Stabilization Wedges and Climate Change[1]

Robert H. Socolow

Department of Mechanical and Aerospace Engineering
Princeton Environmental Institute
Princeton University, Princeton, NJ 08542
Socolow@princeton.edu

Abstract. An informal pedagogical tour provides quantitative views of the magnitude of the challenge of mitigating climate change and many of the energy technologies available to address this challenge. The importance of energy efficiency is emphasized, as is the societal context for technological change.

Past, Present and Potential Future Carbon Levels in the Atmosphere

The atmosphere can be thought of as a bathtub (Figure 1). There's a certain amount of carbon in our Earth's atmosphere today, 800 billion tons. 200 years ago, the Earth's atmosphere contained 600 billion tons of carbon. In the depth of the ice age, approximately 20,000 years ago, it contained about 400 billion tons of carbon.

The ice core records are a marvelous piece of science. When we drill an ice core in the Antarctic, it's just like drilling into a tree to examine the tree rings; the deeper you go the further back in the past you are. Bubbles trapped in the ice tell us about the atmosphere when they were trapped. These records show that the quantity of carbon in the CO_2 in the atmosphere has gone back and forth between 400 and 600 billion tons

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1 This manuscript is similar to one being published in the New York State Bar Association's *Journal of Government Law and Policy*, produced by Albany Law School, in a special issue on climate change, (Kevin Healy, guest editor). Both manuscripts are based on a keynote talk I gave at Albany Law School, Albany, New York, on July 19, 2007, at the invitation of Judge Eleanor Stein, Administrative Law Judge for the New York State Public Service Commission, at a meeting of the Public Service Commission. Both manuscripts are the result of an overhauling and rewriting of a transcript of that talk. I appreciate having received permission from the *Journal of Government Law and Policy* to allow the publication of this second reworking of the same talk.

CP1044, *Physics of Sustainable Energy, Using Energy Efficiently and Producing It Renewably*
edited by D. Hafemeister, B. Levi, M. Levine, and P. Schwartz

of carbon in about 100,000 years cycles, which are the ice-age cycles. For at least six cycles back, ice cores drilled into the Antarctic ice sheet provide such data.

Six hundred billion tons is the reference number for the pre-industrial quantity, and people talk about doubling or tripling it. When they just say "doubling," they mean 1,200 billion tons of carbon in the atmosphere. From the numbers in Figure 1, you can see that at the present time we are both as far above the pre-industrial level as the depths of the ice ages were below and one-third of the way to doubling.

Another unit is the fraction of the molecules in the atmosphere that are CO_2 molecules. It is now 380 out of every million (380 ppm). The concentration was about 285 ppm in the pre-industrial period. The connection is that 2.1 billion tons of carbon is one part per million.

A third unit is tons of carbon dioxide. A ton of carbon is contained in 3.67 tons of carbon dioxide, since the atomic numbers of carbon and oxygen and 12 and 16, respectively. Most of the prices used in the discussions of the economics of carbon are in dollars per ton of carbon dioxide, not dollars per ton of carbon. However, of these three units, here I'm going to use the unit "tons of carbon."

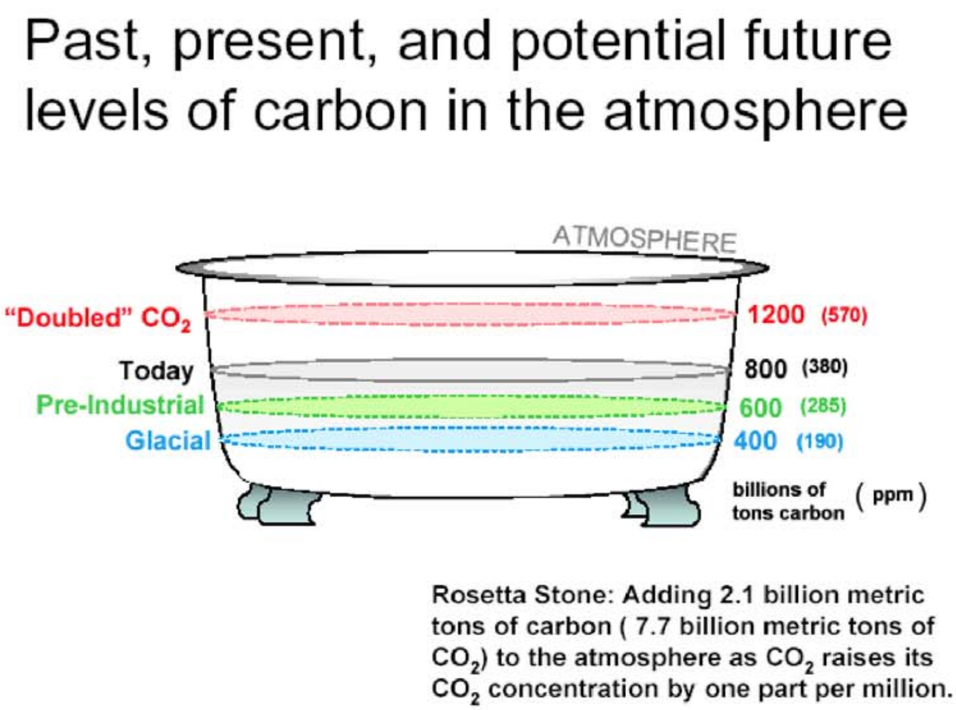


FIGURE 1. Carbon in the atmosphere.

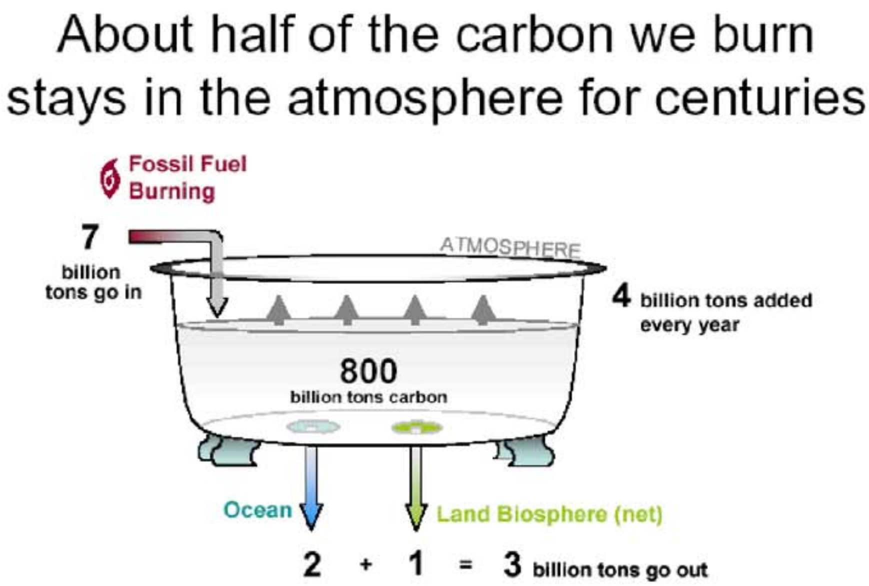


FIGURE 2. Three of seven billion tons/year of carbon do not enter the atmosphere.

Carbon Removal Mechanisms

Now let's look at what's going into that bathtub and what's going out (Figure 2). Each year, seven billion tons of carbon come out of the ground. Approximately the same amount of carbon is going into the atmosphere, because not long after it's taken out of the ground, typically months, it will be burned and become CO_2.

The atmosphere does not grow each year by seven billion tons of carbon, but by something less. That's because there are two removal mechanisms, drains in the bathtub. One is that at the surface of the ocean. If there's extra CO_2 in the atmosphere, some of it goes into the ocean and dissolves in the ocean. About two billion tons out of the seven get removed in this way. There are impacts on the ocean when this happens; notably, the ocean becomes more acidic.

The size of the other removal mechanism is found, in fact, by subtraction. It's hard to measure, and no one can model it terribly well. On average there's a net movement of CO_2 *into* terrestrial plants. This flow outward from the atmosphere happens in spite of deforestation, whose representation in Figure 2 on its own would be shown by the "land" arrow pointing *up*. Deforestation brings between 1 and 2 billion tons of carbon *into* the atmosphere each year. However, the net exchange between the biosphere and the atmosphere, including deforestation, is one unit going *out* of the atmosphere, a land arrow that goes down.

When the measurement of CO_2 in the atmosphere started at Mauna Loa, Hawaii, in 1958, there were less than 700 billion tons of carbon in the air, and in the 50 years since, that number has climbed to 800 (Figure 3).

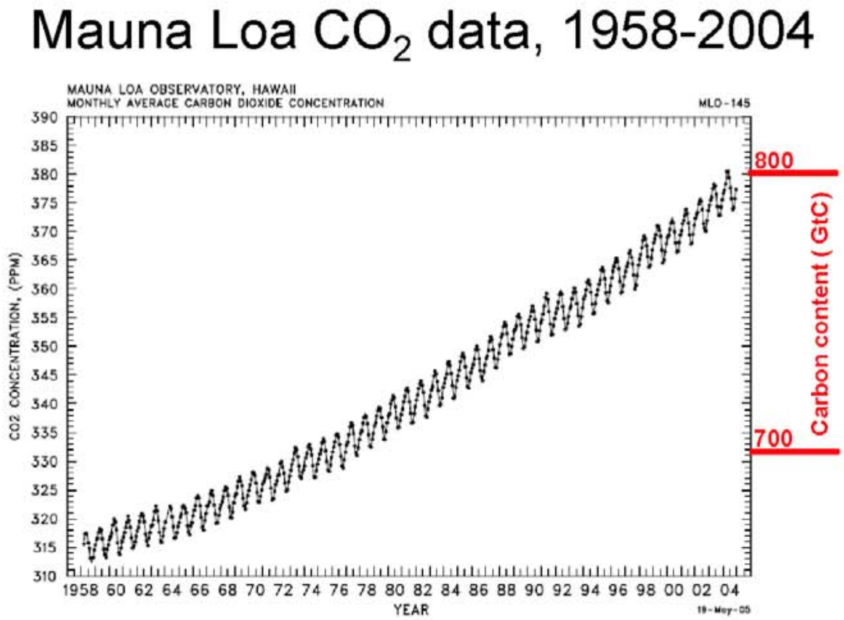


FIGURE 3. Carbon dioxide concentration in ppm at Mauna Loa, Hawaii, 1958–2004. The carbon content of the atmosphere rose from 700 to 800 gigatonnes between 1975 and 2005. [Source: Oak Ridge National Laboratory, Carbon Dioxide Information Analysis Center http://cdiac.ornl.gov/trends/co2/graphics/mlo145e_thrudc04.pdf]

The oscillation in Figure 3 is a result of an exchange of CO_2 between the forests and the atmosphere on an annual basis. When the forests grow, CO_2 comes out of the atmosphere into the leaves. When the leaves decay on the forest floor, the CO_2 goes back where it came from. The rise in the curve is because we're burning fossil fuels and to a lesser extent deforesting. The climb would be twice as steep, were it not for those two sinks in Figure 2.

Climate Change Impacts

Sea-level rise will strongly affect those places that are near sea level and flat, such as Florida. Much of southern Florida will disappear if sea level is eight meters higher than it is right now. Will it get eight meters higher? The answer used to be: "We don't have to worry about that for a long time." In the last couple of years, it's: "Well, maybe we do have to worry about that, even now."

There are two ice masses on the planet that are secure for the moment. One is the glaciers of Greenland and the other is what's called the West Antarctic Ice Sheet, which juts northward toward Argentina and Chile. Each of those, if it were to melt, would be worth about six to eight meters of sea level. You just melt the mass of the ice, spread the water over the surface of the ocean, which is two-thirds of the surface of the planet, and that's how much sea-level rise you get.

Which of the impacts of Climate Change are the ones that are going to be politically salient? Is it going to be sea level rise -- with a lot of uncertainty about whether it's something we have to be concerned about? Suppose we were told that there is a 10% chance that sea level will rise by 10 meters over the next 1,000 years if we do not address climate change, and that only after 100 years will we know whether this is the track we're on? Would that be enough to engender political action?

What about hurricanes instead of sea-level rise (both sometimes affecting the same territory, e.g., southern Louisiana)? Will salience adhere to the impacts of rare events becoming more frequent? If a bell curve describes the occurrence of intense storms, droughts, very hot days, and other unwanted environmental phenomena, and climate change simply shifts these bell curves to the right, enriching the upper tail, then there's bigger change for extreme events than a focus on average values would suggest. Is that what's going to drive people to action?

We can think of our response to climate change as buying insurance. My colleague, Stephen Pacala, calls these dangers "the monsters behind the door." There are quite a few monsters. As we learn more, we find out about more monsters. Every once in a while, we discover that a monster is not as fearful as we thought it was. There was a lot of concern about the shutting down of the Gulf Stream five years ago, and that was a monster. This outcome may not be as likely as people thought it was. Not everything is getting more scary. But usually new knowledge reveals more ways by which our adding CO_2 to a complex climate system brings problems for us. Yes, for other species too, but clearly, primarily, for us.

The Stabilization Triangle and the Size of the Job

Pacala and I tried to make sense of what all this had to do with energy and policy. Start with Figure 4 and look back in the past. Fifty years ago the global emissions rate was less than one-third of what it is today. In 1955 it was 2 billion tons of carbon per year and now it is about 7 billion tons of carbon per year.

The first question we asked is: "If the world does not care about carbon for the next 50 years, what will the emissions rate be?" Suppose, for example, that everyone were to buy into Senator Inhofe's view that climate change is a hoax being perpetrated on the American people. What would be the global emissions rate in 2055? There are thousands of papers answering this question, generally written by people called econometricians. They use the past as a guide to the future, try to develop what the rate of increase of the Gross National Product will be and how fast new technology will come in. They come up with lots and lots of answers, a wide band of answers.

The other question we asked is: "If the world really cares about the climate problem and works very hard, what should the goal be for fifty years from now?" Another thousand papers exist on that topic.

Because the many papers, in aggregate, produced so much noise and so little signal for those of us who are onlookers, Pacala and I asked: "Can't we cut through this?" And we drew Figure 4. This picture says that about double the carbon extraction rate, 14 billion tons of carbon a year, fifty years from now, is where the world is heading if we ignore climate change. Of course, you can make cases for higher or lower numbers, but we needed to make a single choice. Pacala and I tried to be in the middle of what is out there. The picture also says that if we humans could keep global carbon emissions to today's level for 50 years, we should be very pleased. Most students reading this are going to be around in 2055; I'd like to endow a party that they could throw themselves if the interim goal is achieved.

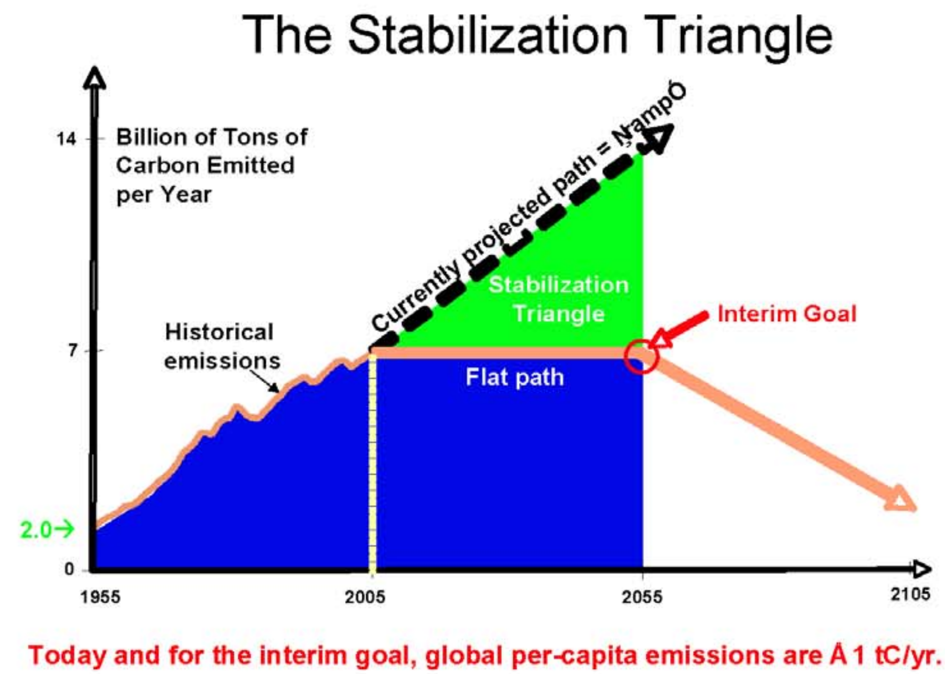


FIGURE 4. Fifty years is projected to double carbon in the atmosphere.

I circled one point on Figure 4 and called it our "interim goal": 50 years from now, the same global CO_2 emissions rate as today. I am optimistic that we can meet this interim goal, for three reasons. First, we have a terribly energy-inefficient energy system. Second, most of what will be the world's capital stock in 50 years is not yet built. Third, we are just beginning to put a price on carbon – so far, only in a few markets, notably in the European Trading System. These are the three reasons why I find it possible to imagine achieving all of the savings in the stabilization triangle in Figure 4.

Most of the criticism of Figure 4 since its publication asserts that it underestimates the job ahead. The rising line isn't rising steeply enough to capture what "Business As Usual" will bring, and the flat line is too timid a course of action to avoid climate change. Keep these criticisms in mind, because to the extent that these criticisms are valid, addressing climate change adequately means doing even more of what we'll be talking about here.

Some of you know that the language of "two degrees" and "three degrees" is another way of talking about climate change goals. These are proposed values for targets expressed in terms of the maximum rise of the average surface temperature of the planet, compared to its -industrial value (in Celsius degrees). We're 0.6°C (one degree Fahrenheit) above the pre-industrial temperature already. Figure 4 can be restated in this language. We're on track for a 3°C temperature rise if we follow the flat path, and for perhaps a 5°C rise if we follow the rising path. Many argue today that 3°C is too much, and that we should aim for 2°C. To do so requires, roughly, cutting the global emissions rate by half in fifty years, a much tougher job than keeping it constant.

Yet another way to illuminate the interim goal is to note that over the next 50 years the average global population will be about seven billion people. So our share as individuals over this period is a ton of carbon per year, taking it out of the ground, putting it in the atmosphere. In later sections of this paper, I'll relate 1 ton of carbon per year to other things.

The Wedge Model

Pacala and I divided the stabilization triangle into seven equal pieces and named these pieces "wedges," creating a unit of discussion for the subject (Figure 5). A wedge is a campaign or a strategy that leads to one billion tons of carbon per year not being emitted on the planet fifty years from now. It could be a campaign of various kinds, and so you can compare campaigns.

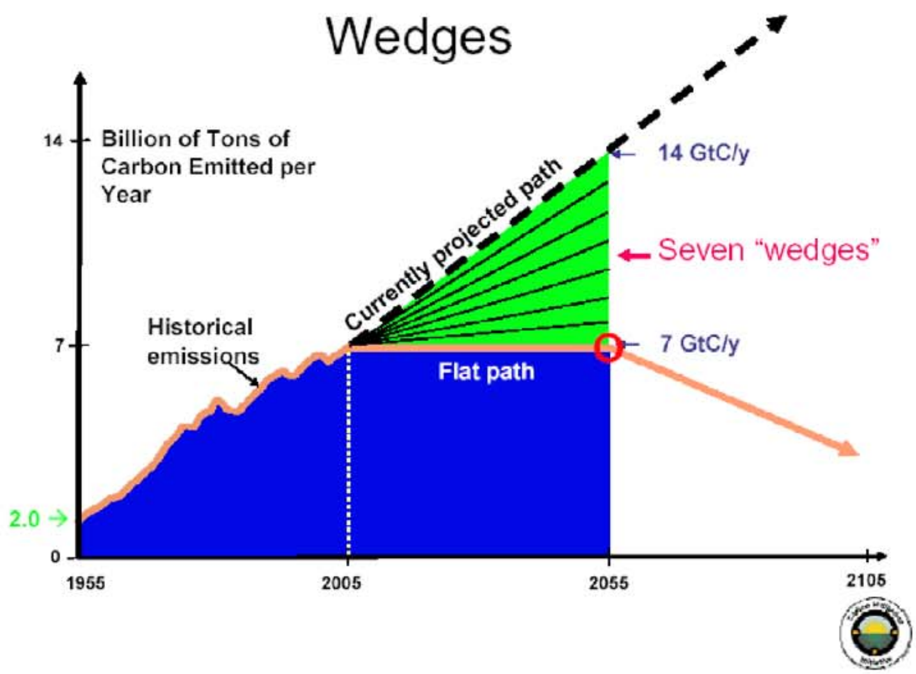


FIGURE 5. Seven wedges of 1 GtC/y each maintain constant carbon emissions in 2055.

Our definition of a carbon wedge is a triangle of carbon emissions reduction over 50 years, which attains 1 GtC/yr in 2055 (Figure 6). So, 25 billion tons of carbon are not added to the atmosphere over the fifty years. Figure 6 also introduces a price for carbon emissions, \$100 per ton of carbon (about \$30 per ton of CO_2). This price, in my view, is the approximate price one ought to have in mind as required to deal with climate change. It's not cheap; I'll say more a little later about how expensive it is. This price makes a wedge a \$2.5 trillion enterprise. That's a lot of jobs around the world.

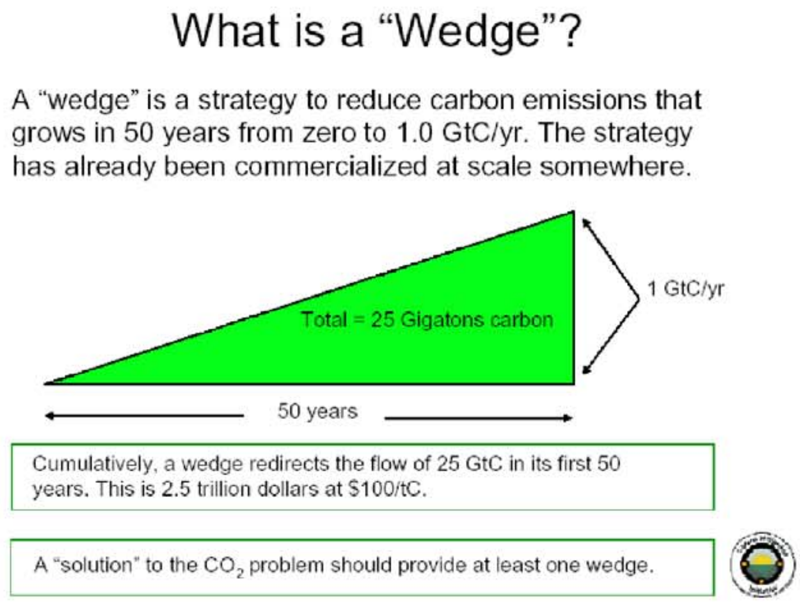


FIGURE 6. Definition of a wedge of carbon reduction.

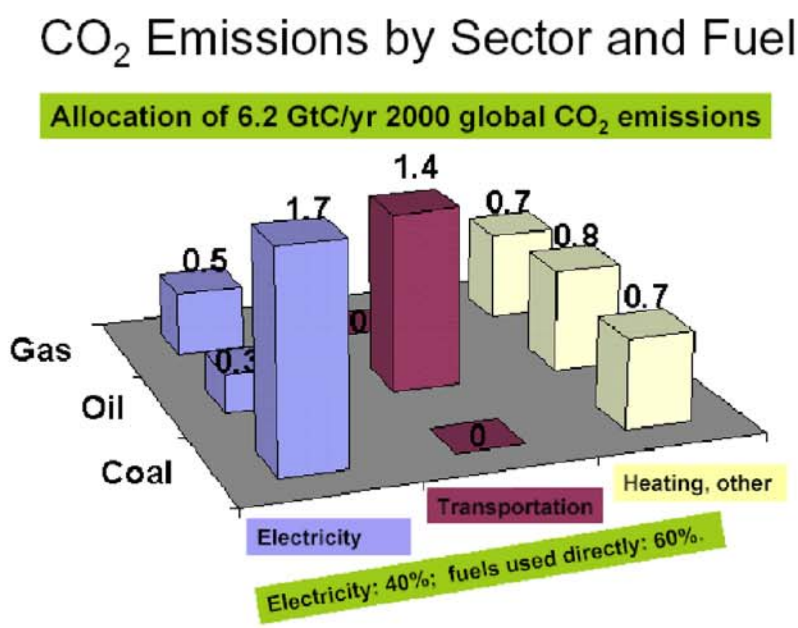


FIGURE 7. Gas, oil and coal consumption by the electricity, transportation and building/industry sectors.

Now, let's go on a hunt for wedges. First, let's find out where the seven billion tons of carbon emissions are originating right now. Take Figure 7 as a starting point. The three-by-three set of skyscrapers shows how emissions are split between gas, oil and coal. These are the three forms of carbon that come out of the Earth. The slide also shows the split between power, mobile applications and stationary applications that are not in the form of electricity but use fuels directly.

The two tallest skyscrapers are about equally high, and between them they add up to half of the total, which was six billion tons of carbon in 2000 (but seven when Pacala and I wrote the "wedges" paper). The two tallest are coal-to-power and oil-to-transport, as you might expect. At the right, you find natural gas and fuel oil going to buildings, gas going to the glass industry, oil going to petrochemicals, and coal going to metallurgy. Focusing on the electricity column, you find that it's 40% of global emissions. Also for the U.S., power plants are responsible for close to 40% of total emissions.

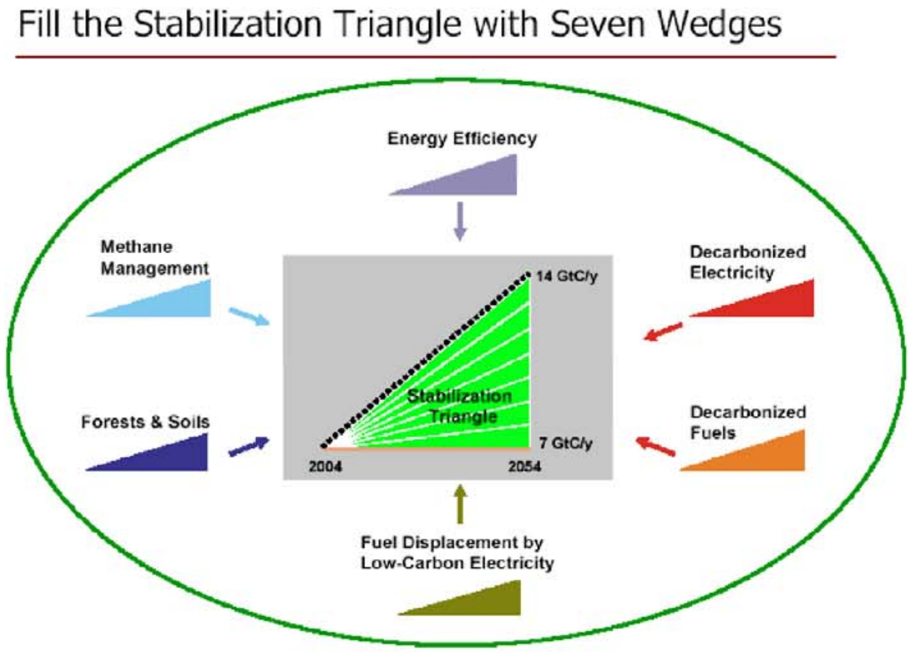


FIGURE 8. Seven wedges (energy efficiency is two wedges) can save 7 GtC/year by 2055.

We seek broad categories for sorting out the wedge strategies (Figure 8). Energy efficiency is at 12 o'clock, because that's where I think it belongs, right at the top. It can provide three wedges or more. At 2:00 and 4:00, we recognize that both power use and fuels use must be decarbonized; because of electricity's 40% share (noted above), neither electricity nor fuels can be ignored. At 6:00, we acknowledge that it's harder to decarbonize the use of fuels than to decarbonize electricity. At least that's our current wisdom. So when there's a price on carbon and the economy tilts away from emitting carbon, there'll be a shift toward electricity and away from direct fossil applications. An example is the plug-in hybrid car, where much of the energy for driving is coming by way of a battery charged from an electric grid. Another example is the electric heat pump for space heating. To be sure, the plug-in hybrid and the electric heat pump are only carbon-saving strategies when power comes from a low-carbon grid.

At 8:00 are forests and soils, deliberately manipulated to store additional carbon. Planting trees stores carbon.

Methane management is at 10:00, reminding us that CO_2 is not the whole story, that there are other important greenhouse gases. Methane is less well-understood and harder to address than CO_2.

Pacala and I wrote two papers, in *Science* in 2004[2] and in *Scientific American* in 2006.[3] Both have the same list of fifteen wedges:

1. Increase fuel economy of 2 billion cars from 30 to 60 mpg.
2. Reduce annual mileage of 2 billion cars from 10,000 miles/yr to 5,000 miles/yr at 30 mpg.
3. Cut electricity use in buildings by 25%.
4. Raise efficiency of 1,400 large (1000 MW) coal–fired plants from 40% to 60%.
5. Replace 1,400 large coal–fired plants with gas-fired plants.
6. Install carbon capture and storage (CCS) at 800 large coal-fired plants.
7. Install CCS at coal plants that produce hydrogen for 1.5 billion cars.
8. Install CCS at coal–to–syngas plants.
9. Add twice today's nuclear output to displace coal.
10. Increase wind power 40–fold to displace coal.
11. Increase solar power 700–fold to displace coal.
12. Increase wind power 80–fold to make hydrogen for cars.
13. Drive 2 billion cars on ethanol using one sixth of world cropland.
14. Stop all deforestation.
15. Expand conservation tillage to 100% of cropland.

People say, "Well, here's one that's not on your list. It must not be important." Read our papers. We said that there are wedges not on our list that are important. Four examples, quite different from one another, are industrial energy efficiency, "upstream" emissions, concentrated solar power, and population.

Industrial energy efficiency didn't happen to be on our list. We included buildings efficiency and vehicle efficiency, but not industrial efficiency, which of course is important. Industrial efficiency is more easily internalized by the decision-makers, who will pay more attention to any carbon price that comes along. Carbon efficiency emerges naturally for many businesses, especially when carbon emissions costs become a significant fraction of the total cost. In businesses where carbon costs are small, the business becomes more like a building.

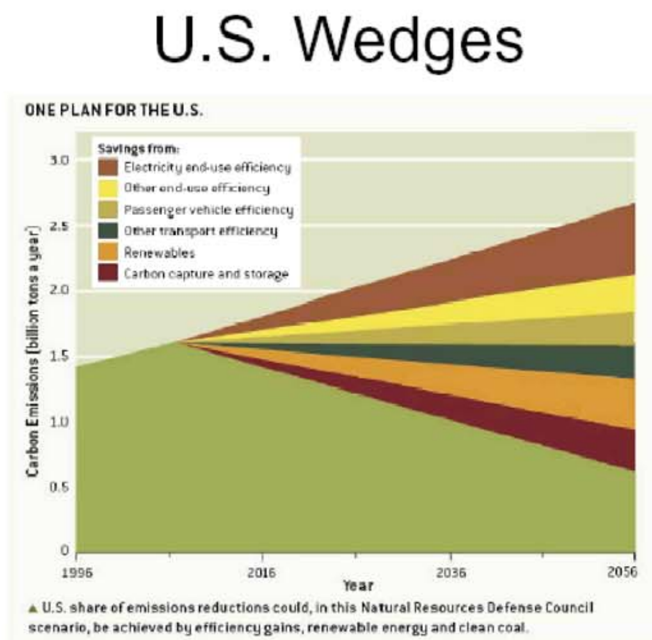
"Upstream" investments are the oil and gas and coal industries' own emissions of carbon during extraction and conversion, as they prepare their product for market. Examples are the emissions come from flaring and venting at oil and gas fields; methane releases at coal mines; energy expenditures to transport coal, oil, and gas; CO_2 that comes out of the ground as a component of natural gas. Reducing such emissions is often a relatively low-cost mitigation opportunity.

[2] "Stabilization Wedges: Solving the climate problem for the next 50 years with current technologies," *Science*, (August 13, 2004).

[3] "A Plan to Keep Carbon in Check," *Scientific American*, (Sept. 2006).

Concentrated solar power (CSP) belongs with wind and photovoltaics. The most intriguing version of CSP is an array of troughs in the desert focusing sunlight onto long tubes to produce high-temperature fluids that can run engines.

Lastly, population. For more than two decades, linking population with environment has been out of fashion. But in the 1970s the link was strong. The best textbook of that period, by Paul and Anne Ehrlich and John Holdren, was called *Ecoscience: Population, Resources, Environment* (Freeman, San Francisco, 1977).. I tell my students that the choice ahead of them that will make the largest impact on the environment is how many children to have. They tell me no one has said this to them before. .



Source: Lashof and Hawkins, NRDC, *in* Socolow and Pacala, *Scientific American*, September 2006, p. 57

FIGURE 9. US wedges could cut deeper. [D. Lashof and D. Hawkins]

"The Wedge Model is the iPod of climate change. You fill it with your favorite things." Thus says David Hawkins of the Natural Resources Defense Council, who produced Figure 9 with his colleague, Dan Lashof. Figure 9 shows U.S. wedges in a world consistent with the Princeton global wedges. Al Gore shows this image in *Inconvenient Truth* to convey the U.S. role in the global story. Compare Figure 4 and Figure 9: if global emissions remain constant, Hawkins and Lashof (and you too, reader, yes?) expect U.S. emissions to fall.

Figure 9 shows how Hawkins and Lashof would fill their iPod. There is no nuclear power, because NRDC doesn't like nuclear power; but there are four efficiency wedges, one renewables wedge, and one carbon capture and storage wedge.

Every wedge strategy can be implemented well or poorly. These are not miracles. In fact, they're dangerous. For example, nuclear power can be done well, but we're nowhere near doing it well. We certainly don't want to trade climate change for nuclear war.

Other examples: Conservation can lead to too much regimentation: how much can you intrude on the way people use energy indirectly and directly? Renewables can be done badly by not paying attention to the competing uses of land. "Clean" coal, a phrase widely used, generally refers only to burning coal well, with minimal emissions, including emissions of CO_2. But "clean" should only be used when coal is handled cleanly upstream too: mining, land reclamation, worker safety all count.

In short, one must assume that any solution to climate change can be done badly. How will it get screwed up? Ask that question at the front end.

Efficiency Wedges

Let's turn to specific wedges. I'm going to discuss only two classes of wedges here: wedges of efficiency and wedges related to substitutes for conventional coal power plants. These two classes of wedges are, I think, the most urgent ones for the next decade or so.

When we search for efficiency wedges, we address the consumers, those people on the planet who already have some means, the members of post-industrial society. They have appliances in their homes, and their vehicles dominate the scene. The significance of consumption for the global environment is relatively new, as you saw in earlier slides. Globally, 60% of oil is used in vehicles and 60% of electricity is used in buildings. In the U.S., 70% of electricity is used in buildings. The CO_2 mitigation challenge is a challenge to both energy supply systems and energy use systems, but here we'll consider the use systems.

Here's a carbon number: If your car gets thirty miles per gallon and goes 10,000 miles per year, you're going to put a ton of carbon into the atmosphere. That was your quota as a global citizen, if you remember, for *all* of your carbon. That one part of your footprint is the global average. Some of you are driving a sixty-mile-per-gallon (60 mpg) car 10,000 miles a year, and some of you are driving a 30 mpg car 5,000 miles a year. If either case, you're putting half a ton of carbon in the atmosphere.

The first wedge calculation concerns auto CO_2 emissions. The auto industry believes there will be 2 billion vehicles on the planet in 2057, about three times as many as we have right now. If they are the reference vehicles that I just referred to, 2 billion tons of carbon will go into the atmosphere. If, instead, by deliberate policy driven by climate concerns, these are 60 mpg vehicles on average, we'll have a wedge from energy efficiency in vehicles. Alternatively, if we have restructured our cities and commute less, and if we are using video-conferencing and drive less on the job, we might actually have a wedge in a different way, 30 mpg cars driven an average of 5,000 miles per year. Or we could do both, and we would have a wedge and a half.

As for efficiency in electricity use, if 40% of CO_2 will continue coming from power plants, and 70% of that power will be used in buildings, and 14 billion tons of carbon is our baseline, then cutting out one quarter of electricity use in buildings will be a wedge. Cutting out half would be two wedges. These are promising and exciting wedges. Obviously, if we're decarbonizing the power system at the same time, we're doing better still. And if we're recarbonizing, moving to coal, these are even more important wedges.

One example of an efficient electricity-using device is the variable-speed-drive motor, Another example is the compact fluorescent bulb. An example of an efficient electricity facility is the cogeneration plant, which uses both electricity and the byproduct heat. The Public Utilities Regulatory Policy Act (PURPA) of 1978 enabled a significant expansion of cogeneration. It forced utilities to allow non-utility generators to sell their electricity to the grid. In particular, industries requiring substantial heat sources were able to build cogeneration plants that sold electricity to the grid while producing the required heat. PURPA was one of the most important carbon related initiatives from the 1970s.

Which policy innovations will the next generation of energy analysts produce, the equivalents of PURPA, that the energy policy community will talk about with admiration twenty years from now?

Five ways to cut 1 tonC/yr by half

	1 ton carbon/yr	Cut in half	How?
a) Drive	10,000 mi/yr 30 mpg	60 mpg	Lighter, less power(?)
b) Drive	10,000 mi/yr, 30 mpg	5,000 miles/yr	Live closer to work
c) Fly	10,000 miles/yr	5,000 miles/yr	Video-conference
d) Heat home	Nat. gas, av. house, av. climate	Insulate, double-pane windows, fewer leaks, condensing furnace,	
e) Appliances	300 kWh/month when all-coal power (600 kWh/month, NJ)	Permanently replace twenty 60W incandescent bulbs, lit 6 hrs/day, with compact fluorescents.	

FIGURE 10. Five ways to cut carbon.

To be concrete about energy efficiency, consider Figure 10. I list activities that emit a ton of carbon per year and how to cut them in half. The first two are from our already discussed reference car, which we can drive less or exchange for a car with better fuel efficiency.

The third is about air travel. A mile flying in a commercial aircraft has about the same associated CO_2 emissions as a mile of driving alone in our reference car. The carbon footprints of only a small fraction of the people on this planet are dominated by air travel, but it's an awkward and common situation among analysts who work on energy efficiency.

The fourth item addresses residential heating. The carbon emissions that accompany the natural gas used to heat of my own home in Princeton, which is not a

McMansion, are very close to a ton of carbon a year. (I split that with my wife, so that's a half a ton of carbon for each of us.) Finding this out was not easy. My gas bill is in therms. A therm is a unit of energy, one hundred thousand Btus, or 105.5 MJ. Approximating natural gas by pure methane, looking up that the heat of combustion of methane (higher heating value) is 55.51 MJ, and assuming that methane is 75% carbon by weight, we find that using a therm of natural gas will send 1.42 kg of carbon into the atmosphere as CO_2.

Not exactly a layman's calculation! But the gas company could do the work for us, giving us this information on our monthly bills, showing carbon emissions histograms that reveal the carbon footprint of our home. The bills could present annual numbers, compare these numbers with past values, compare them to a reference group, and lots more.

For electricity consumption, the final item in Figure 10, the story is slightly more complicated than with gas. We need extra information from the electric utilities. With gas, you can go from therms to carbon without further information, and so you can work out your emissions directly from the consumption data on your bill. But for electricity calculations, you need another number: the carbon intensity of the electricity supplied by your particular utility for some particular time period. What exactly were the energy sources that produced the electricity you bought last month? That's known inside each utility, but it's not known by consumers today.

If someone uses 300 kilowatt hours per month (about a third of my own actual electric bill) his or her carbon footprint will be a ton of carbon a year – provided that all the electricity is coal-based. But New Jersey is about half as carbon intensive as that, so for someone living in New Jersey, 300 kilowatt hours would be associated with half a ton of carbon. The carbon footprint for electric power is geographically dependent, even within a state, because the key conversion factor depends on the mix of hydropower, nuclear power, natural gas, and coal

Lessons Learned about Efficiency from the 1970s and 1980s.

I was one of the researchers learning about energy efficiency in the 1970s and 1980s. Here's a summary of what we need to convey to our successors:

Measure, measure, measure. Don't give prizes for the design of a building before it's built. Too often there is a large shortfall in performance when people move in. President Reagan said, "Trust, but verify." That principle sums up the most important lesson we learned about efficiency the first time around.

For existing buildings, go building by building. They're all different. In the 1970s and 80s, trained workers were going building by building, sometimes working for the gas and electric utilities, which had put these costs in their rate base. My own research group at Princeton developed diagnostic tools using an infrared camera and equipment to pressurize a building, so that trained personnel could understand energy efficiency opportunities, which were numerous and were usually related to deficiencies in building design and construction.

For new buildings, anticipate the undoing of good intentions. My own group monitored nominally low-energy buildings that were designed so that daylight would penetrate deep into the interior. The designer imagined that the perimeter office would be occupied by an executive who would be perfectly happy to have a glass interior wall. But, alas, he wasn't, or she wasn't. The executive valued privacy and used a curtain. As a result, daylight did not go to the interior

Nominally "low-energy" or "low-carbon" buildings generally assume a low demand for the energy that enables the occupants to do whatever they choose to do inside. But this assumption is often wrong. The interior decorator in one building we studied thought that there should be oil paintings on the walls and that they should be lit by task lighting. So to save energy in buildings, we must get the interior decorators into the electricity efficiency business. So far, they've not been told that saving energy is what their client wants them to do. The same can be said of lighting specialists, who could find lighting solutions using less energy if asked to do so.

Performance standards. These clearly have great impact. They determine appliance efficiency, interior temperature, and light levels. Buildings researchers in the 1970s learned that lighting standards were captives of the lighting industry, which found ways to justify the need for great amounts of interior light in order to do various tasks. We asked for evidence that you need the extra light in order to do some particular task. We asked whether there might be a concept called over-lit?

Bounty. Decades ago, California authorities were paying people to give up their old, inefficient refrigerators, and trucks would come to your house to pick them up. Some of these inefficient units had been put in the basement when a person bought a new refrigerator; they were often running while hardly being used. California was doing same thing for old cars.

Time of day pricing and congestion charges. Adam Smith can help conserve energy.

Lifeline rates. One of the arguments against efficiency improvements that should always be challenged is that such improvements inevitably hurt the poor. This never needs to happen, because one can always implement lifeline rates, where the first block of consumption is less expensive than the next block of consumption. It's a progressive policy idea. If the overall result of some policy is that retail electricity or retail gas gets more expensive on the average, there's nothing conceptually difficult about protecting the first block of kilowatt hours or therms from a price increase. The richer consumers then carry a bit more of the total burden. Any governing body can use lifeline rates as much as it wishes, perhaps after a political fight.

Decouple profits from sales. This is a goal Amory Lovins, in particular, has been articulating for as long as I have been in this game. The regulatory body sets utility revenue rules that create incentives to sell not raw kilowatt-hours but the services that power produces. With such an arrangement, an investment in energy efficiency that reduces kWh sold is rewarded, not penalized.

Anticipate increases in kWh consumption via shifts from fuel to power As I already noted, strong carbon policy is likely to add kilowatt-hours to sales as a result of shifts to heat pumps and hybrid vehicles. You don't want to set electricity production goals that result in fighting these shifts. A goal of simply reducing kilowatt hours is not sufficiently subtle.

Wedges of Energy Supply

In the United States, the electricity sector is becoming more carbon-intensive, which is not good news from a climate change perspective. This development reverses a trend of a very long period, fifty years or more, when the nationally averaged carbon emissions per kilowatt-hour produced fell steadily. The surprise of the last five years has been that natural gas is turning out to be a less competitive electricity source for incremental power in most of the country, relative to coal, than had been expected earlier. This is bad news from a climate perspective.

Another useful carbon number is this one: seven hundred 1,000-megawatt power plants (big ones), running on coal, will put a billion tons of carbon into the atmosphere a year. So not building those plants is a wedge.

The International Energy Agency said in 2005 that we're going to put the equivalent of 1,400 new coal plants of 1000-megawatt capacity into place globally, a lot of that in China, but some of it here, by 2030. So we have a tremendous challenge to build a different plant than the kind we're heading for. And because coal plants run for many decades, carbon policy makers lock in lots of future emissions when they procrastinate.

Carbon bookkeeping today keeps track of expenditures this year, but not expenditures in future years incurred as a result of capital investments made this year. Carbon analysts do only one-column bookkeeping, and they could be doing two-column bookkeeping. The new column would report future carbon emissions commitments resulting from investments. Private industry does such double bookkeeping all the time: expenditures and investments. Firms routinely estimate future obligations when they build something. Carbon analysts don't yet do that.

Of course, an additional assumption is required, before one can make estimates of future committed emissions, namely how long is the thing going to be around? I might argue that a coal plant is going to generate electricity for 60 years, and someone else might argue for 45 years; this would need to be settled. To institutionalize "commitment accounting," a government would have to debate these additional assumptions and then embed its choices in its reporting methodology. Commitment accounting could include the lifetime fuel consumption of not only new power plants, but also new residences and commercial building.

The case for commitment accounting is implicit in Figure 2, where the atmosphere is a bathtub. From the perspective of long-term climate impact, it doesn't matter if CO_2 enters the atmosphere next year or twenty years from now. Carbon is around for so long that we really can sum over future years and learn something meaningful.

Figure 11 shows when the currently operating U.S. power plants were built. The bottoms of each bar are the coal plants and the light parts of the bars in the 1970s and 80s are the nuclear plants. We have many power plants that are thirty to forty years old. As a result, industry and government are confronting relicensing, grandfathering, retirement, and "scrap and build." Grandfathering means exempting old plants from new rules. Scrap and build means tear down the current plant, stay at the same site, and build something new and spiffy, a process with considerable virtue from an environmental perspective.

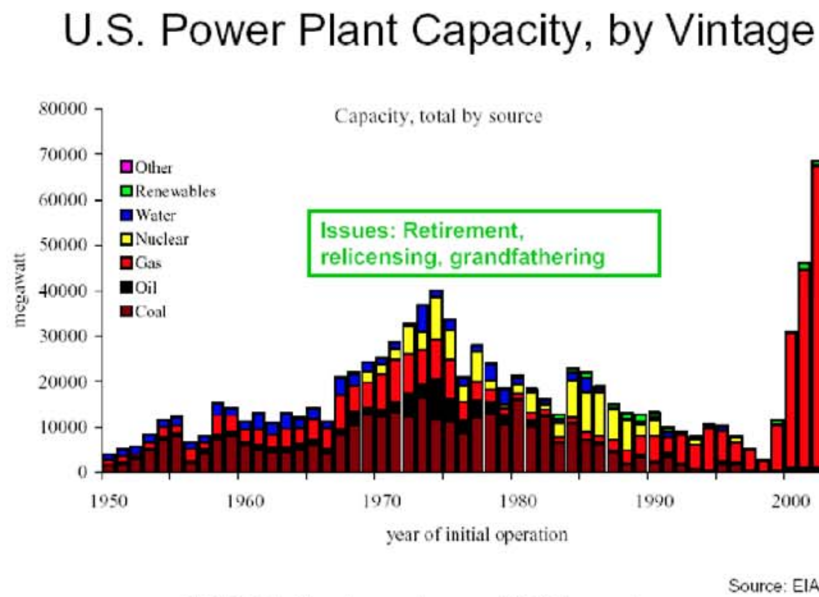


FIGURE 11. Age and type of US Powerplants.

Note the remarkable lemming-like behavior at the far right. Less than a decade ago, companies built an extraordinary amount of natural gas power, when many investors persuaded themselves that this was a brilliant thing to do. It may have been brilliant if each of them had been the only builder on the scene, but it was not brilliant when many others were doing the same thing. The price of natural gas went way up with all this new demand (and for other reasons), with the result that many of the plants on the right in Figure 11 are today either mothballed or running many fewer hours a year than they were expected to. Several firms went bankrupt. It is sobering that very few years ago, a large number of investors made a collectively wrong decision.

What can we build instead of conventional coal plants? Wind power is one answer. You need a huge amount of wind. To replace 700,000 megawatts of coal requires about 2 million megawatts of wind. (The reason the two numbers don't match is because the watt that we're talking about in both cases is a peak watt, and the intermittency of wind costs you about a factor of three when you compare wind to coal.) Wind is growing 30% per year globally. It's growing substantially but fitfully in the U.S.

Decentralized electricity production is another option. Every roof is a potential energy collector. It's not obvious exactly how to count decentralized kilowatt-hours versus centralized kilowatt-hours, because of the cost of intermittency and the benefit of no transmission and distribution. "Net metering," where a single meter runs forward when a consumer buys from the utility and backward when the consumer sells to the utility, provides a simple, but far from perfect, measure of the value of decentralized energy.

Nuclear energy is another option. Today's nuclear reactors have a 40-year operating license. As Figure 11 shows, many key issues over the next ten years will involve relicensing.

Last of the alternatives to coal-as-we-know-it is the option where coal plants capture their own CO_2 emissions so that they don't reach the atmosphere. Coupled to such "capture" plants must be "storage" facilities, typically places where CO_2 is injected deep underground. This half-a-loaf strategy is matched to a world that is unwilling to shut down coal power plants and, moreover, continues building new ones. I described carbon capture and storage (CCS) in an article I wrote in the August 2005 *Scientific American*, called "Can We Bury Global Warming?"

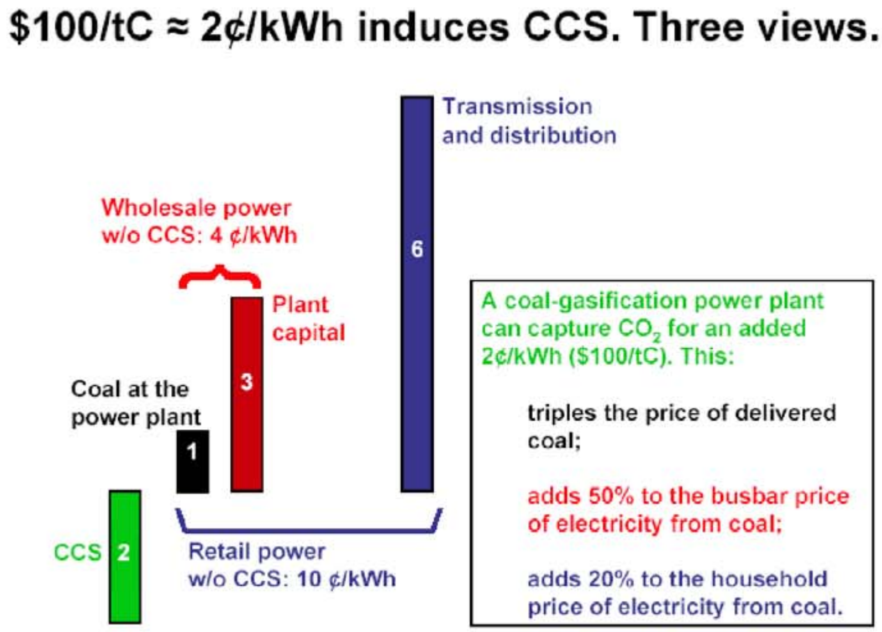


FIGURE 12. Costs to produce electricity with carbon capture and storage.

Carbon management is going to increase the price of electricity. Figure 12 presents three ways of thinking about this increase. Suppose the cost of adding CCS to a power plant is two cents per kilowatt-hour. The cost of power from such a plant will be about the same as the cost of power for the same coal plant without CCS when its CO_2 emissions are charged at a rate of \$100 a ton of carbon (about \$30/tonCO_2) – called the breakeven price. To what can we compare two cents per kilowatt-hour? There are three interesting answers: We can compare it to the cost of coal, to the wholesale cost of power, or to the retail customer's cost of power.

We'll use ballpark numbers, all in cents per kWh. It's about one cent for the coal burned, three cents more for paying off the capital costs for building the plant, and another six cents for the transmission, distribution, and retail handling costs between the power plant and the residential consumer. Those numbers aren't exactly right for any specific situation, but they get us to the important insights. If you're in the coal industry, you're looking at a tripling of the cost of your product, and you could be losing out in your competition with natural gas. If there is a \$30/ton CO_2 carbon tax, it will triple the cost of your coal when delivered to the utility. By contrast, the utility is looking at a 50% increase in its plant-gate ("busbar") costs, and the residential customer is looking at a 20% increase in the costs on the bill. How hard people will fight a carbon policy that leads to a \$30/tonCO_2 emissions price (whether they will tie you up in court, for example) is implicit in the numbers in Figure 12.

To be sure, Figure 12 assumes that the extra CO_2 cost gets passed from one transaction to the next with neither overheads being charged nor costs being absorbed. Legislation could assure this outcome; similar legislation governs the pass-through of fuel escalation costs in electricity markets. Without such legislation, all along the value chain from coal mine to retail customer, percent overheads could be charged, whereupon two cents per kilowatt-hour on the coal could turn it into seven at your home. Not a good outcome.

The utilities have the opposite concern. They want to make sure they can recover the full two cents. The policy maker should assure that the cost of carbon mitigation moves through all the transactions right in the middle of the fairway.

Avoid Mitigation Lite

Carbon emission charges in the neighborhood of \$30/tCO_2 can enable scale-up of most of the wedges, if supplemented with sectoral policy to facilitate transition.

Form of Energy	Equivalent to \$100/tC or \$30/tCO_2
Natural gas	\$1.50/1000 scf
Crude oil	\$12/barrel
Coal	\$65/U.S. ton
Gasoline	25¢/gallon (ethanol subsidy: 50¢/gallon)
Electricity from coal	2.2¢/kWh (wind and nuclear subsidies: 1.8 ¢/kWh)
Electricity from natural gas	1.0¢/kWh

\$100/tC was the approximate EU trading price for a year ending April 2006, when it fell sharply.

FIGURE 13. Fuel Equivalency Cost of \$30/tCO_2

How can we understand \$30/tonCO_2? First, it's more than the emissions price usually being talked about in Washington today. It's far more than that the price that will come into being with the Regional Greenhouse Gas Initiative (the interstate initiative designed by northeastern U.S. states, scheduled to come into force in January 2009).

How much is \$30/ton CO_2 in other energy units? It would help if more people could know the answers. Because there's a specific amount of carbon in any ton of fuel or gallon of fuel, these answers are well defined. See Figure 13

Natural gas is measured in the U.S. either in therms or in standard cubic feet. A value of \$30/tonCO_2 is about fifteen cents per therm or \$1.50 per thousand standard cubic feet. Wholesale natural gas prices, at the point where the gas enters our interstate pipeline system, are about four times higher than that today, and for the residential consumer, often ten times higher. The corresponding price in the unit used for crude oil is twelve dollars per barrel. Coal prices are usually in tons, and \$30/ton CO_2 is about \$65 per ton of coal, approximately twice what many coal-burning utilities pays for coal.

Coal, oil, and gas are affected unequally by a price on CO_2 emissions, because the three feedstocks produce different amounts of CO_2 when they deliver the same amount of energy. Natural gas emits only a little more than half as much CO_2 as coal and about two thirds as much as oil. The underlying reason is a difference in the amount of hydrogen in each fuel, relative to the amount of carbon. Hydrogen burns to water and produces no CO_2. As a result, when more hydrogen is present for the same amount of carbon, more energy is produced for the same amount of CO_2. Natural gas has the highest hydrogen-to-carbon ratio of the three fuels. Accordingly, a \$30/ton CO_2 price on CO_2 emissions to the atmosphere has a truly big impact on the competition between coal and natural gas for electric power (favoring natural gas) and the competition between fuel oil and natural gas for home heating fuel (again, favoring natural gas)..

Returning to Figure 13, you see that by the time the price of \$30/ton CO_2 reaches the consumer, if it's a straight pass through, it's twenty-five cents per gallon of gasoline, a price that isn't likely to have a big effect on driving. It's two cents per kilowatt-hour for a customer who gets his or her electricity exclusively from coal power plants. It's one cent per kilowatt-hour for a customer whose power comes from natural gas. As noted above, it's also about one cent per kilowatt-hour for an average New Jersey resident, given the mix of the nuclear, coal, and gas power plants that produce our electricity.

Given the way these numbers work, I think you will see why it is important for U.S. carbon policy to levy the CO_2 emissions charge far "upstream," ideally, where the fossil carbon comes out of the ground or across our borders. The further upstream, the higher the percent impact on the price of the product for the same CO_2 charge, and also the fewer the emissions that escape notice. If one places the charge far downstream, where gasoline is purchased and electricity bills are paid, the result of the same CO_2 emissions charge is likely to be much less CO_2 emissions reduction. If there is a CO_2 tax, impose it on the fossil fuel producer and importer; if there is a CO_2 cap and trade system, cap the carbon flows of the same players. I think designers of CO_2 policy haven't focused enough on putting under the cap the largest possible fraction of the economy's carbon emissions.

If for societal buy-in you desire involvement of the downstream consumer (the retail consumer of gasoline and electricity) in carbon policy, you will need to supplement the CO_2 price signal with targeted policy. An example of targeted policy is CAFE, the corporate-average fuel economy standard that governs the new-car market.

We can't expect to arrive at \$30/tonCO_2 instantly. We need a ramp. It seems in this particular discussion that it falls to academics to make options vivid, so, to be specific, I recommend a ramp that climbs to thirty dollars per ton of CO_2 in ten years – an increase of three dollars per ton of CO_2 every year throughout the decade? Five years into the policy, the price is fifteen dollars per ton of CO_2. The start date might be 2010.

If, instead, we lock in much lower CO_2 prices, we set up what I call "Mitigation Lite." I say: Avoid Mitigation Lite. Mitigation Lite has the right words and the wrong numbers. Advocates of Mitigation Lite argue that we can fix the numbers after we've gotten used to the right words. The trouble with this line of reasoning is that industry negotiators are saying, "We'll take anything you want to throw at us as long as you promise not to change it." Mitigation Lite is a poor option, if regulatory certainty for a decade or more is attached to it.

Can We Do It?

Finally, can we do it? People, *we*, are becoming increasingly determined to lower the risk that we and our children will experience major social dislocation and environmental havoc as a result of rising CO_2 in the atmosphere, and we are learning that there are many ways of changing how we live, what we buy, and how we spend our time that will make a difference.

We are in the midst of a discontinuity. What once seemed too hard has become what simply must be done. Precedents include abolishing child labor, addressing the needs of the disabled, and mitigating air pollution.

What once seemed too hard has become what simply must be done.

Acknowledgements.

I would like to thank Judge Eleanor Stein, Administrative Law Judge for the New York State Public Service Commission, for inviting me to give the keynote talk at the meeting of the New York Public Service Commission on July 19, 2007, and for taking the first steps to turn the transcript of my talk into a readable manuscript. I would like to thank Margaret Barry and Rose Mary Bailly for follow-up editing in Albany that will result in publication of a different and longer version of this article in the New York State Bar Association's *Journal of Government Law and Policy*, produced by Albany Law School, in a special issue on climate change, (Kevin Healy, guest editor). I wish also to thank Jim McMahon and Dave Hafemeister for their parallel editing of the Albany manuscript for inclusion with the talks presented at the Short Course on Energy held at the University of California at Berkeley, March 1–2, 2008. For both articles, I have done much rewriting. Responsibility for the final versions of these articles is entirely mine.

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