ISSUES ONLINE
IN SCIENCE AND TECHNOLOGY

A Publication of
National Academy of Sciences
National Academy of Engineering
Institute of Medicine
University of Texas at Dallas

JAY APT
DAVID W. KEITH
M. GRANGER MORGAN

Promoting Low-Carbon Electricity Production

To encourage utilities to emit less carbon dioxide, the government should implement—soon—a carbon portfolio standard with predictable requirements and guarantee loans for building advanced generating facilities.

The electric power industry is the single largest emitter of carbon dioxide in the United States, accounting for 40% of CO_2 emissions in 2006, up from 36% in 1990 and 25% in 1970. The electricity sector is therefore a natural target as federal and state governments begin to get serious about managing CO_2 emissions. Moreover, because the marginal cost of reducing emissions in the electricity sector appears to be lower than in other sectors such as transportation, the electricity sector may deliver the largest proportional carbon reductions under an economically efficient climate policy.

Several strategies have been proposed to constrain CO_2 emissions. Many economists argue that an emissions tax is the ideal tool. But although such a tax may be a good idea in theory, in the real world there are a variety of problems. The fact that it is called a "tax" may present political obstacles in some locales, even though revenues might be used to offset less efficient and politically less desirable taxes. And unless its future is clearly and irrevocably specified, an emission tax may not provide sufficient leverage to overcome the risks and encourage private investments in large capital projects that can deliver cost-effective emissions control.

Cap-and-trade systems are often advanced as a more practical alternative. Such a system requires an initial allocation of permits for CO_2 emissions up to the capped limit. Ideally, emission permits should be auctioned so as not to privilege any party. In reality, there are strong political pressures to allocate permits to existing emitters—to "grandfather" permits—and these pressures can produce ineffective and politically unacceptable transfers of wealth to existing large emitters.

Experience with cap-and-trade systems in the European Union (EU) proved less than encouraging, as the system turned chaotic in 2006. Prices for CO_2

allowances in the trading market crashed from 30 euros per metric ton of CO_2 to a low of 3 euros, as every EU member but the United Kingdom reported that their emissions were not as high as their too-generous allocations. The resulting mess has stymied investment. Companies that had made plans to install carbon controls that were economical at prices of 25-30 euros per metric ton of CO_2 found themselves unable to justify the cost at the lower prices. The temptation for governments to manipulate emissions estimates used for permit allocations may be an intrinsic problem with cap-and-trade.

Some observers have argued that the best bet for promoting reductions in CO_2 emissions is for government to establish renewables portfolio standards (RPSs), which mandate that electricity distributors must rely on specific renewable energy sources to provide a set percentage of power supplied to their customers. Twenty U.S. states have enacted some form of RPS, with quotas that range from 1% to 30% of electric power.

RPSs are not without drawbacks, however. Although achieving "energy renewability" is loosely correlated with the objective of reducing carbon emissions, it is not the same thing. An RPS is a policy instrument with many objectives. Recent RPS debates have cited numerous goals, including reducing air pollutants, keeping down fluctuating prices of fossil fuels, encouraging energy independence and diversity of fuel supply, promoting resource sustainability, and creating jobs. Although this kitchen sink approach may make it politically easier to pass RPSs than more focused regulations, there are significant cost penalties. One penalty is that some of the renewable sources encouraged or mandated by an RPS produce electric power only intermittently, making poor use of expensive capital investments. Another is that set-asides and subsidies for sources such as solar photovoltaic, which are now much more expensive than wind, conservation, or new carbon-controlled fossil and uranium energy sources, significantly increase the cost of power provided to consumers.

Given such considerations, we believe that the best method to promote reductions in carbon emissions is for individual states, which typically regulate energy matters, to adopt a carbon emissions portfolio standard (CPS). Under such a strategy, each supplier of electricity would be responsible for assuring that it meets an overall constraint on its carbon emissions. The company must supply the mandated fraction of low-carbon power, from wherever it is purchased. A CPS avoids the thorny problem of allocating permits because it requires distributors to buy a set amount of low-carbon power but allows them to seek the most inexpensive suppliers. Moreover, a CPS can be written to allow trading among those jurisdictions that have similar rules. A CPS can send a clear market signal to generators and provide a robust incentive to make long-term investments in generation technologies with low- or no-carbon emissions.

To complement state adoption of CPSs, the federal government should guarantee loans for construction of advanced generating plants that emit significantly less CO_2 than current facilities. Such loan guarantees may be critical to obtaining financing from investors who have demanded risk premiums to compensate for the uncertainty of electric competition, lowering the bond rating of most investor-owned utilities.

Technology options

Technologies to produce electric power with low-carbon emissions already are in use at various scales. These sources include nuclear, hydroelectric, biomass, geothermal, wind, and solar power. Together they account for roughly 28% of all U.S. electric power production, with nuclear representing the majority (20%), followed by hydroelectric (7%). However, demand for power is increasing, driven by increased population and per capita demand. If the current rates of electric generation construction are maintained, by 2020 the percentage of low-carbon sources is projected to fall to 21% of total production.

Clearly, the nation will need to develop—or, in some cases, simply adopt—other power-generating technologies that use coal, an abundant resource, but greatly reduce CO_2 emissions or control their dispersal. (See sidebar.) Studies presented at the International Energy Agency's Greenhouse Gas Technology Conferences have shown that if the electric power industry adopts technologies to greatly reduce CO_2 emissions, the wholesale cost of power would rise by roughly two to three cents per kilowatt-hour for fossil-fuel, wind, and nuclear options, four to five cents for geothermal, and more than 20 cents for solar.

Based on available estimates of the likely cost of future low-carbon options, we have estimated that the cost of eliminating most CO_2 emissions from the electricity system would reach a range from 0.4% to 0.9% of the U.S. gross domestic product (GDP) as the proportion of low-carbon power is increased over the next four decades, provided the transition is achieved in a gradual and orderly manner. Although this is a significant amount of money—roughly $60 billion to $125 billion per year—it is certainly manageable. Despite dire predictions, the nation's economy thrived while spending 1.5% of GDP to reduce air pollution discharges in the 1970s and 1980s.

BEGINNING NOW WITH MEASURES SUCH AS CARBON PORTFOLIO STANDARDS AND LOAN GUARANTEES FOR LOW-CARBON PLANTS WOULD REDUCE THE LONG-RUN COST OF CONTROLLING CARBON.

If the United States waits to encourage low-carbon technologies, foreign companies may seize the early market advantage. Both Shell and GE are working hard on coal gasification, but Shell has ready markets close to home in Europe. The benefits to the economy of taking the leading market share can be very large.

Cost of regulatory uncertainty

The electric power industry is well aware of the possibility that the federal government will impose carbon constraints, perhaps in the near future. The chief executive officer of Exelon, one of the nation's largest electric power producers, said that he is in favor of a carbon tax, but would also support the idea of tradable CO_2 emissions permits with a cap. The CEO of Duke Energy came out in favor of a carbon tax in April 2005. Cinergy's CEO wrote to shareholders in December 2004 that "we eventually will operate our business in a carbon-constrained world and it is our responsibility to prepare for that likelihood."

Power producers and distributors could make better planning decisions if the government was clearer about its regulatory timetable. If companies were certain that the government will require specific reductions in levels of CO_2 emissions by certain dates, they would make decisions accordingly. A power plant has a life of many decades (13 coal plants from the 1920s are still operating). If a carbon constraint costing, say, $50 per ton of emitted CO_2 were to come into force 10 years into a plant's 40-year planned lifetime, managers could easily calculate whether it was in their interest to install low-carbon technology.

In the real world, however, the timing and stringency of pollution constraints remain uncertain. In this climate, companies will likely continue to build conventional high-carbon-emissions plants, because they are cheaper. Indeed, uncertainty may encourage utilities to rush now to build conventional plants in the hope that they will be grandfathered under any new regulations, which would increase total costs by imposing more stringent emission constraints for plants built later. For this reason, state legislatures and public utility commissions (PUCs) would be wise to make it clear that investors, not rate payers, will bear future regulatory costs if conventional plants are built today without at least leaving space to later add postcombustion capture and storage of CO_2.

Retrofits of this sort have been done for years for other pollutants, and lessons learned in those applications can help to avoid some costs in retrofitting for CO_2 capture and storage. For example, one lesson from retrofits for controlling emissions of sulfur dioxide and nitrogen oxides has been that allocating space for postcombustion capture units during construction can reduce retrofit costs significantly. Retrofits have total costs greater than those of a purpose-built low-carbon plant but allow the decision to be postponed until it becomes mandatory. The public would bear the extra costs of this decision in the form of higher electricity bills; the total bill would be more than if a low-carbon plant had been built from the start. The company is making a rational decision, ensuring its survival by not expending too much capital when the carbon tax is still uncertain.

The decision to build from the start with a low-carbon technology or to retrofit will depend, in part, on the scale of the extra costs that are imposed by the retrofit. The higher the extra retrofit costs, the more likely the tendency to install a low-carbon technology before the carbon-control details are clarified. For example, Joule Bergerson of the University of Calgary and Lester Lave of Carnegie Mellon University have determined that building an integrated gasification combined cycle (IGCC) coal-fired plant—one of the promising technologies becoming available—and then later adding the capability to capture CO_2 and sequester it deep underground costs 50% more than building in CO_2 capture and storage at the beginning. In addition, they determined that a company would be better off building in carbon capture at the start only if they believe a $100-per-ton CO_2 penalty will happen within seven years of the plant's commissioning. If they believe the $100 penalty will occur later than year 13, they would be more likely to build a conventional coal-fired plant with retrofit capability for capturing and storing CO_2.

In another study, Peter Reinelt of the State University of New York at Fredonia and David Keith of the University of Calgary have quantified the costs of regulatory uncertainty in a simplified dynamic model. They find that if it is technically feasible to retrofit a plant for later CO_2 capture and storage, uncertainty in carbon regulation may increase the social cost of controlling carbon emissions by 10% to 30%, whereas if retrofits are not feasible and if natural gas prices are high enough to eliminate its use as a bridging strategy, the cost of regulatory uncertainty may rise to nearly half the total social cost of carbon abatement.

BUILDING COMMERCIAL SCALE PLANTS IS THE BEST WAY TO STIMULATE THE RESEARCH AND DEVELOPMENT THAT WILL DRIVE DOWN THE COSTS AND RISKS OF CARBON MANAGEMENT.

The costs and risks of carbon management could clearly be reduced through further research and development. However, the electric power industry is notorious for its low investment in R&D. Given that regulatory uncertainty is quite likely to continue, and that large fluctuations in the price of carbon allowances will occur even after the introduction of carbon controls, R&D that lowers the cost of retrofit options can significantly reduce the cost of regulatory uncertainty.

At the same time, because most of the basic technologies are already in commercial use in other settings, it is even more important to begin to build full-scale plants and thus move upward on the learning curve. As a recent editorial in Nature declared, “Bringing carbon sequestration into a fast track requires more than scattered demonstration projects and vague hope that prudent industries might voluntarily adopt it at some point in the future.”

Decisions by power-generating companies

Improving coal-fired power plants will be critical, as more than half of all U.S. electricity is produced by coal. Also, the average coal-fired generator is 34 years old, and 10% of plants are at least 48 years old. Many plants will be replaced soon, and new ones will be added to meet increased demand.

However, one of the largest barriers to corporate investment in low-carbon technologies is the rate of return on capital invested in such technologies as compared to the rate of return on alternative investments. State public utility commissions set electric rates, giving companies a set rate of return on approved investments. In the states where PUCs set utilities’ prices—some states have turned away from this practice in recent years—the PUCs can play a significant role in stimulating low-carbon investments, if they can be reconciled with the PUCs’ statutory obligations, as is the case when a requirement for pollution control devices exists.

Profits are based on a set rate of return on capital, so more investment means more profit. When the PUC approves such investments, utilities find that they can borrow capital at reasonable rates, since the lenders correctly perceive that they face low risk because the rate of return is guaranteed and the utility faces no competition within its service territory. On the other hand, investors lending funds to competitive power producers face uncertain returns and so lend at much higher rates. Not surprisingly, the majority of utilities contemplating investments in large low-carbon plants are in regulated states, where they are attempting to secure access to capital by partnering with their public utility commissions to build such facilities.

Federal policy, such as the loan guarantees enacted in 2005 for the first few new coal gasification and nuclear plants, can significantly lower the capital cost. These policies are much less costly to the government than are direct subsidies because the government pays only when the borrower defaults.

REGULATORY UNCERTAINTY MAY DISCOURAGE INVESTMENT IN LOW-CARBON TECHNOLOGIES.

Will companies invest on their own because they feel that low-carbon technologies are likely a good way to meet current pollution regulations? Dalia Patiño-Echeverri at Carnegie Mellon has used historic market data for SO2 and NOx allowances, along with estimates for

CO_2 and mercury allowances, to compute the value of such options. She found that in the absence of a carbon price, only if the owners have a planning horizon longer than 20 years would they replace a conventional coal-fired plant with a high-performance unit; otherwise, they would install SO2 and NOx controls on the existing plant. Without a carbon price, installing advanced technology would not be profitable.

Moreover, even in an era when CO_2 allowances in a cap-and-trade system cost an average of $30 per ton of CO_2, it is still unlikely that building an IGCC coal-fired plant will be profitable. At current prices for low-carbon technologies, an allowance price of roughly $35 to $50 per metric ton of CO_2 would be required to trigger major commercial investment in low-carbon technologies.

Power plant operators are very conservative. Most of them do not count government-funded plants using advanced technology as effective demonstrations. They prefer to wait until a fellow company has operated a plant using new technology before ordering one themselves. Incentives to encourage companies to build and operate such plants can reduce the barriers to widespread adoption.

Conversely, if the government concentrates on supporting large and lengthy demonstration projects, this might delay commercial adoption of new technology by a decade or more. For example, the Department of Energy's (DOE's) Future-Gen project, which will construct an IGCC coal-fired plant with CO_2 capture and sequestration, may be far less effective in inducing rapid adoption and technological progress than loan guarantees that encourage development of similar technology under private control. Like similar projects in the past, FutureGen's effectiveness is likely to be blunted because the project in all probability will incorporate too many new (government-driven) technologies that, in combination with a lack of a champion who has the financial commitment to push the project to success, will make CO_2 capture look more risky and costly than it will be under commercial development.

Time to act

Who should act first in advancing the industry? State public utility commissions can approve reasonable and prudent investments in low-carbon plants that will be used and useful. State legislatures can enact carbon portfolio standards, or change renewables portfolio standards to CPS as the expenses of RPS mandates loom large. States can expand regional low-carbon initiatives. The DOE should implement the provisions of the Energy Policy Act of 2005 calling for federal loan guarantees for developing low-carbon generating capacities. These steps will greatly lessen the cost of implementing federal carbon standards.

Whatever is done, the nation must start soon. There are three penalties for delayed action on carbon control. First, a 15% discount rate (which many companies use for investment decisions) lowers the present discounted cost of a $100-per-ton CO_2 emission tax or allowance cost imposed in 2030 to $3-per-ton this year, far too low to affect investment decisions. Thus, a perception that carbon control can be put off stifles investment.

The second penalty is that since much of the CO_2 emitted stays in the atmosphere for more than a century, delaying steps to curtail emissions today increases the likelihood that draconian measures will be needed toward the middle of the century to cope with emerging environmental problems. Put another way, the cost of carbon control would nearly double if introduced in a panic after dangerous effects began to be observed. If those dangerous effects were large enough, some nations might unilaterally embark on "geoengineering" projects that may pose security risks and have highly uncertain long-term ecological impacts.

As a third penalty, if controls are delayed, the nation's aging coal plants will be replaced with new plants with high-carbon emissions. If carbon controls are then enacted, these new plants, which operate for 40 years or more, would make the cost of meeting a future carbon constraint much higher.

China will soon pass the United States as the largest CO_2 emitter. Many argue that for this reason, the United States should do nothing to control emissions from its power plants until China does more to curtail greenhouse gas emissions. When people hear this argument, they probably think in terms of familiar air pollution, such as sulfur dioxide. Once it enters the atmosphere, normal pollution stays there only a few hours or days. Carbon dioxide is not like that. Much of it stays in the atmosphere for a century or more. Climate change is caused by the cumulative impact of all the CO_2 that human activities have added to the atmosphere since the beginning of the industrial revolution.

When past emissions are factored in, the United States is responsible for just over a quarter of all anthropogenic CO_2 from fossil fuels currently in the atmosphere. Europe, China, and India are responsible for 19%, 9%, and 3% respectively. The EU has agreed to reduce emissions to 8% below 1990 levels by 2012; the United States has not. EU emissions are the same as in 1990; U.S. emissions have increased by 20%. And because CO_2 emissions remain in the atmosphere for over a century, the largest single share of CO_2 will continue to belong to the United States for many decades, despite China's growth.

Since the United States has put the largest single share of CO_2 into the air, it must begin to take the lead in reducing it. In a few decades, China, India, Brazil, and other developing countries also will have to undertake serious controls. But they will not do so until we take the lead and show how it can be done in an efficient and affordable way.

Beginning now with measures such as CPSs and loan guarantees for low-carbon plants can make later actions much less costly. A CPS is the least-cost national solution, and has many of the benefits espoused by proponents of RPSs. But there is no escaping the conclusion that effective control of carbon in the U.S. electric power industry requires regulators to act quickly to set a clear timetable for emission reductions.

Low-Carbon Technologies

Conventional coal-fired plants, which burn pulverized coal in boilers, emit more CO_2 per kilowatt-hour than any other method of producing electricity. High-performance coal plants, called supercritical plants, and very high-performance plants, called ultra supercritical plants, are more efficient than even the newest pulverized-coal generation plants. Replacing an old, inefficient coal plant with a supercritical or ultra supercritical plant can reduce CO_2 emissions by a third.

Emissions can be reduced much more by chemically capturing the CO_2 produced during combustion and injecting it deep underground, a process called CO_2 capture and deep geological sequestration. The technologies required to capture CO_2 from all types of pulverized-coal plants, transport it long distances by pipeline, and inject it into underground reservoirs exist at commercial scale today.

A few pilot coal-fired plants use a method in which coal is burned, but in the presence of a much higher percentage of oxygen than is present in ordinary air (95% instead of 20%). This “oxyfuel” method produces an exhaust gas with much higher concentration of CO_2, making capture more efficient than with a conventional boiler.

At 130 coal-burning facilities around the world, including some plants that produce electricity, coal is used in a very different fashion. Instead of being burned in open flames, it is fed into a refinery vessel along with oxygen. The process results in exhaust streams of CO_2, hydrogen gas, sulfur powder, and a glassy slag containing various other impurities. The CO_2 gas stream can be injected deep underground instead of being released into the atmosphere, reducing emissions by 85%. When used to produce electricity, these plants are called integrated gasification combined cycle (IGCC) plants.

Among other current low-carbon energy sources, nuclear power is the largest deployed technology. But the capital cost of building a nuclear station is considerably larger than that of a coal-fired plant with conventional pollution control. If nuclear power is to keep its present 20% share of electricity production—from 103 plants now operating—30 new nuclear plants must be brought into service by 2020 to keep up with increasing demand. After 2020, many existing nuclear plants may have to close because of age, and construction will have to reach very high levels if market share is to be maintained.

Hydroelectric power is the second major source of low-carbon electricity.(Hydro produces only small amounts of CO_2 as a byproduct of dam construction and operation, but in some cases may produce significant amounts of another greenhouse gas, methane.) Fifty years ago, hydroelectric power made up a third of all electric generation. But almost all potential domestic large water power sites are already in use, and environmental and social costs make a significant increase in hydropower unlikely in North America, although small scale projects may continue to be built.

For a time in the 1990s, electricity generation was switching from coal to natural gas. (Gas plants emit about half as much CO_2 per kilowatt-hour produced as do coal plants.) The supply of North American natural gas is limited, however, and imports will be minor until huge fleets of liquefied natural gas tankers ply the seas. The inevitable result of increased demand arising from the switch to natural gas was a fourfold increase in gas prices, and investment in new natural gas-electric generators has virtually ceased. In any case, conventional natural gas does not provide the deep cuts in CO_2 emissions that are likely to be required by future regulations.

Biomass currently is used to produce just less than 1% of the nation's electricity. This fraction can be increased, both in advanced biomass plants and by blending biomass with other fuels in power generators. Some studies indicate that biomass may be an important transportation fuel, and the land and water resources required may be applied more economically to that use than to growing crops for electric power production.

Geothermal power from 22 facilities in California, Hawaii, Nevada, and Utah now accounts for roughly 0.4% of U.S. electric power. In a 2006 report, the Department of Energy forecast generation from geothermal facilities to increase to 0.9% in 2030.

Wind power supplies roughly the same amount of electricity as geothermal, and new wind facilities are being built at a rapid pace. But even at the best sites, wind can produce power only an average of 10 hours per day, and windy sites often are far from cities and factories, requiring expensive and controversial transmission lines. Thus, the effective capital cost per delivered kilowatt is higher than current electricity sources. In addition, the source of power that must be paired with wind to supply continuous power (typically coal or gas) emits CO_2. However, because the fuel cost for wind is zero, the total cost per kilowatt-hour is roughly competitive with other low-carbon sources, such as new nuclear power plants.

The amount of solar energy that reaches the United States each year is equivalent to approximately 4,000 times the nation's total electric power needs, but tapping that energy is expensive. Costs for solar photovoltaic (PV) power are five to 10 times higher than those of other low-carbon technologies, and the average power produced at even the best sites is less than a quarter of the energy produced at noon on a sunny day. Significant research efforts are under way in basic science to improve the performance of PV cells, which may lead to cost reductions in the future.

Energy conservation and demand reduction also represent ways to reduce CO_2 emissions. Experience in Vermont and California shows that aggressive policies can significantly reduce the growth of electricity demand. California's per capita consumption grew by just 5% during the past 25 years, markedly less than the 35% national per capita growth.(Some of the decline may have been due to large electricity consumers relocating outside the state.) The cost of such measures, however, is hotly debated. Also, population increases have continued to boost overall electricity consumption. And given that the nation must achieve deep reductions in emissions while the population and economy continue to grow, there is clearly a limit to how large a role conservation and demand management can play in meeting the carbon challenge.

Recommended reading

Scientific American, September 2006, Special Issue: Energy's Future Beyond Carbon.

Intergovernmental Panel on Climate Change, 2006. Special Report on Carbon Dioxide Capture and Storage, Chapter 8: Cost and Economic Potential. IPCC, Geneva. Available at http://arch.rivm.nl/env/int/ipcc/pages_media/SRCCS-final/SRCCS_Chapter8.pdf.

U.S. Environmental Protection Agency, The Benefits and Costs of the Clean Air Act, 1970 to 1990. Washington (1997). Available at http://www.epa.gov/air/sect812/copy.html.

K. Dobesova, J. Apt, and L. B. Lave, "Are renewables portfolio standards cost-effective emission abatement policy?" *Environmental Science & Technology* 39 (22): 85788583 (2005).

S. Pacala and R. Socolow, “Stabilization Wedges: Solving the Climate Problem for the Next 50 Years with Current Technologies,” *Science* 305 (5686): 968-972 (2004).

E. A. Parson and D. W. Keith. “Fossil fuels without CO_2 emissions,” *Science*, 282 (5391): 1053-1054. (1998).

M. G. Morgan. “Don’t Grandfather Coal Plants,” *Science*, 314 (5802): 1049. (2006).

Jay Apt (apt@cmu.edu) is executive director of the Electricity Industry Center at Carnegie Mellon University’s Tepper School of Business and the Department of Engineering and Public Policy, where he is a Distinguished Service Professor. David W. Keith (keith@ucalgary.ca) is Professor and Canada Research Chair in Energy and the Environment in the Department of Chemical and Petroleum Engineering and the Department of Economics at the University of Calgary. M. Granger Morgan (granger.morgan@cmu.edu) is University and Lord Professor and department head of the Department of Engineering and Public Policy at Carnegie Mellon University and co-director of the Electricity Industry Center.