GEOENGINEERING AND CARBON MANAGEMENT: IS THERE A MEANINGFUL DISTINCTION?

DAVID W. KEITH*
Carnegie Mellon University, Pittsburgh, PA

INTRODUCTION

A broad and expanding suite of responses to the CO_2-climate problem have been proposed ranging from energy conservation to the construction of space-based sunshields that could counter some of the effect of increasing CO_2. Proposed measures vary widely along many dimensions including their technological feasibility and their distribution of costs, benefit and risks. Here I focus on assessment of industrial carbon management (ICM), defined as the linked processes of capturing the carbon content of fossil fuels while generating carbon-free energy products such as electricity and hydrogen and sequestering the resulting CO_2. Put simply, I address the question: Is ICM an advanced emissions control technology or is it geoengineering?

I define *geoengineering* as intentional large-scale manipulation of the environment. Climatic geoengineering aims to mitigate the effect of fossil-fuel combustion on the climate without abating fossil fuel use; for example, by placing shields in space to reduce the sunlight incident on the Earth. Climatic geoengineering is marked by four characteristics, scale, intent, technology and countervailing action (Keith 2000). Two examples serve to demonstrate the roles of scale and intent. First, intent without scale: Ornamental gardening is the intentional manipulation of the environment to suit human desires, yet it is not geoengineering because neither the intended nor realized effect is large-scale. Second, scale without intent: The modification of global climate due to increasing atmospheric CO_2 has global effect, yet it is not geoengineering because it is a side effect resulting from combustion of fossil fuels with the aim of providing energy services. Finally, such proposals are primarily technological rather than social and their mode of action is by counterbalancing some other human impact rather than my minimizing that impact. Put simply, geoengineering is a technological fix on a grand scale.

The contextual framing of response modes will likely play a central role in climate politics. By framing I denote the ways by which choice of response modes is related to other social and technological choices. In particular, I mean judgments about where a mode lies along common dimensions of differentiation. Its it green or brown? Command-and-control or market driven? High technology or off-the-shelf? The aim of this paper is to place ICM in context by analysis of its relation to other climate response modes with respect to various important attributes. My motivation is the likely importance of these framings to the political economy of the CO_2 climate problem.

The analysis presented here is necessarily subjective. While analysis can reasonably assess the direct cost of various responses, for example the agricultural sequestration of carbon versus the expanded use nuclear power, and can (sometimes) quantify the direct efficacy of technological choices, for example the effect of increased use of nuclear power on urban air quality, an analyst cannot objectively judge the importance of incommensurate impacts such as the increased land use required by agricultural sequestration versus the long-term risk of radioactive waste due to nuclear power.

There has been little systematic effort to probe public perception of the merits of various responses to climate change. (This lack is particularly unfortunate given the comparatively large effort to probe public option on basic understanding of the climate problem.) Moreover, public knowledge of the available

* Department of Engineering and Public Policy, Baker Hall 129, Pittsburgh PA 15213-3890. keith@cmu.edu

response options is probably now so slight that current perceptions are not robust. When (or if) the climate problem becomes more salient in the public agenda, it is likely that public perceptions about the extent to which proposed solutions resemble geoengineering will strongly influence their acceptability.

The costs of response modes is largely ignored in the following analysis. Cost is, of course a centrally important metric of comparison, and in principle, cost-effectiveness or cost-benefit analysis should play a central role in clarifying climate policy choices. The applicability of cost-benefit analysis to the CO_2-climate problem is frustrated by two root problems, (i) the difficultly of monetizing incommensurate impacts, and, (ii) the importance of induced technological change.

In comparing response modes, I will argue that three distinction are of central importance.

- Regulating atmospheric CO_2 concentration is different than regulating climate; and,
- regulation of atmospheric CO_2 by minimization of sources is different than regulation of CO_2 by counterbalancing sources with sinks; and finally,
- regulation of human impact on climate by reduction in the consumption of final goods and services is different than limitation of impact by technological or process improvements that reduce the net environmental impact per unit of final product.

EXAMPLES OF RESPONSE OPTIONS

The following sections provide brief descriptions of various response options. I describe only the technical response options that are likely to be least familiar. More familiar response options such as improving energy efficiency and living with less discussed in the next section but are not describe here. The description are purely technical and omit discussion of issues such as cost, risk and historical background.

Industrial Carbon Management with Geological Sequestration

The long-term use of fossil energy without emissions of CO_2 is an energy path that may substantially lower the economic cost of mitigating anthropogenic climate change (Parson and Keith 1998). I call the required technologies Industrial Carbon Management (ICM), defined as the linked processes of capturing the carbon content of fossil fuels while generating carbon-free energy products such as electricity and hydrogen and sequestering the resulting carbon dioxide. Although many of the component technologies are well known, the idea that ICM could play a central role in our energy future is a radical break with recent thinking about energy system responses to climate change.

The carbon dioxide generated from oxidation of fossil fuels can be captured by separating CO_2 from products of combustion or by reforming the fuel to yield a hydrogen-enriched fuel stream for combustion and a carbon enriched stream for sequestration. In either case, the net effect is an industrial system that produces carbon-free energy and CO_2—separating the energy and carbon content of fossil fuels. The CO_2 may then be sequestered in geological formations or in the ocean. If hydrogen was used as a primary energy carrier then the existing cost advantage of carbon management over non-fossil alternatives is augmented due to the technical advantages of thermochemical over electrochemical hydrogen production.

A large body of recent engineering studies have addressed the technical feasibility of capturing CO_2 from power plants and compressing it for sequestration in the ocean or underground. The rough consensus of the studies is as follows.

- For new power stations, the amortized additional cost of CO_2 capture and sequestration would raise electricity prices by 30 to 150%, a cost that is less than the current costs of non-fossil alternative energy sources such as solar.
- The costs would probably be substantially higher for retrofitting existing power plants.
- Most costs arise from the separation of CO_2 from other exhaust gases, rather than from its compression and sequestration.

The options for geological sequestration may be summarized as follows. Three types of reservoirs have been seriously considered: depleted oil and gas fields (global capacity ~ 200-500 GtC), deep coal beds (~ 100-200 GtC), and deep saline aquifers (~ 10^2-10^3 GtC).

Ocean Fertilization with Iron

Carbon can be removed from the atmosphere by fertilizing the "biological pump" which maintains the disequilibria in CO_2 concentration between the atmosphere and deep ocean. The net effect of biological activity in the ocean surface is to bind phosphorus, nitrogen, and carbon into organic detritus in a ratio of ~1:15:130 until all of the limiting nutrient is exhausted. The detritus then falls to the deep ocean providing the pumping effect. Thus the addition of one mole of phosphate can, in principle, remove ~130 moles of carbon. (This ratio includes the carbon removed as $CaCO_3$ due to alkalinity compensation, and this first order model of the biology ignores the phosphate-nitrate balance. Much of the ocean is nitrate limited, thus adding phosphate to the system will only enhance productivity if the ecosystem shifted to favor nitrogen fixers.)

Over the last decade it has become evident that iron may be the limiting nutrient over substantial oceanic areas (Behrenfeld and Kolber 1999). The molar ratio Fe:C in detritus is ~1:10000, implying that iron can be a very efficient fertilizer of ocean-surface biota. Motivated in part by interest in deliberate enhancement of the oceanic carbon sink, two field experiments have tested iron fertilization *in situ*, and have demonstrated dramatic productivity enhancements over the short duration of the experiments (Coale, Johnson et al. 1998). However, it is not at all clear that sustained carbon removal is realizable.

Shielding Sunlight with Space Based Scattering Systems

The possibility of shielding the earth with orbiting mirrors is the most technologically extravagant geoengineering scheme. While expensive, it has clear advantages over other geoengineering options. In principle, the use of space-based solar shields has significant advantages over other geoengineering options. Because solar shields effect a "clean" alteration of the solar constant, their side effects would be both less significant and more predictable than for other albedo modification schemes. Assuming that the shields were steerable, their effect could be eliminated at will

The obvious geometry is a fleet of shields in low-earth orbit. However, solar shields act as solar sails and would be pushed out of orbit by the sunlight they were designed to block. The problem gets worse as the mass density is decreased in order to reduce launch costs. A series of studies published in 1989-92 proposed locating the shield(s) just sunward of the L1 Lagrange point between the Earth and Sun where they would be stable with weak active control (Seifritz 1989).

Recently, Teller et al. (Teller, Wood et al. 1997) note that a scattering system at the L1 point need only deflect light through the small angle required for it to miss the earth, about 0.01 rad as compared to ~1 rad for scatterers in near earth orbit or in the stratosphere. For appropriately designed scattering systems, such as the metal mesh described in the previous section, the reduced angular deflection requirement allows the mass of the system to decrease by the same ratio. Thus, while a shield at the L1 point requires roughly the same area as a near-earth shield, its mass can be ~10^2 times smaller. Teller et al. estimate the required mass at ~3×10^3 t. The quantitative decrease in mass requirement suggested by this proposal is sufficient to warrant a qualitative change in assessments of the economic feasibility of space-based albedo modification.

Agricultural Sequestration

The use of intensive forestry to capture CO_2 as a tool to moderate anthropogenic climate forcing was first proposed in the late 1970s. It is now a centerpiece of proposals to control CO_2 concentrations under the Framework Convention on Climate Change, particularly under the Clean Development Mechanism. The focus of interest has moved beyond forests to other managed ecosystems such as croplands. Uncertainty about the duration of sequestration is crucial. For example, recent analysis has demonstrated that changes in management of cropland, such as use of zero-tillage farming, can capture significant carbon fluxes in soils at low cost, but continued active management is required to prevent the return of carbon to the atmosphere by oxidation (Rosenberg, Izaurralde et al. 1998). For both forest and cropland, uncertainty about the dynamics of carbon in these ecosystems limits our ability to predict their response to changed management practices or to climatic change, and thus adds to uncertainty about the duration of sequestration.

DIMENTIONS OF COMPARISON

I describe four important dimensions along which we may analyze responses to the CO_2-climate problem mode of action, risk, importance of auxiliary benefits and strength of social/technological coupling. This list is not exhaustive. Important dimensions of comparison that I ignore here include, for example, the temporal distribution of costs and benefits.

Mode of Action: Countervailing or Minimizing?

Actions to mitigate anthropogenic climate change may work either by reducing anthropogenic climate forcing—directly reducing our impact on climate—or they may act by countervailing against an existing anthropogenic forcing. Responses that act by countervailing include most obviously the grand geoengineering methods such at those that alter the amount of sunlight absorbed by the earth, for example by placing sulfates in the stratosphere or more down-to-earth schemes such as increasing the albedo of build environments. But countervailing actions also include the manipulation of atmospheric CO_2 concentration by the enhancement of carbon fluxes into terrestrial or oceanic ecosystems or by use of industrial processes that directly capture CO_2 from the air.

Risk and Uncertainty

Responses to climate change poses risks that combine natural and social aspects. For example, will stratospheric aerosols destroy ozone? Will the availability or implementation of geoengineering prevent sustained action to mitigate climate forcing? Here we focus on the technical risks.

Risks may be roughly divided into two types; risk of side effect and risk that a response strategy will fail to achieve its central aim. For albedo modification, the division is between side effects such as ozone depletion, that arise directly from the albedo-modifying technology, and risk of failure associated with the difficulty of predicting the climatic response to changes in albedo. Side effects of CO_2 control include loss of biodiversity or loss of aesthetic value that may arise from manipulating ecosystems to capture carbon, and risk of failure is associated with unexpectedly quick re-release of sequestered carbon.

In decisions about implementation, judgment about the risks of geoengineering would depend on the scalability and reversibility of the project: Can the project be tested at small scale, and can the project be readily reversed if it goes awry? These attributes are vital to enabling management of risk through some form of global-scale adaptive ecological management (Gunderson, Holling et al. 1995) (Allenby 1999).

Auxiliary Benefits

All responses to the climate problem can reasonably claim some beneficial side effects, but they differ significantly with respect to the overall importance of such benefits. In the case of agricultural sequestration, for example, the benefits claimed include enhancement of soil quality, crop productivity and hydrological capacity. Whereas for geological sequestration the principle benefit claimed is reduced emission of conventional atmospheric pollutants.

Claims of auxiliary benefit must be examined skeptically, as its magnitude is often strongly dependent on the choice of baseline. Consider agricultural sequestration. If we choose average farms as a baseline then joint improvements in soil quality and carbon sequestration are likely possible given the known performance of the best farms. On the best managed farms, however, it is far less plausible that significant increases in carbon sequestration can be achieved without loss of some other desiderata such as productivity. In general, where the existence of significant auxiliary benefits depends on the nonoptimality of the reference state we should suspect the existence of pre-existing barriers that will frustrate attempts to reap the claimed auxiliary benefits.

The crux of the issue is not, therefore, the existence of auxiliary benefits but their likely weight in real decisions about implementation of new technology. Here strong differences arise.

Table 1A.

Response Mode	Auxiliary Benefit	Import of Aux. Ben.	Risk
Living with less	Systematically reducing consumption would likely require a large-scale social transformation with myriad implications.	Highest.	?
Energy efficiency	Reduction of pollution associated with fossil fuel extraction and use.	Low	Low
Non-fossil renewables	As above.	Low	Biological impact of land use.
Nuclear	As above.	low	Radioactive contamination, weapons proliferation.
ICM/geological	Reduction of pollution associated with fossil fuel use.	low	Leakage of CO_2 from sequestration sites.
Forest sequestration	Protection of old forests and enlargement of forested area.	Moderate	Biological impact of land use.
Agriculture sequestration	Enhanced agricultural productivity?	Moderate	
Ocean fertilization	Enhance fisheries?	Moderate	Biological impact.
Space-based solar shields	?	low	Uncertainty about climatic and biological response to changed solar forcing. For Aerosols: impact on stratospheric chemistry
Stratospheric aerosols	?	low	

Coupling of Technological and Social Systems

All large-scale technologies comprise a coupled system of technical process knowledge and social organization. Responses to the climate problem differ sharply, however, in the degree to which their implementation would require changes in social and economic systems. The root question is, to what extent can the response be implemented as an isolated technology-focused effort?

The capture of CO_2 from electric power producers, for example, and its sequestration in geological repositories could be nearly invisible outside the electric generation sector, excepting its impact on producer prices. Diffusion of technical improvements in energy efficiency, on the other hand, would require diffusion of new end-user technologies and financial instruments throughout the economy. Achieving the maximum technologically feasible reductions in energy use in housing, for example, would arguably require broadening of the current energy service company model to encompass new financial arrangements linking home builders, energy suppliers and end users. If energy efficiency was pursued with the vigor required to achieve significant and sustained reductions in energy use the transformation would likely be visible to all.

Table 1B.

Response Mode	Social-technological coupling	Cost of mitigation @ 50% emissions cut by 2050	Countervailing
Living with less	Highest	NA	No
Energy efficiency	High	300-1000 @ 50% ~0 @ 50%	No
Non-fossil renewables	low		No
Forest sequestration	moderate	100-250	Yes
Agriculture sequestration	moderate		Yes
Nuclear	low	100-200	No
ICM/geological	low	50-200	No
Ocean fertilization	low	1-10	Yes
Space-based sunshields	low	0.2-2	Yes
Stratospheric scatterers	low	<<1	Yes

SUMARY AND IMPLICATIONS

As responses to the CO_2-climate problem, countervailing actions distinct from conventional mitigation for two reasons. First they break the link between CO_2 emissions and the action required to mitigate emissions. Second, they raise a kind of global moral hazard. Knowledge of geoengineering has been characterized as an insurance strategy; in analogy with the moral hazard posed by collective insurance schemes, which encourage behavior that is individually advantageous but not socially optimal, we may ascribe an analogous hazard to geoengineering if it encourages sub-optimal investment in mitigation. If, for example, the existence of low-cost biological sinks encourages postponement of effective action on emissions mitigation and if such sinks prove leaky then there existence of these sinks poses a moral hazard.

In this paper I drawn the line between geoengineering and industrial carbon management at the emission of CO_2 to the active biosphere. Three lines of argument support this definition. First, and most importantly, the capture of CO_2 from the atmosphere is a countervailing measure, one of the three hallmarks of geoengineering identified above. It is an effort to counteract emissions, and thus to control CO_2 concentrations, through enhancement of ecosystem productivity or through the creation of new industrial processes. These methods are unrelated to the use of fossil energy except in that they aim to counter its effects. The second argument is from historical usage; the capture of CO_2 from the atmosphere has been treated explicitly as geoengineering (MacCracken 1991; Watson, Zinyowera et al. 1996; Flannery, Kheshgi et al. 1997; Michaelson 1998) or has been classified separately from emissions abatement and grouped with methods that are now called geoengineering. Finally, the distinction between pre- and post-emission control of CO_2 makes sense because it will play a central role in both the technical and political details of implementation.

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