The Challenge of Managing U.S. Coal in a Climate-Constrained World

Testimony for the Record
Submitted to the Senate Finance Committee

Professor Robert Socolow[1]
Princeton University
February 27, 2007

Mr. Chairman, Senator Grassley, and members of the Committee: Thank you for inviting me to testify today on "America's Energy Future: Bold Ideas, Practical Solutions." I am pleased to be here in my capacity as co-director of Princeton University's Carbon Mitigation Initiative; as a Professor of Mechanical and Aerospace Engineering at Princeton; and as an individual concerned about the future of U.S. and global energy policy. We have tremendous challenges before us when it comes to energy policy. But I firmly believe those challenges can be met, and I commend you for your efforts to that end.

When William Shakespeare took a breath, 280 molecules out of every million entering his lungs were carbon dioxide. Each time you draw breath today, about 380 molecules per million are carbon dioxide. That portion climbs about two molecules per million every year. In my view, we already know enough about the negative impacts on human civilization and the natural environment that lie ahead to warrant taking action now to cut CO_2 emissions.

In 2004 Stephen Pacala and I published a paper in *Science* magazine called "Stabilization Wedges: Solving the Climate Problem for the Next 50 Years with Current Technologies." Our article's thesis was that, when it comes to energy policy and climate change, there's no silver bullet. Rather, a portfolio of strategies must be implemented to address this issue. Each strategy uses technologies that have passed beyond the laboratory bench and demonstration project and have already been implemented somewhere at full industrial scale. Among these strategies are the deepening of energy efficiency in buildings, transport, and industry; the replacement of coal plants with renewable energy and nuclear power; the use of biofuels; and the capture and sequestration of carbon dioxide produced at coal power plants and coal-to-liquids plants. A portfolio is needed because none of these elements is a credible candidate for doing the entire climate mitigation job, or even half the job, by itself.

Today, I will focus my testimony on the strategy that has moved to near the top of the list from the perspective of urgency: carbon capture and sequestration, or CCS for short.

Two trains are on a collision course, but there is a switch.

Mr. Chairman, this really is a time of Bad News and Good News. The Bad News is that two trains are on a collision course. The Good News is that there is still time to switch one of the trains onto a different track.

[1] A short c.v. is found at the end of this testimony.

Only a few years ago, the U.S. saw very few new coal plants in its near future. The coal industry was pleading for regulatory relief so as not to be completely dismissed from the scene in favor of natural gas. I remember hearing comments like: “Watch out, you may not need us now, but you will need us later.” All this has changed. Train Number One is the rush to coal power in the U.S., a consequence of a much higher natural gas price than had been anticipated even quite recently.

Train Number Two is the urgency of dealing with climate change. Here too, a few years ago not many Americans saw our country dealing aggressively with climate change in this decade. Now, appropriately in my view, and none too soon, climate change is high on the agenda for U.S. policy.

The collision is simple to explain. Coal, burned as we have burned it in the past, sends more CO_2 into the atmosphere for each unit of useful energy produced than any other energy source. About twice as much CO_2 goes into the sky for each kilowatt-hour of electricity produced, when the electricity is produced at a conventional coal power plant, compared with a conventional natural gas power plant.

So, the rush to coal makes the already difficult challenge of climate change even more challenging.

But I said there was a switch that can prevent this collision. There are ways to burn coal so that the CO_2 produced by oxidizing its carbon does not end up in the atmosphere. The switch is called CO_2 capture and storage, or CO_2 capture and sequestration, or CCS.

CO_2 capture and sequestration is ready right now for full-scale deployment.

Relative to energy efficiency, renewable energy, and nuclear power, CCS is new on the scene. But nonetheless it is mature. If Congress enacts legislation that enables CCS, the technology will spread rapidly.

How could CCS be both new on the scene and commercially mature? The answer is that CCS uses proven technologies in new combinations. CO_2 has long been captured at natural-gas power plants and coal power plants for use by the food industry. At nitrogen fertilizer plants CO_2 is also captured and combined with ammonia to make urea. Many of the components required for CO_2 capture have long been used at full scale where hydrogen is made at refineries and where natural gas is upgraded between the wellhead and the pipeline. A 500-mile carbon dioxide pipeline built 20 years ago has brought carbon dioxide from across New Mexico from southwest Colorado to oil fields in west Texas. Ever since then CO_2 has been pumped into those fields and managed there for enhanced oil recovery.

I cannot emphasize strongly enough that from a technological perspective *CCS is ready for full-scale deployment.* Some technology strategies that may contribute to mitigating climate change in a decade or two are *not* ready for full-scale deployment today; an example is the hydrogen fuel-cell car, which awaits further work on hydrogen storage and on fuel cells. By contrast, there are no technological reasons to delay full-scale deployment of CCS. Industry leaders will tell you that once supportive policies are in place the industry will move ahead, learning as it goes, steadily improving the many component technologies with which it is already familiar, and lowering costs through experience and R&D.

The best evidence I know for the readiness of CCS for full-scale deployment is the project at BP's Carson refinery, near Long Beach, California. BP and Edison Mission Group (a power company) announced this project a year ago, and it is one of the projects that has received investment tax credits under Section 48B of the tax code, per the 2005 Energy Policy Act. The project is expected to gasify 4500 tons per day of petcoke, a negative-cost fuel that is the solid residue left behind at the refinery when all the marketable products are extracted from crude oil. After processing the petcoke, 800 tons per day of hydrogen will be burned in turbines for 510 MW of power, and four million tons of CO_2 will be sent off-site each year for enhanced oil recovery (EOR).

From the perspective of gasification, petcoke and coal are essentially identical. The gasifier, shift reactor, gas cleaning technology, gas separation technology, CO_2 compressor, and hydrogen turbine are exactly the systems one envisages for coal power with CCS. The Carson project is a testament to the readiness of the whole CCS approach.

At a new coal plant, CO_2 capture and sequestration is likely to break even, relative to CO_2 venting, at a CO_2 emissions price somewhere near \$30 per U.S. ton of CO_2.

CO_2 capture and sequestration is likely to become a favorable economic strategy for a coal utility at a price for CO_2 emissions of \$30 per U.S. ton of CO_2, approximately[2]. Prices on emissions in the same range should also bring an end to flaring at the oil field and should enable other "upstream" carbon-saving strategies, such as investments at oil refineries. CO_2 policy should reach far upstream, because the low-hanging fruit is upstream.

Efficiency in energy use is where the other low-hanging fruit are to be found. Approximately 70% of U.S. electricity is consumed in buildings. Mandatory federal standards for household and commercial lights, motors, air conditioners and other appliances are the most important policy legacy resulting from the attention to energy efficiency in the 1970s and 1980s. Whatever package of climate-change policies emerges from this Congress must contain a new set of mandatory standards assuring much higher efficiency in the use of electricity. Advances in modern electronics and materials can be incorporated in a new generation of efficient energy-using devices and systems, thereby bringing into the market energy-efficiency achievements considerably more impressive than the best we used to be able to do. A low-tech air-conditioner cooling a poorly designed and poorly instrumented office building is as out of place in a climate-constrained world as a coal plant without CO_2 capture and sequestration.

Any CO_2 policy restricted to creating a price for CO_2 emissions can be expected to have more effect on technological decisions in the energy industries than on consumer behavior. This is because any price on CO_2 emissions to the atmosphere will be a much higher percent of the wholesale price of energy than of the retail price of energy. This is exactly like a tax on copper, which affects the owner of the copper mine more than the buyer of copper wire. Overheads

---

[2] The estimate that \$30 dollars per U.S. ton of CO_2 is the incremental cost of CCS is uncertain for at least four reasons. 1) It pertains to the "Nth" plant, where N may be about 10, with the assumption that the incremental CCS cost will fall steeply before the Nth plant is built, but slowly after that. 2) It describes the least expensive CO_2 capture strategy now known, which is capture at an integrated gasification combined-cycle (IGCC) coal power plant running on bituminous coal. The incremental cost may be twice as high for capture from a modern pulverized-coal steam plant. 3) It does not take into account the likely fall in costs as new technology becomes available. 4) It assumes that permitting is not a costly process with long delays, so that the costs of sequestration are well approximated by the costs of CO_2 pipelines and wells.

accumulate as the material progresses along the value chain, lowering the percentage impact on the price. As a result, federal policy can induce a large amount of carbon mitigation activity in the energy industries (including CCS deployment) at a price on CO_2 emissions that induces only small changes in the behaviors of energy consumers. The price of $30 per U.S. ton of CO_2 cited above as probably sufficient to elicit the deployment of CCS at new coal plants will increase in the cost of gasoline at the pump by only 25 cents per gallon. (See the Table at the beginning of the Second Supplement at the end of this document.)

Enhanced oil recovery connects CO_2 capture and sequestration to national energy security.

Carbon dioxide is the mischief molecule in the atmosphere, but the miracle molecule below ground. In the atmosphere, the gas traps the Earth's infrared radiation heading to outer space, thereby impeding the Earth's dominant cooling strategy and raising the Earth's average surface temperature. Below ground, injected into the porous rocks where crude oil is trapped and hard to recover, CO_2 combines with the oil to produce a fluid that flows more easily, increasing the amount of oil recovered – an industrial strategy called enhanced oil recovery (EOR). Carbon dioxide injects new life into old fields.

Quantitatively, a new one-thousand-megawatt coal plant will produce about six million tons per year of CO_2. If captured and used for EOR, this CO_2 should increase oil production at mature fields by between 30,000 and 80,000 barrels per day. Domestic oil production is less than six million barrels per day, so the incremental oil production from even 20 new coal power plants would have a significant positive effect on vexing domestic and international oil problems. Any CO_2 heading for the sky is domestic oil not produced – and more imported oil.

In one plausible model, the coal industry will hand CO_2 to the oil and gas industry at the power plant gate, and the oil and gas industry will put it under ground. The coal industry and the oil and gas industry have little history of cooperation. Your committee has hard work ahead as it figures out the policies that can promote this cooperation.

"No CTL without CCS": Any plant built in the U.S. that produces synthetic fuels from coal must capture and sequester the CO_2 that would otherwise be emitted at the plant.

In response to the growing demand for imported oil to fuel vehicles, your committee is considering subsidizing synthetic gasoline and diesel fuel from domestic coal. From a climate change perspective, unless synfuels production is accompanied by CO_2 capture and sequestration, this is a big step backward.

In synthetic fuels (synfuels) production from coal, only about half the carbon in the coal ends up in the fuel, later to be emitted as CO_2 at the tailpipe. The other half of the carbon originally in the coal is emitted as CO_2 at the synfuels plant. As a result, burning a coal-based synthetic fuel in a car engine, instead of burning gasoline made from crude oil, sends approximately twice as much carbon dioxide to the atmosphere when driving the same distance, *unless CCS is incorporated into the synfuels production process.* Engineers can modify the design of a coal-to-liquids (CTL) plant to capture its CO_2 emissions rather than venting them, and to send the captured CO_2 below ground. A fuels system based on synfuels produced only at plants where CCS is deployed is no less bad for climate than a fuels system based on petroleum fuels.

"*No CTL without CCS*" isn't the world's most exciting bumper sticker, but it carries a vitally important message.

To produce a million barrels per day of synthetic fuel from coal requires transforming about 100 million tons per year of coal into synfuels. CO_2 is produced at these plants at a rate of about 150 million tons of CO_2 per year. This is the approximate rate of CO_2 production at 25 one-thousand-megawatt coal power plants.

"Carbon Price, Plus": For CCS to take off, cap-and-trade policy must be supplemented with policies specifically supportive of CCS.

The day will come when the CO_2 emissions price trajectory established in legislation is regarded as nearly free of political risk. This time has already arrived for sulfur trading, brought into being in the early 1990s – a spectacular success from the perspective of environmental policy and the template for every cap-and-trade proposal since then. (I understand that our chairman is one of the architects of that policy, and I welcome this opportunity to congratulate him personally.) But during the early years of a carbon management regime, this credibility will be missing. Moreover, the price will be low, relative to where it is heading.

These considerations militate in favor of putting in place, in parallel with a schedule governing CO_2 emissions, strong technology-forcing sectoral policies. Examples of sectoral CO_2 policies include appliance efficiency standards, renewable portfolio standards, and many of the investment tax credits that this committee has added to our laws. The deployment of CCS will require its own supplemental policies in the early years. For example, laws modeled on the renewable portfolio standard can require the early costs of CCS deployment to be widely shared among ratepayers. Especially important are the next investment tax credits. *I strongly recommend that your committee restrict the next investment tax credits only to coal power plants and coal synfuels plants that capture and sequester carbon dioxide.*

There are dozens of variants of CCS, and therefore one should anticipate that CCS will develop along many tracks at once. The optimal CCS strategy may depend on the details of the coal; the best way to capture CO_2 appears for now to be via gasification with oxygen, but there are many kinds of gasifiers, many capture technologies, and alternatives to gasification. There are also many different sequestration destinations. I recommend that policies specify only that CO_2 must be sequestered, with penalties for failure, but then leave it to the market to discover, for each circumstance, the cheapest alternative.

Policy must distinguish industrial from natural CO_2.

There are some remarkable gas fields in nature where the trapped gas is nearly pure CO_2. Several federal and state energy policies in the 1980s promoted the development of these fields, sending into the atmosphere CO_2 that otherwise would have remained trapped below ground millions of years into the future. This adverse impact on climate was inadvertent; the purpose of these policies was to subsidize domestic oil production by subsidizing enhanced oil recovery. Existing policy that does not distinguish natural from anthropogenic CO_2 should be repealed, and no further policy of this kind should be legislated.

Needed immediately are binding policies that encourage early good action and penalize early bad action.

Some of those currently planning new coal-fired power plants apparently have expectations of receiving a windfall from these plants. For example, they imagine that emissions permits will be granted to these plants when a cap-and-trade system for CO_2 emerges. Such grandfathering of the newborn would be extraordinary.

Often, policy makers seek ways to “encourage early action” during the period when policy is being constructed, with the assumption that early action will be good action. In this instance, early action is perverse. Urgently needed for the current period, during which the U.S. is evaluating alternative climate-change mitigation policies, are policies that give clear and persuasive signals to those contemplating the construction of new conventional coal plants, carrying the message that all such plants will be penalized, not rewarded, no matter what the climate-change mitigation policy that emerges.

I was one of many who were delighted by the news this past weekend that eight new coal plants with conventional technology proposed for rapid construction in Texas will not be built. I can’t prove it, of course, but it seems likely to me that the op ed in the Dallas News last month from Senators Bingaman and Boxer, warning investors and the TXU leadership that, in effect, there would be *no* grandfathering of the newborn, was instrumental in derailing the construction of these eight backward-looking plants.

Supplement One. Thoughts about economy-wide CO_2 policy.

"Mitigation Lite" must be avoided.

The political process will need to resist the temptation to settle for "Mitigation Lite," a CO_2 strategy with the right words but with the wrong numbers. Mitigation Lite leads to very little investment in CO_2-saving technology. Under Mitigation Lite, the CO_2 emissions price is internalized, especially by the coal power industry, as just another cost of business. Mitigation Lite results in a revenue stream flowing to the government that is compromised by being unrelated to the intended function of the policy. To avoid the pathologies of Mitigation Lite, CO_2 policies must be technology-forcing – in other words, CO_2 policies must be stringent enough to lead to significant investments that reduce CO_2 emissions within the energy industries.

A low safety valve in a Cap and Trade System is a sure-fire way to arrive at Mitigation Lite.

A ramp from zero to \$30 per ton of CO_2 over 10 years is probably strong enough to avoid Mitigation Lite.

For purposes of encouraging discussion of specifics, consider a trajectory for the CO_2 price which is a ramp that grows over ten years from zero to 30 dollars per U.S. ton of CO_2 in ten equal increments of 3 dollars per U.S. ton of CO_2. Thus, after five years, the price will be 15 dollars per U.S. ton of CO_2.

Very roughly, a CO_2 emissions price of \$30 dollars per U.S. ton of CO_2 is the breakeven cost where building a coal plant that vents its CO_2 costs the same as building a coal plant that captures its CO_2 and paying for sequestration. (See footnote 2, above.) Such a price places distinctly different pressure on the coal producer, the power plant operator and the home owner who consumes the electricity. A coal producer sees a charge of about \$70 per ton of coal, roughly tripling the cost of the coal delivered to an electric utility customer. The owner of a new coal power plant faces a 50 percent rise in the cost of the power the coal plant puts on the grid, about two cents per kilowatt-hour (kWh) on top of a base cost of around four cents per kWh. The home owner buying only coal-based electricity and paying a retail price of 10 cents per kWh experiences one-fifth higher electricity costs – provided that the extra two cents per kWh cost for capture and sequestration is passed on without increases in the charges for transmission and distribution.

CO_2 policies must soon become prescriptive for a decade or more.

It is essential to develop the credibility of any legislated trajectory for the CO_2 emissions price – whether it be the trajectory of the shrinking size of the cap in a cap-and-trade system or the trajectory for the rising emissions price in a tax system Probably, a shake-out period lasting two or three years is a good idea. Even after the shake-out period, periodic revision, such as every five years, is probably desirable, allowing new information about climate change science, about technology, and about the workings of the mitigation system itself to be incorporated. But policy design should not be built on "foot in the door" assumptions: low emissions prices for only a few years, followed by unspecified ratchets.

Supplement Two: Further observations

1. A Table of Costs expressing the same CO_2 emissions price in different ways suggests that price policy will modify the practices of energy producers more than energy consumers.

Form of Energy	**Price increment at $100/tC, or $27/tCO$_2$** ("t" is metric ton; 1 metric ton = 1.1 U.S ton)
Natural gas	**$1.50/1000 standard cubic feet**
Crude oil	**$12/barrel**
Coal	**$65/U.S. ton**
Gasoline	**25¢/gallon (ethanol subsidy: about 50¢/gallon)**
Electricity from coal	**2.2¢/kWh (wind and nuclear subsidies: 1.8 ¢/kWh)**
Electricity from natural gas	**1.0¢/kWh**

Notes to Table

Gasoline:	1 m^3 = 264.2 U.S. gals; 630 kgC/m^3 gasoline.
Crude oil:	1 bbl = 42 U.S. gals; 730 kgC/m^3 crude oil
Coal:	1 U.S. ton = 907 kg; 0.71 kgC/kg coal
Natural gas:	1 Nm^3 = 37.24 scf; 0.549 kgC/ Nm^3 natural gas
Electricity from coal:	29.3 GJ/t coal (12,600 Btu/pound); 40% conversion.
Electricity from natural gas:	55.6 GJ/t natural gas; 0.75 kgC/kg natural gas; 50% conversion.

2. Enhanced oil recovery is a CO_2 emissions reduction policy, even though it produces hydrocarbons.

EOR traps some CO_2 below ground. The baseline for thinking about the oil produced by EOR is oil produced without EOR. Thus, EOR is a CO_2 emissions reduction strategy. There is another perspective, technically correct but misguided, which observes that, for EOR as practiced today, more carbon atoms come out as oil than are tucked away as CO_2. The reason this argument is misguided is that for most oil production, *no* carbon atoms are tucked away. Some is better than none.

With a high price on CO_2 emissions, EOR will be different. The field operator's strategy today is to leave behind as little as possible of the CO_2 brought to the field, because buying the CO_2 is costly and releasing it to the atmosphere is cost-free. Once there is a substantial price on CO_2 emissions, the same operator will leave behind and sequester as much CO_2 as possible. The industry will be transformed into one with two commercial purposes instead of one.

3. Sequestration capacity will grow, much as any other non-renewable reserve grows, as technology develops.

Space below ground for CO_2 sequestration in geological formations ("pore space"), already large, will be subject to the same logic as oil or a metal or any other non-renewable energy or mineral reserve. The quantity of pore space available will increase as exploration is extended, experience with sequestration increases, and technologies improve.

4. Slow leakage of CO_2 from sequestration sites is not a catastrophe, only a loss of money.

Safe sequestration has two very different meanings. Safe sequestration requires absolutely preventing fast and sudden release of CO_2 that could result in serious hazards to humans. For a sequestration operation to earn a license, regulators will need to be satisfied that sudden leakage is virtually certain not to occur. But safe sequestration is compatible with very occasionally losing the CO_2 slowly, in spite of best intentions. Gradual leakage of carbon dioxide merely returns some of the greenhouse gas to the air. The risks of safe sequestration in the second sense can be managed by carrying insurance to reimburse whoever paid for the sequestration. Slow loss of CO_2 is far from a catastrophe, and regulatory regimes should reflect this.

5. Clean coal must be clean upstream.

CCS technology has the potential to transform the image of the coal industry into one that commercializes cutting edge, environmentally friendly, jobs generating, and profitable technology. But this can happen only if the coal industry makes significant social and environmental investments at the coal mine as well as at the coal power plant.

6. US leadership should accelerate the development of CO_2 policy in China and elsewhere.
China is now building coal power plants at a faster rate than we ever will. A coherent U.S. CO_2 policy should result in gaining some influence on China's construction program. Benefits to both parties include reductions in overall costs resulting from shared learning about new technology (including CCS technology), harmonized rules, and new markets for specific technologies. Levers producing influence over China and other countries may be hard to find. What is certain is that there is no point looking for such levers until the U.S. embarks on its own vigorous climate-change mitigation policies. We must practice before we preach.

Mr. Chairman and members of the Committee, thank you for your attention.

January 2007

ROBERT H. SOCOLOW
Professor
139 Guyot Hall, Princeton University, Princeton NJ 08544
(609) 258-5446/5445, fax: (609) 258-7715; e-mail: socolow@princeton.edu
Website: http://mae.princeton.edu/people/e9/socolow/profile.html

Robert H. Socolow is a Professor of Mechanical and Aerospace Engineering at Princeton University. He was the Director of the University's Center for Energy and Environmental Studies from 1979 to 1997. He teaches in both the School of Engineering and Applied Science and the Woodrow Wilson School of Public and International Affairs.

Socolow's current research focuses on the characteristics of a global energy system responsive to global and local environmental and security constraints. His specific areas of interest include carbon dioxide capture from fossil fuels and sequestration in geological formations, nuclear power, energy efficiency in buildings, and the acceleration of deployment of advanced technologies in developing countries. He is the co-principal investigator (with ecologist, Stephen Pacala) of Princeton University's Carbon Mitigation Initiative (CMI) www.princeton.edu/~cmi/, a ten-year (2001-2010) project, supported by BP and Ford. Pacala and Socolow are the authors of "Stabilization wedges: Solving the climate problem for the next 50 years with current technologies," which appeared in the August 13, 2004 issue of *Science*.

Socolow was the editor of *Annual Review of Energy and the Environment*, 1992-2002. He served on the Board of Directors of the National Audubon Society from 1992-99. In July 1997 he co-chaired the Workshop on Fuels Decarbonization and Carbon Sequestration, sponsored by the U.S. Department of Energy. In 1995, Socolow was a member of the Fusion Review Panel of the President's Committee of Advisors on Science and Technology (PCAST). In the l970s and 80s, he directed a team of physical scientists, engineers, architects, statisticians, and behavioral scientists in a series of unique research projects on energy conservation in housing. With John Harte, Socolow co-edited *Patient Earth* (Holt, Rinehart, l97l), one of the first college textbooks in environmental studies.

Socolow earned a B.A. in l959 (summa cum laude) and Ph.D. in theoretical high energy physics in l964 from Harvard University. He was an assistant professor of physics at Yale University from l966 to l97l. He is a Fellow of the American Physical Society and the American Association for the Advancement of Science. He was awarded the 2003 Leo Szilard Lectureship Award by the American Physical Society: "For leadership in establishing energy and environmental problems as legitimate research fields for physicists, and for demonstrating that these broadly defined problems can be addressed with the highest scientific standards." In 2004 he was made a lifetime National Associate of the National Academies of the U.S., "in recognition of extraordinary service to the National Academies in its role as advisor to the Nation in matters of science, engineering, and health." In 2005, he received the Axel Axelson Johnson Commemorative Lecture award from the Royal Academy of Engineering Sciences, Stockholm, Sweden. The award, given every five years, in principle, had last been given in 1995. The inscription on the medal reads (translation from Swedish): "For a remarkable effort in the application of engineering science research in mankind's service."