical steps that can be taken that will prepare us for the moment when that political will finally arrives.

The scientific questions about carbon sequestration are primarily associated with concerns about the reliability of storage of vast quantities of CO_2 in underground repositories. Will the CO_2 escape? The good news is that the reservoirs 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 pre-industrial levels. The ocean contains 50 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 time scale of mixing of the deep ocean, roughly 1000 to 2000 years, natural uptake of CO_2 by the ocean, combined with dissolution of marine carbonate, will absorb 90% of the carbon released by human activities. As long as the geologic storage of CO_2 can prevent substantial leakage over the next few millennia, the carbon cycle can handle it.

Our current understanding of CO_2 injection in sedimentary reservoirs on land suggests that leakage rates are likely to be very low (*2*). Despite many years of experience with injection of CO_2 for enhanced oil recovery, few studies have accurately measured the leakage rates over time intervals long enough to be certain that the CO_2 will stay put even for the next few centuries. In most of the geological settings under consideration, such as deep saline aquifers or old oil and gas fields, CO_2 exists as a supercritical fluid with roughly half the density of water. CO_2 is trapped by low-permeability cap rocks and by capillary forces, but can 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 per year, a tiny amount compared to the need for as much as 10 billion tons per year by the middle of the century. 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.

A recent proposal identified a leak-proof approach to storage by injecting CO_2 in sediment below the sea floor (*3*), which avoids the hazards of

Table 1. Carbon content in gigatons (Gt) of fossil fuel proven reserves and annual production (2005) (*6*).

Country/region	Coal		Petroleum		Natural gas	
	Reserves	Production	Reserves	Production	Reserves	Production
United States	184.0	0.64	3.6	0.30	3.0	0.29
Russia	117.1	0.15	9.0	0.42	26.2	0.33
China	85.4	1.24	1.9	0.16	1.3	0.03
India	69.0	0.22	0.7	0.03	0.6	0.02
Australia	58.6	0.23	0.5	0.02	1.4	0.02
Middle East	0.3	0.00	90.2	1.11	39.4	0.16
Total world	678.2	3.23	145.8	3.59	98.4	1.51

Department of Earth and Planetary Sciences, Harvard University, Cambridge, MA 02138, USA. E-mail: schrag@eps.harvard.edu

direct ocean injection, including impacts on ocean ecology. In this case, CO_2 would stay separate from the ocean, because it exists in the sediment at high pressure and low temperature as a dense liquid or combined with pore fluid as solid hydrate. Despite higher possible costs, this approach may be important for coastal locations, which are far from appropriate sedimentary basins, and may also avoid expensive monitoring efforts if leakage from terrestrial settings is found to be a major problem.

In terms of capacity, the requirements are indeed vast. Conservative estimates of reservoir needs over the century are more than 1 trillion tons of CO_2, and might exceed twice that much. This far exceeds the capacity of oil and gas fields, which will be among the first targets for sequestration projects because of additional revenues from enhanced oil recovery. Fortunately, the capacity of deep saline aquifers and deep-sea sediments is more than enough to handle centuries of world coal emissions (*3*, *4*). This means that the locations first used to store CO_2 underground may not be the ones used by the middle of the century as sequestration efforts expand. It suggests that a broad research program must be encouraged that focuses not just on what will be done in the next few decades, but also on approaches that will be needed at the scale when all coal emissions will be captured.

Additional questions surround the more expensive part of carbon sequestration, the capture of CO_2 from a coal-fired power plant. Conventional pulverized coal plants burn coal in air, producing a low-pressure effluent composed of 80% nitrogen, 12% CO_2, and 8% water. CO_2 can be scrubbed from the nitrogen using amine liquids or other chemicals, and then extracted and compressed for injection into storage locations. This uses energy, roughly 30% of the energy from the coal combustion in the first place (*4*), and may raise the generating cost of electricity from coal by 50% (*5*), although these estimates are uncertain given that there is not yet a coal plant that practices carbon sequestration. Pulverized coal plants can also be retrofit to allow for combustion of coal in pure oxygen, although the separation of oxygen from air is similarly energy intensive, and the modifications to the plant would be substantial and likely just as costly (*4*).

Gasification of coal, which involves heating and adding pure oxygen to make a mixture of carbon monoxide and hydrogen, can be used either for synthesis of liquid fuels or for electricity. These plants can be designed to produce concentrated streams of pressurized CO_2, often referred to as "capture-ready," although this also comes at a high cost. Much attention has been given to coal gasification as a means for promoting carbon sequestration because studies suggest that the costs are lower than retrofitting an existing pulverized coal plant (*4*). However, experience with gasification plants is limited; there are only two such plants in the United States, and neither is capture ready. More encouragement of coal gasification technology is important to discover whether the promises of lower sequestration costs can be realized. But regardless of the emphasis on such advanced coal plants, the world's existing arsenal of pulverized coal plants (excluding the 150 new pulverized coal plants that are currently in the permitting process in the United States) produce roughly 8 billion tons of CO_2 per year, more than any responsible climate change policy can accommodate. Thus, the investment in advanced coal gasification plants must be matched by an effort to optimize our ability to capture the CO_2 from existing pulverized coal plants.

Compared with the cost of most renewable energy sources, increasing the cost of electricity from coal by 50% to add sequestration seems like a bargain. When one includes the distribution and delivery charges, electric bills of most consumers would rise only 20% or so. So why is this not a higher priority in climate change legislation? Most legal approaches to climate change mitigation have focused on market mechanisms, primarily cap and trade programs. A problem is that the cap in Europe and any of the caps under discussion in the U.S. Congress yield a price on carbon that is well below the cost of capture and storage. Even if the cap were lowered, power companies might hesitate to invest in the infrastructure required for sequestration because of volatility in the price of carbon. Thus, it seems that another mechanism is required, at least to get carbon sequestration projects started.

And there are many other questions. Who will certify a storage site as appropriate? How will the capacity be determined? Who will be responsible if CO_2 leaks? How will we safeguard against cheating? It is clear that governments need to play some role in CO_2 storage, just as they do in other forms of waste disposal, but the exact details of a policy are unlikely to be decided in the near future, long before carbon sequestration becomes normal practice. But the uncertainty about these and other issues contributes to a general cloudiness that discourages industry from making investments toward sequestration efforts.

Despite these obstacles, a variety of carbon sequestration activities are proceeding. Regional partnerships have been established in the United States, supported by the U.S. Department of Energy (DOE), to study the possibilities for sequestration around the country. In 2003, President Bush announced a commitment to FutureGen, a DOE project to build a zero-emission coal gasification plant that would capture and store all the CO_2 it produced. FutureGen is an exciting step forward, but a single coal gasification plant that demonstrates carbon sequestration is unlikely to convince the world that carbon sequestration is the right strategy to reduce CO_2 emissions. Moreover, a power plant operated by the government may fail to convince power companies that the costs of sequestration are well determined.

Luckily, FutureGen has competitors. British Petroleum (BP), in cooperation with General Electric, plans to build two electricity-generating plants, one in Scotland and one in California, that would sequester CO_2 with enhanced oil recovery. Xcel Energy has also made a commitment to build a coal gasification plant with sequestration. And more projects may soon be announced as companies begin to view legislation controlling CO_2 emissions as a political inevitability.

Given the current questions about sequestration technology, the current economic realities that make it unlikely that many companies will invest in sequestration over a sustained period, and the political realities that make it unlikely we will see in the next few years a price on carbon high enough to force sequestration from coal, what can government do to make sure that carbon sequestration is ready when we need it? Whatever the path, it is time to get going, not just with small test projects but with full-scale industrial experiments. The announcements by BP and Xcel Energy are encouraging because the world needs many such sequestration projects operating at different locations, with a handful of capture strategies and a wider variety of geological settings for storage. The U.S. government can encourage these efforts, and sponsor additional ones, making sure that there are 10 to 20 large sequestration projects operating for the next decade so that any problems that do arise with capture or storage can be identified. By creating a competitive bidding process for long-term sequestration contracts, the United States can ensure that the most cost-efficient strategies will be used while testing a variety of capture and storage options including retrofitting older pulverized coal plants. The United States and the world need carbon sequestration—not right now, but soon and at an enormous scale. Our challenge today is to ensure that the technology is ready when serious political action on climate change is finally taken.

References and Notes

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6. Data on proven reserves and production are from (*1*). Carbon content was calculated assuming 25.4 tons (1 ton = 10^3 kg) of carbon per terajoule (TJ) of coal; 19.9 tons of carbon per TJ of petroleum; and 14.4 tons of carbon per TJ of natural gas. Differences between anthracite, bituminous, lignite, and sub-bituminous coal were not included.
7. The author benefited from discussions with K. House and J. Holdren.

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