THE CENTURY-LONG CHALLENGE OF FOSSIL-CARBON SEQUESTRATION

Robert Socolow

The Time Scale Is a Century

The time scale of the Greenhouse problem is a century. This is an unfamiliar time scale for political action.

The Greenhouse problem arises if the global energy system is dominated by fossil fuels throughout this century. Such dominance is likely. But there is a fossil-fuel-based solution. It is conceivable that most of the carbon in the next hundred years of fossil fuels can be prevented from reaching (can be "sequestered" from) the atmosphere.

Fossil-carbon sequestration is conceptually entirely different from biological-carbon sequestration, yet, unfortunately, both kinds of sequestration are usually called, simply, "sequestration." Biological carbon sequestration removes carbon from the atmosphere. Fossil-carbon sequestration redirects carbon not yet in the atmosphere.

The politics of fossil-carbon sequestration are unlike the politics of carbon management strategies designed to bring the fossil fuel era to a rapid close. The fossil fuel industries are willing participants,and they are showing leadership. So are many countries and portions of countries rich in fossil fuel resources. The

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result should be new coalitions supportive of policies intended to mitigate climate change.

Why is the time scale a century, not a decade or a millennium?

I recommend committing two numbers to memory:

1) *Six* billion metric tons of carbon are in the fossil fuels used currently each year.

2) *One thousand* billion metric tons of carbon extracted from the ground as fossil fuels,if used as today, will produce,approximately, a doubling of the carbon content of the atmosphere. (A metric ton is ten percent larger than a U.S. ton.)

From these two numbers one sees why, given modest growth in global use of fossil fuels, the greenhouse problem has a century time scale. A century is the time associated with a doubling of the amount of carbon (or, equivalently, CO_2) in the atmosphere. And doubling is the most widely used boundary between acceptable and unacceptable greenhouse-related environmental disruption. Doubling is roughly where thresholds for serious damage are thought to be.

Complications being swept under the rug include: carbon sinks, greenhouse gases other than CO_2, and the reference atmosphere in discussions of doubling – usually the pre-industrial atmosphere, not today's (already containing a third more carbon).

There is lots of room to argue about whether doubling is the appropriate reference ratio. Here is where the important scientific uncertainties and human judgments are found. But it will take decades to understand climate change substantially better than we do right now. We should expect the focus on doubling to be robust, and therefore the century-scale of the Greenhouse problem to be robust.

Why must century-scale solutions focus on coal?

Coal is at the root of the Greenhouse problem. Conventional oil and gas are not sufficiently abundant to generate a serious Greenhouse problem on their own.

Well before their cumulative carbon content reaches 1000 billion metric tons, both are expected to become non-competitive as a result of growing costs of access (costs related to resources being very deep underground, or below very deep water, or very remote, or very small.) But the carbon content of coal is many times larger than 1000 billion metric tons. The world will not be saved from a serious Greenhouse problem by fossil fuel depletion,if energy from coal remains competitive with energy from non-fossil sources for a century. Fossil-carbon sequestration will initially target conventional oil and gas as well as coal, but the century's assignment is to capture the carbon in coal and store it.

I am oversimplifying. Non-conventional oil and gas may compete with coal throughout the century. Non-conventional oil is oil in tar sands and oil shales. Non-conventional gas is gas in methane clathrates – methane trapped under pressure below the permafrost or at the ocean floor. All these are also abundant. The century's assignment may also be to capture and store their carbon.

Fossil-carbon sequestration has two elements: carbon capture and carbon storage. Work is under way on both fronts, with an emphasis on understanding costs and risks. The issues are new, recruits are pouring in, fresh ideas are sprouting everywhere. Below, I give a quick tour.

Carbon Capture

Nearly all of the industrial experience with the capture of the carbon in fossil fuels is in applications unrelated to global climate and without accompanying storage. The carbonated beverage industry uses CO_2 produced from fossil fuels. There are ammonia plants in Trinidad that sell byproduct CO_2 to nearby methanol plants.

The cost of capture is strongly dependent on the concentration of CO_2 in the gas stream from which it is separated. Much of the early analysis of carbon capture assumed that separation would occur at low concentrations in flue gases,after combustion in air. Capture costs are reduced if combustion is done in oxygen instead of air, or if capture occurs as an accompaniment to the production of synthesis gas prior to energy extraction.

A significant fraction of the cost of electricity from coal is attributable to the avoidance of emissions of pollutants containing sulfur, nitrogen, chlorine, mercury, and other elements originally in the fuel. Co-sequestration (co-capture plus co-storage) of one or more of these pollutants with the CO_2 may be a cheaper alternative. Savings resulting from discarding some conventional pollution controls may offset costs of restricting carbon emissions. Co-sequestration won't be easy: along the way, the gas mixtures must not create costly complications – within the plant (degradation of turbine blades, contamination of catalysts), in pipelines, or below ground.

I am assuming here that the carbon in fossil fuels must be captured within the fossil fuel system – at some facility where fuel is handled. Note, however, that schemes to capture atmospheric CO_2 in dedicated industrial facilities are being investigated. If carbon capture in such facilities can be done cheaply, perhaps the fossil energy system would need much less change. We would put carbon in the air at one place and take it out at another. Of course, that is also the appeal of biological carbon sequestration.

The Hydrogen Economy

About one half of carbon from fossil fuels that is emitted to the atmosphere has first been distributed to small users – mainly to buildings and vehicles. The costs of retrieval of such highly dispersed carbon are likely to be prohibitive. To capture most of the century's fossil fuel carbon cost-effectively, the energy system must evolve into one that distributes energy largely in forms free of carbon. Electricity and hydrogen are fine, but only a small fraction can be natural gas, gasoline,and diesel. Electricity and hydrogen must be produced and carbon captured at facilities comparable in size to today's refineries and power plants. An all-electric economy is one possibility. The other is an economy in which both electricity and hydrogen are used, each where it is best suited. If the latter, an entirely new fuels infrastructure for hydrogen production, distribution, and end use must be created.

This past year colleagues at Princeton and Milan have been analyzing one of the many ways that hydrogen might be produced from coal, while most of the carbon in the coal is captured as CO_2. First, coal is gasified in a small amount of oxygen to produce synthesis gas. Then the synthesis gas is processed so that nearly all becomes either hydrogen or CO_2 , and most of the hydrogen is separated from the CO_2 using a membrane permeable only to hydrogen. The CO_2 is extracted from the residual gas that has not gone through the membrane – after the residual gas (which has some of the hydrogen) has passed through a turbine and produced electricity. The hydrogen-separation membrane, today still in the laboratory, is the novel element here. Design variables include the fraction of the hydrogen sent through the membrane, various temperatures and pressures at intermediate stages, and clean-up strategies for the contaminants inevitably present in the coal.

The purpose of this analysis is to arrive at estimates of the cost of hydrogen, given specific costs for fuel and the components of the plant. One critical assumption is that all technologies are mature; the costs of learning have somehow been absorbed, and estimation focuses on the cost of the "Nth unit" (with N, in practice, being perhaps 10). My colleagues will report that their approach has the potential to produce hydrogen under carbon emission constraints more cheaply than all other approaches, fossil-fuel-based or non-fossil-fuel-based. Critical to their result is a cost credit for the sale of the byproduct electricity. Their work can be expected to stimulate both government and industry to increase their research on hydrogen-separation membranes.

Hydrogen is a secondary fuel. It has to be made from something else. Hydrogen has such broad political support because advocates of each primary energy source – wind, photovoltaic cells, hydropower, nuclear fission, natural gas, coal – persuade themselves that theirs is the preferred route to hydrogen.

Today, when hydrogen is made in large quantities, in petroleum refineries and ammonia plants, it is almost always made from fossil fuels – not from renewable or nuclear energy. Production from fossil fuels does not require the costly intermediate step of electrolysis of water. The route from fossil fuels to hydrogen is cheaper today, and will remain cheaper for a long time.

Hydrogen can be converted to energy either in combustion devices or in fuel cells. Because hydrogen fuel is carbon-free, no hydrocarbon or carbon monoxide emissions result in either case. Although fuel cell energy conversion is cleaner from other perspectives, the first hydrogen-powered cars on the road will probably have internal combustion engines.

Hydrogen is used safely by trained workers in industry. One of the most important open questions that will determine the practicability of globally significant carbon capture is whether hydrogen can be used safely by ordinary people.

Carbon Storage

Retaining our century-long perspective, we ask where one can credibly put 1000 billion metric tons of carbon. There appear to be only two destinations: the deep ocean and deep underground saline aquifers.

Deep Ocean Storage

Those who wish to develop the oceans option explain that the oceans already receive a portion of the carbon extracted in fossil fuels. Add CO_2 to the atmosphere and some will move to the oceans, as equilibrium is sought at the ocean surface. Additional CO_2 in the near-surface ocean has its own impacts – for example, on coral reefs. Why not use technology to put CO_2 deep in the ocean, directly, and thereby disturb the near-surface ocean less? At present, the environmental community is not finding such arguments persuasive. It is weighing in to prevent even small studies of environmental impacts (on fish, for example). It perceives too slippery a slope.

Saline Aquifer Storage

At least for now, that leaves deep aquifers. The world's first large aquifer storage project has been underway since 1996 in the North Sea in Norwegian territory at the Sleipner gas field 200 kilometers offshore. There, Statoil, a Norwegian oil company, is producing natural gas that contains 90% combustible gases and 10% CO_2 . The maximum allowed concentration of CO_2 in the European natural gas grid is about 2.5%, so Statoil must "strip" CO_2 from the Sleipner gas before sending it to the grid. Normally, stripped CO_2 is vented to the atmosphere, but Norway has imposed a tax on such CO_2 emissions. Statoil has responded by injecting the stripped CO_2 into a deep aquifer, and it has convinced the Norwegian government that the stripped CO_2 will remain in the aquifer indefinitely. The Norwegian government is exempting Statoil from the tax.

Sleipner has made many issues vivid that any permitting regime must confront:

> *Public approval.* How can a permitting regime be designed that the public accepts? To what extent can openness, lack of bias, fairness, and vigilance be achieved?
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> *Storage integrity.* Staying below some maximum rate of escape averaged over all storage sites is required to achieve the greenhouse objective. Escape of CO_2 from a few sites is inconsequential. How can the permitting process include permission to fail?
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> *Goals.* What constitutes a victory? Is removal from the atmosphere for 500 years, for example, good enough?
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> *Property rights to storage space.* The Sleipner CO_2 is not being stored on private property, but other CO_2 will be. Are ownership rights below ground clear? What about below the ocean floor? And in the ocean?
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> *Site-specific risks.* Concentrations of more than a few percent of CO_2 in air are dangerous, so bulk releases of CO_2 must be avoided. Upward migration of injected CO_2 could contaminate hydrocarbon reservoirs or surface drinking water supplies, so certain slow releases may also be of concern. How can such risks be minimized? What additional risks will experts dismiss but others insist on addressing?
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> *Infrastructure.* Who will create the CO_2 pipeline infrastructure to connect large numbers of capture and storage sites? Will a combined CO_2-plus-hydrogen infrastructure evolve?
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> *Monitoring.* Can infrastructure and storage be designed in ways that facilitate monitoring (e.g., by adding a tracer to the injected gas)? How can long-term monitoring be institutionalized?

Uncertainties in storage costs implicit in these questions are probably the largest cost uncertainties of fossil-carbon sequestration.

Storage in Hydrocarbon Reservoirs and Coal Seams

Oil and gas reservoirs and coal seams are below-ground alternatives to aquifers, available at much smaller scale but with potentially favorable economics for the next decade or two. Storage in oil and gas reservoirs builds on extensive experience with enhanced oil recovery (EOR) using CO_2, by far the largest industrial use of CO_2. EOR provides an economic return on separated CO_2. To date, EOR has not been a carbon storage strategy; it has not mattered whether the CO_2 remained below ground after it did its work. Once CO_2 emissions have costs,EOR will be reoptimized, and carbon will be stored at EOR sites.

Storage of CO_2 in deep coal seams is another way to use and store carbon at the same time. The key idea is to produce coal-bed methane by a displacement process, where CO_2 dislodges methane adsorbed on coal. The target coal is "unminable," too deep ever to be commercially attractive. However, the hundred-year perspective is not always adopted when unminable is defined. If new technology someday makes such coal minable,there will be additional costs to manage the adsorbed CO_2.

Biological Carbon Sequestration

Biological carbon sequestration removes carbon from the atmosphere by photosynthesis. On land, storage will usually take place at the same site as capture – for example, in a tree. In the ocean,capture is at the surface and storage is in the deep ocean, with an intermediate step where the organism falls by gravity. Initial costs of biological carbon sequestration on land are small, and the vision of joint gains (land improvement plus carbon storage) is seductive. Yet, biological carbon sequestration on land is not a century-scale strategy. The stock of carbon above-ground in terrestrial vegetation is roughly the same size as the stock of carbon in the atmosphere. So if future carbon (now in fossil fuel resources below ground) that would otherwise double the atmospheric carbon stock were to end up, instead, in forests and grasslands, their carbon stock would become double what it is today. Ecologists warn that such a change is too big and too fast to be consistent with the retention of ecosystem quality. At the local level, it is quite easy to invent ecologically disastrous ways of storing carbon that a poorly designed incentive system would elicit.

Table 1 compares geological and terrestrial biological sequestration strategies. "Geological" strategies, here, are all underground strategies. I measure "storage capacity" in units of time: a decade of storage capacity means the capacity to store all the carbon in a decade of global fossil fuel production. For biological strategies, I claim only "decades" of "time until escape," because I expect sites of storage, on average, to be put to new uses within a few decades – perhaps a forest will be cleared for agriculture or a grassland will give way to a suburb. The time until escape is not the lifetime of a tree, because a managed forest can be replanted.

TABLE 1 - GEOLOGICAL VS. TERRESTRIAL BIOLOGICAL STRATEGIES

Geological Strategies	**Terrestrial Biological Strategies**
Coal, oil, gas sectors	Forestry and farming
Large unit scale, point source	Large or small scale, non-point source
Storage capacity: *Centuries*	Storage capacity: *Decades*
Time until escape: *Millennia*	Time until escape: *Decades*
Even first storage is expensive.	First storage is cheap.
Benefits: Enhanced oil recovery	Benefits: Land restoration
Risks: Reservoir contamination	Risks: Ecological abuse
Measurement of injection is easy.	Measurement of storage is daunting.
Measurement of escape is daunting.	Measurement of escape is daunting.

Why Start Now on a Century-Long Challenge?

Even if it will take the better part of a century to change the global energy system, why start now? Postponement of action, say for a generation, seems to have in its favor that general learning in the meanwhile will improve the understanding of risks and benefits of each option now known and will add new items to the list of options. The Greenhouse challenge itself could be recast within a generation, if global lifestyle choices evolve in some unexpected direction.

I come out in favor of early action (and not just because I find the whole enterprise of fossil-carbon sequestration intellectually irresistible). The Greenhouse problem has thresholds, yet we know little about their proximity and importance. If we delay action for a generation and in the interim learn that action is urgent, catching up could be costly.

Early action carries low costs and low risks. The first steps involve combining already commercialized technologies in new ways. And there are willing actors: Many fossil fuel companies currently see a competitive advantage accruing from early experience. They see good will to be earned.

The goal of early action should be to gain experience with both carbon capture and carbon storage. Because of economies of scale, learning will entail costs that come in large increments – a well known and difficult challenge to public policy. Cost savings can be achieved via global thinking about where investments are best done. Developing countries are targets for early investments in advanced above-ground infrastructure where energy conversion facilities and transportation infrastructure are being built from scratch. Industrialized countries are targets for early below-ground investments where geology is especially well understood and lowest-cost production opportunities for fossil fuels have already been exhausted.

Learning about capture can be made less costly by well designed subsidies that promote the incorporation of not fully proven technological components into new facilities and systems. Similar recommendations apply to subsidies to learn about hydrogen production, distribution and use.

Learning about storage will require early experiments with institutions. Moving early to develop the permitting of storage facilities should generate constructive debate about goals, division of responsibility, and verification.

We must not expect perfection. All of the carbon in fossil fuel entering an individual facility cannot be captured. Nor can all the fossil fuels in the economy be treated in facilities designed to capture carbon. Neither carbon capture nor carbon storage can be achieved without using more energy than would be required if these activities were not attempted. Thus, the quantities of carbon reaching the atmosphere will still be large.

The consequences of learning are unpredictable. In particular, we may learn that we are underestimating the cost of avoiding carbon emissions, by every option, because we discover a less costly way to provide some product or service with CO_2 emissions. We may also discover some aspect of fossil carbon sequestration,in particular, that creates costs that reduce its appeal.

As a carbon management strategy, fossil-carbon sequestration is in competition with the substitution of renewable energy for fossil fuels and with the substitution of nuclear energy (fission and fusion) for fossil fuels. At this time, one can only guess how the three strategies will compete. My guess is that for the next hundred years all three will co-exist, each of them contributing substantially to carbon management. The sooner we come to grips with the costs and risks of fossil-carbon sequestration, the sooner we will be able to place this strategy properly in the portfolio of options for addressing the Greenhouse problem.