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Feature Article

Geoengineering:

The Inescapable Truth of Getting to 350

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In Brief

To avert dangerous and potentially catastrophic climate change, it has been argued that society must set a goal of stabilizing the atmospheric CO_2 concentration at 350 ppm by the end of the twenty-first century. The time window is relatively narrow for society to find workable solutions for achieving this ambitious goal.

In our opinion, society will need to employ aggressive emission reductions and geoengineering to stabilize atmospheric CO_2 at 350 ppm by the end of the century. Most of the geoengineering technologies that have been explored to date fall into two general categories: solar radiation management (SRM) and carbon dioxide removal (CDR). SRM is a highly controversial climate-intervention approach that involves altering the Earth's radiation budget to counterbalance the warming effects of greenhouse gases. In contrast, CDR is a less controversial remediation approach that involves directly reducing atmospheric CO_2 concentration to lower levels. While SRM technologies may postpone an inevitable rise in mean global temperature from greenhouse warming, CDR technologies have the potential to offer real solutions to the CO_2 stabilization problem.

Of the CDR options currently being explored, air capture with bioenergy and storage looks especially promising. The use of algal bioenergy products to power the air capture process is one way to substantially reduce the financial costs and environmental impacts of this technology. With a properly valued carbon market, the cost estimates for using this technology to supplement an aggressive emission-reduction plan targeting stabilization at 350 ppm compare favorably with the cost estimates for using an aggressive emission-reduction plan alone to stabilize atmospheric CO_2 at 450 ppm.

During the past 2.5 million years, Earth's climate has demonstrated remarkable volatility, shifting in and out of glacial and interglacial conditions in synchrony with cycles in the Earth's orbital configuration relative to the sun. This same 2.5 million-year period coincides with the time frame for the evolution of modern humans from their proto-human ancestors. While it may be tempting to suggest that evolution should have prepared humans to adapt readily to large changes in climate, it is important to recognize that human civilization did not evolve until relatively recently, during the stable interglacial conditions of the Holocene epoch, which began about 10–12 thousand years ago.

The favorable climatic conditions of the Holocene accelerated the pace of human ingenuity. With the advent of agriculture and animal husbandry about eight thousand years ago, humans began to alter the landscape on an unprecedented scale. However, it was not until the industrial era started during the late eighteenth century that humans began to impact Earth's climate on a global scale. This is what led the Nobel Prize winning atmospheric chemist Paul Crutzen to coin the term "Anthropocene," describing the new geologic era in which humans have become the principal agents of change in Earth system evolution.[1]

Most of the anthropogenic climate change to date has been the unintentional consequence of human society's rapid exploitation of fossil fuels. The amount of fossil fuels currently exploited each year required millions of years to accumulate in the geologic past, making this energy source essentially nonrenewable on a time scale relevant to human civilization. At current exploitation rates, society will exhaust Earth's extractable fossil energy reserves in just a few centuries and will be forced to find alternatives. Whether society will move to alternative energy sources is not in question; the critical questions are when will the transition begin in earnest, how quickly will it happen, and how much will Earth's climate be altered before it is complete?

Until the recent global economic recession, greenhouse gas emissions associated with the burning of fossil fuels had been increasing more rapidly than the worst-case scenarios used in previous assessment reports by the Intergovernmental Panel on Climate Change (IPCC).[2] Hence, there is no clear indication that the fossil to alternative energy transition has begun yet. Furthermore, with the mixed signals coming out of the 2009 UN Climate Change Conference in Copenhagen, Denmark, the speed of this future transition is difficult to project.[3] Given these uncertainties, we use the current calendar year, 2010, as a starting point for exploring some of the potential climatic consequences of society's continued emission of fossil fuel derived CO_2.

The Consequences of Warming in the Pipeline

At present, the atmospheric CO_2 concentration is 390 ppm, approximately 40 percent higher than the pre-industrial level of 280 ppm. Although mean global temperature has risen 0.8° C (1.4° F) since the start of the industrial era, several recent studies[4,5] suggest that, even if the atmospheric CO_2 concentration were to stabilize at today's level, we are already committed to a mean global temperature increase of approximately 2.4° C (4.3° F) by the end of the century (2.0° C/3.6° F is the threshold for dangerous climate change agreed upon at the recent UN Climate Change Conference in Copenhagen). This committed temperature increase has been called *warming in the pipeline*[4] and corresponds to the gap between the observed mean global temperature and the one expected at a given atmospheric CO_2 concentration once various climatic feedback processes achieve equilibrium.

The committed warming in the pipeline is time-scale dependent, and until a 2008 paper by Hansen and colleagues,[5] the distinction between fast and slow feedback processes was not fully appreciated. Fast feedback processes include decadal-scale changes in the Earth's heat budget associated with water vapor, clouds, aerosols, and sea ice. In contrast, slow feedback processes include centennial- to millennial-scale changes in the heat budget, especially those associated with alterations of surface albedo linked to advances and retreats of the planet's cryosphere and vegetation cover. The approximately 2.4° C (4.3° F) committed temperature increase projected for the twenty-first century at today's atmospheric CO_2 concentration only includes the fast feedback processes. When the slow feedback processes are included, the projected warming in the pipeline for several centuries from now increases by a factor of two. In other words, the Earth's climate sensitivity to elevated CO_2 can be twice as high on these longer time scales.

Key Concepts

- **Due to its dependence on fossil fuels, society is on a CO_2 emissions trajectory committing itself to dangerous climate change by the end of the twenty-first century and potentially catastrophic climate change several centuries thereafter.**
- **It has been suggested that society may be able to avert dangerous and eventually catastrophic climate change by stabilizing the atmospheric CO_2 concentration at 350 ppm.**
- **After evaluating the challenge of stabilizing CO_2 concentration at 350 ppm, we conclude that society will only be successful in meeting this goal by supplementing aggressive reductions in greenhouse gas emissions with geoengineering.**
- **Of the geoengineering options currently being explored, CO_2 removal using air capture with bioenergy and storage looks especially promising.**
- **Aggressive reductions in greenhouse gas emissions and CO_2 removal using air capture with bioenergy and storage have the potential to stabilize CO_2 concentration at 350 ppm by the end of the century and at a cost that is affordable.**

Hansen and colleagues conclude that committing the Earth system to this level of climate warming will likely lead to the destabilization and eventual collapse of the cryosphere.[5] Such an outcome should be viewed as not only dangerous, but catastrophic.

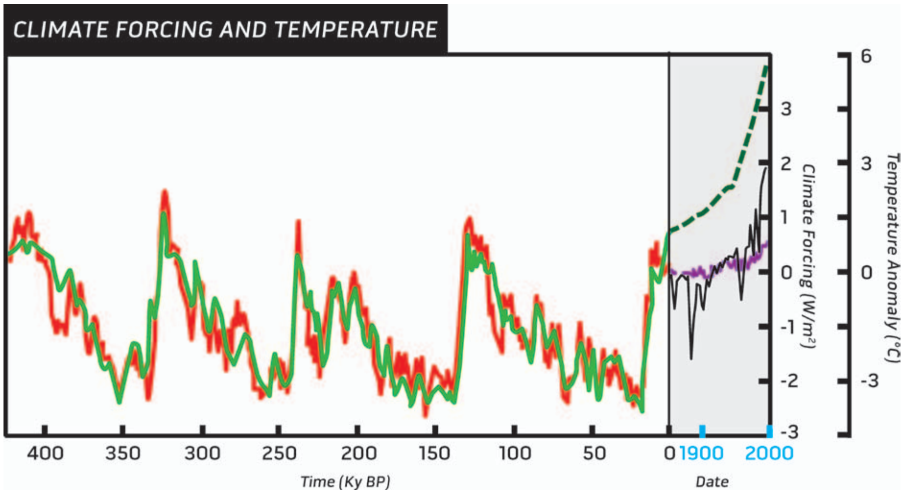
To describe future climate change as catastrophic may sound alarmist; however, warming Earth's climate to a point that it can no longer sustain the planet's cryosphere demands the use of such strong language. With the cryosphere's collapse, global sea level will rise by greater than 80 meters (262 feet), inundating coastal plains and low-lying islands around the world. Over a billion people will be displaced to higher ground, amplifying the other impacts of climate change such as extreme weather events, floods, and droughts. While the Earth system has experienced comparable cataclysmic events during its evolution, human civilization certainly has not. So, if society is already on an emissions trajectory committing itself to dangerous climate change by the end of the twenty-first century and catastrophic climate change several centuries thereafter, is there anything that can be done to avert such a fate?

Averting Catastrophic Climate Change

Hansen and colleagues suggest that stabilizing atmospheric CO_2 at approximately 350 ppm may be sufficient to save the cryosphere and enable society to avert catastrophic climate change.[5] While we are already at a concentration of 390 ppm, it is conceivable that stabilization at 350 ppm could be achieved by the end of this century. However, to do so by reducing fossil fuel emissions alone is a scenario that appears highly unlikely for a couple of reasons. First, given a rapidly growing global population and the desire of most developing nations to achieve an improved standard of living, society currently lacks the sense of urgency and political willpower necessary to alter its energy consumption habits in the short amount of time available. Second, even if the political willpower could be raised and the proper economic incentives adopted,[6] there are limits on the rate at which new low-carbon energy technologies can be deployed globally.[7] This is clearly a case of so much to do and so little time to do it.

Some scientists and policymakers have suggested that society could significantly overshoot the goal of 350 ppm by the end of the century and then return to it later as emission reductions eventually have their desired effect on the atmospheric CO_2 concentration. The problem with this approach is that climate warming from an elevated CO_2 concentration is largely irreversible after only a few decades.[8] Because of CO_2's long residence time in the atmosphere, its concentration will stabilize over the long term (1000-year time scale) at a level that is approximately 40 percent of its peak enhancement over the pre-industrial period. Even more significantly, once the mean global temperature reaches equilibrium at a certain peak atmospheric CO_2 concentration, it will not drop markedly over the next millennium even as the CO_2 concentration declines.[8] This irreversibility comes about because the atmosphere's loss of heat to the ocean is even more gradual than its loss of CO_2. The ocean's thermal inertia, which is delaying the rate of greenhouse warming today, will delay the rate of greenhouse cooling in the future.

The window of time is relatively narrow for society to find workable solutions that will enable it to avert catastrophic climate change. The solution of reducing CO_2 emissions to meet this threat may have been viable one or two decades ago; however, such an option by itself is no longer tenable. The inescapable conclusion we draw from this line of reasoning is that society will need to supplement an aggressive emission-reduction plan with geoengineering to achieve a CO_2 stabilization level of 350 ppm by the end of the twenty-first century.



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This figure illustrates global temperature anomaly as a function of time from 425,000 years ago to the present. For most of this period, the global paleotemperatures determined from proxy data (red curve) match the temperatures predicted from forcing by the greenhouse gases measured in the Vostok ice core (solid green curve) if one assumes a global climate sensitivity of 1.5°C per watt per square meter (W/m^2), or 6°C for a doubling of atmospheric CO_2 concentration. This climate sensitivity is twice as large as the 0.75°C per W/m^2 value typically assumed for fast feedback processes only. The time scale in the figure is expanded for the industrial era, revealing the growing gaps between the observed global temperature (purple curve) and the expected equilibrium temperatures for only fast feedback processes (black curve) and for all feedback processes (dashed green curve). Source: Hansen, J et al. Target atmospheric CO_2: where should humanity aim? *Open Atmospheric Science Journal* 2, 217–231 (2008).

The Case for Geoengineering Research

In its broadest sense, geoengineering involves deliberately modifying the Earth system and its processes to suit societal needs and improve the planet's habitability. During recent years, discussions of this controversial concept have been confined largely to global-scale engineering approaches intended to counteract the effects of anthropogenic climate change. Proponents of geoengineering point out that humans have been modifying the Earth system and its processes unintentionally for some time; therefore, why not do it in a deliberate manner with specific goals in mind? Those opposed to the concept counter that our understanding of the Earth system is much too limited to undertake such planetary engineering, pointing out that our track record for engineering a better world has not been particularly impressive.

Previously, Greene and colleagues advocated for a larger investment in the scientific, engineering, and policy research necessary to assess the costs and benefits of geoengineering.[9] Advocating for further research in geoengineering technology should not be confused with advocating for its deployment and use. Like any human activity carried out on a global scale, geoengineering will entail risks to the Earth's environment and the socioeconomic well being of society. These risks need to be evaluated in the same economic, ethical, legal, and political framework as other climate mitigation efforts.

Properly assessing the financial and environmental costs and benefits of each geoengineering technology will require scalable experiments conducted with reasonable levels of control and replication. As geoengineering experiments are scaled up, they will become increasingly difficult to control and replicate. Additionally, their financial costs and environmental impacts will increase. Policymakers will need to evaluate the results and decide what levels of environmental and socioeconomic risk are acceptable to society. The decision to employ any

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Governing Geoengineering Research: Principles and Process

by Jane C. S. Long and David E. Winickoff

Research to develop geoengineered climate solutions will require not just new technical knowledge, but also new societal capacity to set effective policy and align oversight with public values. Although technological governance that uses an accountable democratic process requires effort, it often results in more effective policy as well as more legitimate outcomes.

A good case in point is the Swedish nuclear waste program and its contrast with the U.S. nuclear waste program.[1] In 1980, Sweden voted to end nuclear power generation and began to build a repository to dispose of nuclear waste. The program proceeded with extensive public consultation and a clear *a priori* statement of the technical and social requirements for an appropriate site. Today, Sweden has a repository site that is scientifically sound and supported by the local population.

In contrast, the goal of the American policy was to override controversy and justify nuclear power by showing that we could store waste. Congress chose the repository site without consulting the public. Astonishingly, the site criteria were established after the site was chosen. Today, the United States does not have a successful nuclear waste storage program.[2] The lack of effective debate and collaboration between policymakers, scientists, and civil society has led to a stalemate on the issue of nuclear waste management.

We cannot afford such inefficacy and deadlock in the context of geoengineering. There is too much at stake. Drawing upon experiences like these, as well as a growing body of work on geoengineering governance, we present a set of values and policies that should be signposts for geoengineering oversight.

The Precautionary Principle

The precautionary principle presents a logical dilemma in the geoengineering context: an intervention could be an important precautionary measure in the face of increasing climate disruption, yet pose serious damage to stressed ecological and political systems. But this dilemma does not lessen the importance of precaution. A precautionary stance demands, for instance, that there be a moratorium on the deployment of high-risk geoengineering technologies while research proceeds. It also counsels that we must factor uncertainty, ignorance, and irreversibility into the assessment of geoengineering experiments and applications.

International Cooperation in Science and Governance

Computer simulations indicate that China is likely to face severe water shortages that might be ameliorated by climate intervention, but the same intervention could interrupt the Indian monsoons and devastate food production. Any indication that a nation is contemplating geoengineering solely to protect national interests, especially at the expense of other countries, would and should be met with suspicion and hostility. National benefit may be the driving force for funding geoengineering research, but research programs should explicitly focus only on technology that will have significant international benefits.

Placing geoengineering research programs within defense programs would seriously undermine the spirit of cooperation needed to address climate intervention peacefully and effectively.[3] On the other hand, the inclusion of international scientists in a national research program or the establishment of international research programs would be investments in the capacity to collaborate. Good cooperative relationships in geoengineering research and research governance may help to develop common norms of behavior that set the stage for collaborative decisions in the future.

Public Ownership and Open Science

Commercial interests should not be allowed to influence government regulation or deployment of geoengineering technologies where the risks of unintended harm are great and political stakes are high. High-risk geoengineering should be treated as a public endeavor because we require effective and accountable control of these technologies, untainted by commercial interests.

Governmental funders should also require open science and employ a presumption of public-sector ownership. Research contracts must obligate researchers to share certain kinds of data and to publish in accessible journals as soon as possible.

On the other hand, for technologies that are low-risk—such as technology that separates CO_2 from the atmosphere—the role of the private sector might be welcome, given limitations on public resources and the advantages of competition for optimizing design. In these cases, regulation might be adequate to protect the public good, and private ownership might be necessary to advance it.

Democratic Due Process

Geoengineering research is not the first case of science requiring government oversight within democratic societies. Nanotechnology, nuclear technology, and recombinant DNA all pose hazards to society. Government agencies must have ultimate authority to govern these technologies, and oversight must evolve through a publicly accountable process. Of course, researchers can initiate the process themselves. In 1975, the Nobelist Paul Berg organized a conference at Asilomar in California to discuss the potential hazards of recombinant DNA (rDNA) research and establish self-governing principles for safe science. Conferees developed a tiered structure for levels of hazard that was presented to the Department of Health and Human Services (DHHS). Based on these principles, DHHS proposed a review process for individual proposals. These rules were subject to public hearings and a review and comment period, after which they were adopted. The vibrant rDNA research program in this country is, in part, a testament to the success of this process. The organizers of a meeting on the governance of geoengineering (held at Asilomar in March 2010) consciously invoked the original rDNA meeting. Although this was a productive step toward developing governance principles for geoengineering, participants also understood the need to extend debate into civil society.[4]

Governments should help the public understand the ramifications of geoengineering and engage in deliberations about the research. Denmark has developed mechanisms for doing this in an institution called the Danish Board of Technology.[5] The board has a menu of methods for assessing technology and deliberating with citizens, including interdisciplinary working groups; seminars; citizens' summits, juries, and hearings; future panels; parliamentary hearings; and conferences where laypeople, experts, and politicians jointly deliberate conflicts and priorities and then vote on action plans. Policymakers are required to take the outcomes of these deliberations into account and are often required to implement the recommendations.

Independent Review

In the oversight of geoengineering experimentation, credible and independent review of research protocols will help ensure the safety, quality, and ethical integrity of the research. Review committees should include a broad array of expertise across the sciences and social sciences, and be in close communication with decision makers. Not all geoengineering research, however, should trigger the same level of review and analysis. For instance, computer modeling studies that simulate proposed interventions are almost certainly benign and should commence quickly. On the other hand, a proposal for full- or even subscale deployment with nontrivial effects would clearly require a very high level of scrutiny.

There should be an initial assessment in which experiments are targeted for either *de minimis* review or full review, using criteria such as degree of perturbation, degree of irreversibility, duration, and impact. The threshold for full review would vary by technology. For example, aerosol injection into the stratosphere raises completely different questions and concerns than does putting small air bubbles on the surface of the ocean. Thresholds might be determined by blue-ribbon committees convened by the National Research Council in the United States or the Royal Society in the United Kingdom, for example, and ratified by accountable regulatory authorities with public input.

Adaptive Management

Adaptive management, also known as "learning by doing," involves learning what works and what doesn't from both scientific and social perspectives, and then modifying research choices to reflect this new knowledge. Adaptive management is critical for geoengineering because climate intervention will likely be highly unpredictable as will the political context in which it takes place. Given these uncertainties, any climate intervention will need to adapt as new information becomes available and conditions change.

Geoengineering research should be couched in an adaptive framework from the beginning. In this way, we can gain experience in the adaptive *management* and at the same time learn how to *do* climate intervention. The exemplar Swedish nuclear waste research program established a structure *a priori* to accommodate modifications. First, scientific objectives were accepted by management teams and various experiments to address these objectives were reviewed and sanctioned. Then researchers predicted the outcome of the experiments. At specified time intervals, the scientific teams made formal comparisons between the predictions and their actual observations. Based on what they learned, the scientists were able to make new decisions about the next phase of an experiment and adjust their predictions for that phase. Over time, the researchers could predict the outcomes with more confidence and the waste program management learned how to adapt the program to new information, lending legitimacy to the process and making public approval more likely.

In the field of geoengineering, the iterative process may include modification of the calculus for evaluating risks and benefits, which could in turn modify experimental protocols or even terminate experiments. For this to work, it is crucial that the experiments be monitored by independent, accountable institutions not invested in the results. This independent monitoring can also provide an important vehicle for transparency and credibility.

Conclusions

Good governance of geoengineering research will build the technical capacity for acceptable options, coupled with the societal capacity to make good decisions about deploying them. If we succeed, these social skills may spill over into approaching other difficult climate problems. In the end, we may ask whether we are building the capacity to do geoengineering or using geoengineering research to build the capacity to solve any climate problem. If we are lucky, the answer will be the latter.

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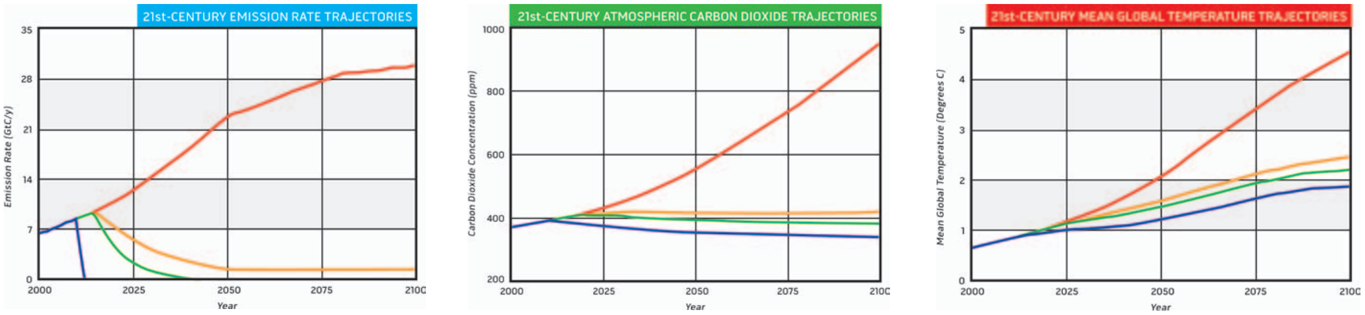
geoengineering technology should only be made after a careful and deliberate assessment process. Society should not be forced into making a quick and desperate decision about geoengineering because it did not have the foresight to conduct the necessary research in advance.

Geoengineering Options: Climate Intervention

Most of the geoengineering technologies that have been discussed to date fall into two general categories: solar radiation management (SRM) and carbon dioxide removal (CDR).[10] The former is a climate-intervention approach that involves altering the Earth's radiation budget to counterbalance the warming effects of greenhouse gases. The latter is a remediation approach that involves reducing atmospheric CO_2 to lower levels, thereby diminishing greenhouse warming directly.

The SRM technologies most frequently advocated entail reducing the amount of incoming solar radiation reaching the Earth's surface by reflecting it back into space. Among these technologies, the injection of sulfate aerosols into the stratosphere has received the most attention because it would mimic natural processes, the global dimming and cooling associated with major volcanic eruptions, and could be employed in the near future at relatively low cost. The addition of sulfate aerosols would increase the albedo of the stratosphere, thereby reducing the solar radiation reaching Earth's lower atmosphere and surface. Another SRM technology that appears to be a realistic and relatively low-cost option entails injecting seawater droplets or other cloud-condensation nuclei into clouds over the ocean. The addition of cloud-condensation nuclei to marine clouds would whiten them and increase their albedo, thereby reducing incoming solar radiation reaching the underlying ocean. Perhaps the most speculative of the SRM technologies suggested thus far would entail deploying sunshades or mirrored shields in space to block incoming solar radiation before it reaches the Earth's atmosphere. The deployment of such space-based technologies would require a long-term, relatively expensive commitment to research and development.

In working out a strategy for averting catastrophic climate change, it is important to recognize that none of the proposed SRM interventions remove CO_2 from the atmosphere; thus, they provide little help in achieving the goal of getting to 350. SRM should be viewed more as a tactical option rather than a strategic one. While such a tactical intervention may buy additional time for society to reduce atmospheric CO_2 before mean global temperature irreversibly rises to dangerous or catastrophic levels, SRM only provides a temporary fix, not a long-term solution. Furthermore, since SRM does not address the CO_2 problem directly, ocean acidification will continue unabated as long as atmospheric CO_2 levels remain elevated and the gas exchange equilibrium favors a drawdown of CO_2 into the ocean. Finally, as with any large-scale modification of the Earth system, SRM will introduce intended as well as unintended changes to the global environment. It has been predicted that SRM interventions may damage the stratospheric ozone layer and result in significant disruptions of global hydrological processes, enhancing droughts in the dry subtropical regions of the world and floods in the tropical and high-latitude regions that already experience high precipitation rates. Despite these limitations and potential drawbacks, we recommend investing



a. Twenty-first-century emission rate trajectories

b. Twenty-first-century atmospheric CO_2 trajectories

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c. Twenty-first-century mean global temperature trajectories

Emission Reduction Scenarios

Stabilizing atmospheric CO_2 at 350 ppm during the twenty-first century is highly unlikely if society relies on emission reductions alone. Here we explore the consequences of a.) four different emission scenarios on b.) atmospheric CO_2 concentration and c.) mean global temperature. The scenarios include the following:

1. Business as usual (red curves) – The emission rate rises so that it increases 500 percent relative to the 2005 rate by 2100. Deforestation and land-use emission rates remain constant, and there is no net increase in sequestration from expanded forests.
2. Aggressive mitigation (orange curves) – The emission rate begins to decline in 2015 and reaches 20 percent of the 2005 rate in 2050. By 2050, deforestation and land-use emission rates are reduced 45 percent. There is a 0.8 GtC per year sequestration in expanded forests.
3. Very aggressive mitigation (green curves) – The emission rate begins to decline in 2015 and reaches zero in 2050. By 2050, deforestation and land-use emission rates are reduced 45 percent. There is a 0.8 GtC per year sequestration in expanded forests.
4. Impossibly aggressive mitigation (blue curves) – The emission rate drops to zero in 2010. By 2050, deforestation and land-use emission rates are reduced 90 percent. There is a 1.6 GtC per year sequestration in expanded forests.

The inclusion of this fourth mitigation scenario is to demonstrate that, even if the emission rate drops to zero immediately and society makes tremendous efforts to grow new forests and reduce deforestation and land-use emissions, stabilizing atmospheric CO_2 at 350 ppm by the end of the century is still very difficult to achieve.

Scientists and policymakers use simulation modeling to project the future trajectories of atmospheric CO_2 concentration and mean global temperature under different mitigation scenarios. The Climate Rapid Overview and Decision-support Simulator (C-ROADS) has been peer reviewed and is widely used at all levels in the climate-change community (www.climateinteractive.org/). A simplified version of C-ROADS is the C-LEARN Simulator (forio.com/simulation/climate-development/). We use C-LEARN in this exploration so that our readers will be encouraged to visit the website and attempt similar simulations on their own.

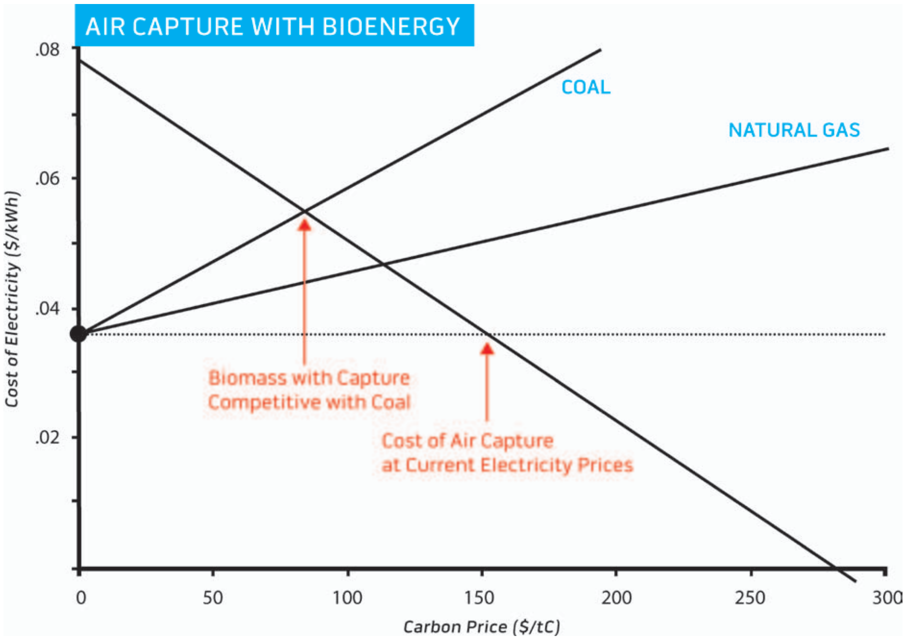
in research on SRM technologies. The potential of SRM to postpone an irreversible commitment to dangerous or catastrophic global warming is an option that we should not ignore despite very legitimate concerns about the environmental, ethical, legal, and political issues associated with this type of intervention into the Earth's climate system.

Geoengineering Options: CO_2 Remediation

Discussions of the geoengineering options available to society often have turned into narrowly focused debates about the environmental costs and benefits of SRM. Advocates for SRM justify this narrow focus by pointing out that, in the event of a climate emergency, one or more of the relevant technologies could be deployed in the near future at relatively low cost. In contrast, CDR options are frequently discounted because of the "technical challenges and large uncertainties surrounding [their large-scale] deployment."[11] This attitude is unfortunate because, while it may be true that CDR technologies will take longer to develop and deploy on a global scale, they offer potential solutions to the climate-change problem that SRM can only postpone. Several of the proposed CDR options can be viewed as natural extensions to mitigation technologies currently being explored for reducing CO_2 emissions into the atmosphere. Thus, the line between mitigation, which reduces CO_2 input into the atmosphere, and remediation, which reduces CO_2 levels already in the atmosphere, will become increasingly blurred in the future.

The CDR technology most frequently advocated involves the use of large-scale industrial air capture systems to remove CO_2 from the atmosphere for subsequent sequestration.[12] These air capture systems are similar to the carbon capture and storage (CCS) technology being developed to remove CO_2 from the exhaust streams of coal-fired power plants. Both approaches expose gases, either air or power plant emissions, to a sorbent material that selectively captures CO_2. The resulting material is then chemically treated to regenerate fresh sorbent and to produce a concentrated supply of CO_2, which can be stored or used industrially.

The basic technology for constructing large-scale air capture systems exists and has the potential to



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Air capture with bioenergy involves using biologically derived energy products to power the air-capture process. These energy products derived from biomass include biofuels, electricity, and hydrogen. While bioenergy production is carbon neutral at best, its combination with air capture and storage results in an integrated process that can be carbon negative. This figure shows the cost of electricity as a function of carbon price. Note that unlike the cost of electricity generated from coal and other fossil-fuel sources, the cost of electricity from air capture with bioenergy systems decreases as the market price of carbon increases. The Y-intercept of the graph corresponds to the assumed current cost of electricity, \$0.035/kW. Source: Keith, DW, Ha-Duong, M & Stolaroff, JK. Climate strategy with CO_2 capture from air. *Climatic Change* 74, 17–45 (2006).

be one of the most environmentally friendly of the geoengineering technologies available to society.[12] An important advantage of air capture relative to CCS is the decoupling of CO_2 removal from the power sources producing emissions. Thus, air capture systems need not be located near power production infrastructure or major population centers. Freed from these constraints, air capture systems can be constructed at remote sites on land of marginal value. This flexibility in site selection means that air capture systems can be built large enough to achieve greater cost efficiencies. In addition, they can be sited close to or even co-located with the geological repositories being used to store the captured CO_2. Perhaps the greatest benefit of decoupling air capture systems from emission sources is that it simplifies the economics of CDR. By removing CO_2 at a fixed marginal cost regardless of its source, air capture provides society with a means to equally address CO_2 emissions from all sectors of the economy. Thus, diffuse emissions from the building and transportation sectors can be dealt with in the same manner as point-source emissions from the power plants generating electricity for the grid.

While air capture systems are attractive for many reasons, a major impediment to their development is cost. The air capture process is energy intensive, requiring power to pump the sorbent material and gas through the contacting system, to regenerate the sorbent, and to compress the CO_2 for pipeline transport. With today's technology, air capture and storage is estimated to cost greater than \$250 per ton of carbon,[12,13] at least an order of magnitude higher than the current price of carbon on the European trading market. While the market price of carbon will undoubtedly rise as policymakers begin to recognize the need for economic incentives to reduce society's dependence on fossil fuels, it is unrealistic to think that air capture systems will be competitive without a substantial reduction in their energy costs.

The Potential of Biogeoengineering

One approach to reducing the energy costs of air capture systems is to combine them with systems being developed for bioenergy production. These integrated air capture with bioenergy systems can be constructed from commercially demonstrated component technologies, the simplest method being to modify biomass gasification systems for CO_2 capture from the resulting syngas stream. Although the economics of using air capture with bioenergy systems for CDR are not fully worked out, Keith and colleagues estimated that, at today's electricity prices, the cost per ton of carbon removed could be half that of simple air capture and storage.[12] Furthermore, unlike the cost of electricity generated from coal and other fossil fuel sources, the cost of electricity from bioenergy coupled with air capture decreases as the market price of carbon increases. This relationship led Keith and colleagues to conclude that electricity from bioenergy coupled with air capture can be cost competitive with electricity from coal-fired power plants (without CCS) at a market price of approximately \$100 per ton of carbon.[12]

The benefits of adding bioenergy production to air capture systems are accompanied by two important constraints. First, by recoupling CO_2 removal to the energy infrastructure, the site-selection flexibility of air capture is greatly diminished. Second, and even more importantly, since bioenergy production is limited by the availability of biomass, air capture with bioenergy brings up many of the same environmental and food-security concerns that have arisen in the debate about biofuels.[14] It has been demonstrated that fossil-fuel subsidies to industrial agriculture greatly limit its potential to produce bioenergy while simultaneously reducing society's carbon footprint. In addition, industrial agriculture's inefficient use of nutrients and freshwater has introduced numerous environmental problems that compromise aquatic ecosystems and the services they provide to society. Finally, even if industrial agriculture could be made more efficient in its consumption of fossil fuels, nutrients, and freshwater, it still could not produce an adequate supply of bioenergy without seriously competing with food crops for high-quality agricultural land. Thus, industrial agriculture, as it is conventionally practiced, does not appear to be up to the challenge of meeting society's current and future bioenergy needs.

The Case for Algae

While industrial agriculture may not be up to the bioenergy challenge, algal aquaculture systems offer an attractive alternative. Many of the major international energy corporations are investing in algal biofuel technologies because of the tremendous production potential of algae relative to terrestrial energy crops. Demonstration projects have shown that land-based algal aquaculture facilities, especially those with a readily available source of excess CO_2 for the growth medium, can yield at least an order of magnitude more biofuel per hectare than the most productive plantations of terrestrial energy crops.[15]

In addition to their greater production efficiency, algal aquaculture systems can avoid or reduce many of the environmental and food-security concerns associated with biofuels. Nutrient cycling is tightly controlled in algal aquaculture systems, and it is possible to minimize the loss of most nutrients except for those actually locked up in the harvested energy product. The freshwater problem can also be minimized by matching the strains of algae under production with local environmental conditions. For example, one demonstration project in Hawaii is producing high yields of biofuels from marine algae grown in a facility sited on a lava bed in the desert-like conditions of the Kona Coast. If bioenergy production can be accomplished successfully on dry, non-arable land like this, then the global implications may be profound. Huntley and Redalje[16] estimate that algal biofuel production using approximately 7 percent of the surplus, non-arable land projected to be available in 2050 could replace fossil-based CO_2 emissions equivalent to approximately 6.5 gigatons of carbon (GtC) per year and at a cost that is competitive with current fossil fuel sources. Should it prove more efficient to convert the algal biomass directly to electricity rather than biofuels,[17] the global potential of bioenergy production might be even higher.

The advantages of algae are not confined to just bioenergy production. The CO_2 removed from the atmosphere by air capture with bioenergy systems must be stored somewhere to make the process carbon negative. Most of the proposed CDR technologies assume that the CO_2 will be stored in geological repositories such as spent oil and gas fields, saline reservoirs, non-extractable coal seams, and marine sediments. To stabilize CO_2 concentrations below 450 ppm, Pielke estimates that the cumulative amount of CO_2 that will need to be stored by 2100 is equivalent to approximately 642 GtC.[18] Using the same assumptions and calculations as Pielke, we estimate the storage requirement for stabilization at 350 ppm to be equivalent to approximately 855 GtC. While the global storage capacity of onshore and offshore geological repositories is estimated to be sufficient to hold this amount of CO_2,[19,20] there may be benefits to considering other options as well. One such option would be to use the biopetroleum produced by algal aquaculture systems for purposes other than just biofuels. For example, there is no reason why biopetroleum could not be used in long-lived plastics and other building materials that are produced primarily from fossil-based petroleum at present. If these plastics and other building materials were used in construction projects on a global scale, then that would be one method of sequestering a large amount of carbon for an extended period of time. Clearly, there would be economic advantages to locking away excess carbon in useful human-made structures rather than simply pumping it into the ground.

Conclusion

With global industrialization over the past two centuries, modern society has achieved an unprecedented level of prosperity. Much of the technology underpinning that prosperity has relied on the availability of inexpensive fossil fuels. The true costs of society's dependence on fossil fuels have become apparent only recently, with steadily increasing recognition that their use is altering Earth's climate and potentially risking dangerous and even catastrophic changes to the planet's climate system. Unfortunately, many of the standard economic models that have been used to evaluate various energy and climate policy options have tended to discount future costs[21] and thus have promoted a continuation of business as usual. The prospect of irreversible climate change has shifted that paradigm—economists can no longer justify energy policies that reap the benefits of present-day fossil fuel use while passing on the environmental and financial costs to future generations.[22,23] It is time to implement an integrated global energy and climate action plan that is sustainable and provides future generations with some semblance of the climatic stability modern society inherited from previous generations.

Development of such an integrated global energy and climate action plan will be the grand challenge of the twenty-first century. Although the scale of this challenge is enormous, the basic technologies for achieving it already exist. Pacala and Socolow outlined an approach for stabilizing CO_2 emissions during the first half of the twenty-first century based on the concept of stabilization wedges.[24] This approach will move society in the right direction; however, stabilizing CO_2 emissions at current or even 1990 rates will not be sufficient. Getting to 350 ppm by the latter part of the century will require society to eliminate net CO_2 emissions and actually become carbon negative. While ambitious, this goal can be achieved through air capture and storage at a cost that "compares favorably with the cost estimates for mitigation."[18]

Making the conservative assumption that the addition of bioenergy technology can bring the cost of air capture and storage down to at least as low as $100 per ton of carbon,[12] the cumulative expense for removing CO_2 equivalent to 855 GtC—the amount of carbon we will need to store—by the end of the century would be about $85.5 trillion. While such an expense is far from trivial, it corresponds to less than 1 percent of global GDP for the remainder of the century (assuming a 2.5 percent growth rate in GDP for the remainder of the century).[18] For comparative purposes, $85.5 trillion is comparable to estimates by the IPCC and the Stern Review for the cumulative mitigation expenses required to stabilize atmospheric CO_2 at 450 ppm.[25, 26] To put these cumulative expenses into perspective, the Stern Review points out that reducing global GDP by 1 percent over the remainder of the century is equivalent to reducing the annual growth rate of global GDP from 2.5 percent to 2.49 percent.

The bottom line, from an economics perspective, is that air capture with bioenergy and storage can help stabilize atmospheric CO_2 at 350 ppm by the end of the century and at a cost that is affordable. If there are other approaches for which the same claims can be made, then we are unaware of them. Promoting development of this technology does not mean we are suggesting a reduction in aggressive mitigation efforts. In fact, those mitigation efforts will remain as important as before in reducing CO_2 emissions and slowing down climate change during the several decades that it will take to deploy this technology on a global scale. In addition, it is important to recognize that the space available for storing CO_2 in geological repositories is finite. Thus, storage space may ultimately set the limit on carbon dioxide removal. Finally, society has a very narrow window of time to formulate and implement its global energy and climate action plan before the damage to our climate system is irreversible. While solar radiation management may buy the next generation some extra time for implementing such a plan, the current generation must devise it and develop the political willpower to move it forward. The fate of human civilization in Earth's evolution hangs in the balance.

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