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The Coming Global Climate–Technology Revolution

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Suppose that averting dangerous climate change meant limiting the concentration of greenhouse gases (measured in parts per million, or ppm, by volume) in the atmosphere so that the world faced a temperature increase of no more than 2°C—a goal endorsed by the European Union. What would it take to meet this goal? Because of "climate uncertainty," we cannot be sure. We can meet the goal with probability greater than 90 percent by limiting concentrations to 350 ppm carbon dioxide "equivalent" (the concentration of carbon dioxide that would cause the same amount of "radiative forcing" as a given mixture of carbon dioxide, or CO_2, and other greenhouse gases), but we have already overshot that level (Anderson and Bows, 2008, p. 2). We can meet the goal with probability close to 50 percent by stabilizing concentrations at 450 ppm CO_2 equivalent, but to do that will require that global net emissions (additions to the atmosphere minus subtractions) peak by around 2015, decline rapidly after that time, and reach zero soon after 2050. We can abandon the 2°C target and accept the likelihood of greater climate change; but stabilization at some other level, like 550, or 650, or even 750 ppm of CO_2 equivalent will also require radical reductions in emissions.

Emissions of CO_2 and other greenhouse gases can be reduced significantly using existing technologies, but stabilizing concentrations will require a technological revolution—a "revolution" because it will require fundamental change, achieved within a relatively short period of time.

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Inspiration for a climate–technology revolution is often drawn from the Apollo space program or the Manhattan Project, but averting dangerous climate change cannot be “solved” by a single new technology, deployed by a single government. The technological changes needed to address climate change fundamentally will have to be pervasive; they will have to involve markets; and they will have to be global in scope.

Bringing about such changes involves several interlocking elements. Most importantly, a price must be put on the externality of (net) greenhouse gas emissions—in short, a carbon price. This is essential not only to create incentives for reductions in emissions but also for the private sector to innovate. Financing is also required for R&D of the fundamental kind that is not rewarded by the patent system (Arrow et al., 2008). As new technologies are developed, practical issues will arise in their dissemination. Some of these will involve intellectual property or technical expertise, both within economies and across national borders. Others will involve right-of-way and not-in-my-backyard disputes related to a new infrastructure, such as would arise for the transmission of pressurized, liquid CO_2. Issues of network markets may also arise, where the market struggles to settle on a certain technology standard. Finally, some of the new technologies will introduce new risks of their own (like storage of CO_2 underground) and these risks will also have to be managed. To understand all these inter-linkages and to steer the evolution of the climate–technology revolution, we need to take technology out of the black box.

Individual countries can undertake all of these steps, but climate change is a global problem. Pricing carbon and developing and disseminating new technologies will require multilateral cooperation between governments working together with the private sector. It is the need for international cooperation that makes the climate–technology revolution unprecedented.

My focus in this paper is not on the moderate emission reductions that can be achieved using existing technologies, but on the breakthrough technologies that are needed to reduce emissions dramatically (see Hoffert et al., 2002, for a technical discussion of some of the technologies discussed here). Of course, the technologies that are ultimately adopted may, and probably will, be very different from the ones discussed here. However, the challenges discussed in this paper are likely to confront any technology that is to play a significant role in this effort. As I shall explain, these challenges are formidable; and they are not only or even mainly technical.

Indeed, it is possible that the revolution needed to reduce dramatically emissions of greenhouse gases will fail. If it does fail, however, other responses can be expected. The incentive to find ways to adapt to climate change will be very powerful, and adaptation will also require technological changes. Should the climate change abruptly, the incentive to “engineer” the climate will be strong. There *will* be a climate–technology revolution, but its nature will depend on the institutions we develop to address the challenge we face.

Table 1
Benchmark Carbon Prices
($/metric ton CO_2)

Benchmark	*Carbon price ($/t$CO_2$)*
Actual values	
Current global marginal cost	0
RRGI auction price	3
EU Emission Trading Scheme price	30
Estimated values	
Social cost of carbon	
Stern (2007)	85
Nordhaus (2008)	7
Optimal carbon tax 2100 (Nordhaus 2008)	55
Cost-effective tax to meet 2°C target	
In 2010 (Nordhaus 2008)	16
In 2100 (Nordhaus 2008)	235

Note: The estimates from Nordhaus (2008, table 5-1), are in 2005 dollars. The estimate from Stern (2007, p. 344) is in 2000 dollars. "RGGI" stands for Regional Greenhouse Gas Initiative.

Carbon Price

The carbon price, always expressed in this paper in U.S. dollars per metric ton of CO_2, is an important value in the discussion that follows.[1] It will help to have some benchmarks in mind. Table 1 presents eight reference values.

The first is the current cost of reducing global emissions by one ton, which is approximately equal to zero. The second is the market price of allowances auctioned off in late 2008 by the new Regional Greenhouse Gas Initiative (RGGI in the table), which is an agreement among 10 northeastern states to cap and then reduce CO_2 emissions from the power sector. (Six states participated in the first auctions: Connecticut, Maine, Maryland, Massachusetts, Rhode Island, and Vermont). The third entry is the price of allowances for carbon emissions traded under the European Union's Emission Trading Scheme (ETS), also as of late 2008.

The remaining values in the table are estimates. Two estimates are presented for the social cost of carbon—the global damage (calculated as a present value) caused by increasing emissions by one ton today, which also represents today's optimal carbon price. These values, estimated by Stern (2007) and Nordhaus (2008), are strikingly different, due mainly to different approaches to discounting. Nordhaus's optimal carbon tax increases over time (as will Stern's), though it remains lower than Stern's current value through the end of this century. However, Nordhaus's optimal program allows temperature change to exceed 2°C (as a point estimate; recall that the equilibrium temperature change associated with any con-

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[1] In the literature, units are sometimes expressed in tons of carbon. One ton of carbon is equivalent to 3.67 tons of carbon dioxide. Prices in $/tC are thus equivalent to 3.67 times the price in $/t$CO_2$.

centration level is uncertain). Nordhaus also calculates the cost-minimizing program for limiting temperature increase to 2°C (again, as a point estimate). The initial value in this sequence (\$16/tCO_2 in 2010) is still small relative to Stern's social cost of carbon, but by 2100 the value is much larger than Stern's initial value (\$235/tCO_2 versus \$85/tCO_2). Hence, whether the carbon price should become very large this century depends not only on discounting but also on the perceived need to limit temperature increase to 2°C.

CO_2-Free Energy

The most obvious way to reduce emissions (apart from conservation) is by substituting CO_2-free energy for fossil fuels. The main alternatives are wind, solar, and nuclear energy. (I discuss bioenergy options later. Geothermal and ocean energy can also play a role, but these options are not discussed in this paper.) Table 2 summarizes the challenges to scaling up use of these technologies. My discussion focuses on the economics of doing this.

Wind and solar power have recently attracted investment by venture capitalists, inspiring visions of a "new, new economy." Google, for example, hopes to develop renewable energy at lower cost than coal (they call their initiative, "RE < C"). If the new energy entrepreneurs succeed, the market will solve a big part of the challenge without the need for government intervention let alone international cooperation. But is their goal realistic?

Wind Energy

Wind energy is already economic on a small scale even at a zero carbon price, and the technology has been improving. Scaling up, however, will require more than the expected improvements in wind turbine technology.

DeCarolis and Keith (2006, p. 402) find that wind power situated near Chicago, the Windy City, can compete with the alternative of natural gas at a carbon price of \$38/tCO_2. To increase the scale of wind power, the carbon price must be even higher. At a price of \$76/tCO_2, wind power can be situated farther from Chicago. Distance from the center of demand increases transmission costs but is valuable because it reduces intermittency (wind speeds at different locations are less correlated) and thus the need for backup gas turbine capacity. Transmission costs currently depend on the installed grid system, which was configured to suit the existing model of electricity generation—large power plants located close to metropolitan areas. To connect areas where wind power is plentiful to population centers where the electricity is needed requires a new transmission infrastructure relying on high-voltage direct current rather than the existing standard of alternating current. The economics of scaling up wind power thus depend on the costs of this complementary technology.

Storage is another complementary technology for irregular power sources like wind. If, when the winds blow strongly, surplus wind power is used to produce

Table 2
Non-CO_2 Energy

	Wind	*Solar*	*Nuclear*
Viability	Wind energy is a proven technology. High-altitude wind power has not yet been demonstrated at scale.	Photovoltaics are proven. Large solar concentrated power projects are being planned. Space solar power has not yet been demonstrated.	Generation III technology already available. Generation III+ and IV under development. Fusion still at the basic science stage.
Economics	Varies by location. Depends also on transmission costs, storage opportunities, and costs of alternatives.	Varies by location. Concentrated solar can compete with fossil fuels in some sun-rich locations at \$35/tCO_2.	Current nuclear technology competitive with coal and natural gas (for a "high" price) in the U.S. at just over \$27/tCO_2 (MIT, 2003).
Risks/co-benefits	Displacement of fossil fuels by wind will lower local pollution, but there has been local opposition to large-scale wind farms, including off shore.	Risks associated with beaming power by lasers or microwaves. Risk of solar satellite being attacked.	Operation safety, long-term waste storage, and proliferation.
Diffusion	Improvements in complementary technologies like transmission and energy storage will facilitate spread.	Depends on complementary technologies. Space solar power could be used to supply power anywhere.	Diffusion may be helped by standardization and development of new, smaller units.
Scale	Wind energy could potentially meet all the world's power needs.	Available solar energy exceeds the world's total power needs.	Nuclear capacity 3–4 times current level by 2050 would displace 3.0–6.6 $GtCO_2$ per year, depending on whether it replaced natural gas or coal (MIT, 2003, p. 3). This is about 5–10% of business-as-usual emissions (IEA, 2008, p. 41). Under this scenario, nuclear's share of generation rises from 17% to just 19% by 2050 (MIT, 2003, p. 3).
Governance	No significant multilateral issues.	Space solar power may have military uses; a treaty on its deployment and use may be needed.	Profound challenges, especially for long-term storage, reprocessing, and proliferation.

Note: $GtCO_2$ is gigatons of carbon dioxide.

hydrogen that is then stored under pressure in a reservoir, then that stored energy could be burned in a turbine (without releasing greenhouse gases) when the winds fail. DeCarolis and Keith (2006, p. 407) estimate that hydrogen storage becomes competitive at a carbon penalty of about \$93/tCO_2. Here again, local conditions are important. Denmark meets an amazing 17 percent of its electricity needs from wind power, but that is only possible because of electricity trade with Norway (International Energy Agency, 2008, p. 361). When the winds are favorable, Denmark exports power to Norway, and Norway conserves its hydropower. When the winds fail, Norway releases the energy stored in its dams to produce more electricity for export to Denmark. This inexpensive form of storage is not universally available.

Wind power can also be scaled up by building capacity in new places, such as offshore, where the winds are often stronger and blow more consistently than on land. A more radical idea is to capture the energy in the jet stream, ten or so kilometers above the Earth, where the wind is even stronger and steadier. "Flying windmills" could generate power both for lift and transmission, via a cable, to a ground station. Kites could turn a generator as they gained altitude and then have their angle changed so that they descended using less power than they generated in their ascent. Though these technologies have yet to be demonstrated at scale, they could, by some estimates, be competitive even without a carbon penalty (Roberts et al., 2007). There is plenty of wind; according to Roberts et al. (2007, p. 137), wind energy could supply "roughly 100 times the power used by all human civilization." But practical obstacles remain to be overcome, such as the need to restrict airspace and to bring flying generators down for maintenance and during storms. Also, the jet stream winds are not available everywhere.

Solar Energy

Solar energy tends to be abundant in places where wind energy is scarce (high pressure areas have fewer clouds but also less wind). Photovoltaic systems, which convert solar energy to direct current electricity, are already in use, but they operate at low efficiency and are only economic in sun-rich off-grid areas.

"Concentrated solar power" is a technology that, as the name implies, raises the density of solar energy using mirrors to produce heat, which can then be used to turn a turbine for electricity generation. An example is the "power tower," a system of sun-tracking mirrors that beam concentrated solar power to a receiver at the top of a tower, through which flows a working liquid for driving the turbine. An advantage of this technology is that it can be scaled to the size of a central power plant (individual units are being designed to generate up to 250 megawatts of power). It can also store thermal energy to produce electricity at night, addressing the problem of intermittency.

Solar energy is abundant; the electricity needs of the entire U.S. economy, for example, can be met with concentrated solar power, taking up an area of just 100 square miles (IEA, 2008, p. 379). However, this technology is only suited to areas with intense, direct solar radiation, such as the U.S. Southwest, North and Southern Africa, Australia, and parts of India, China, and Central Asia. (Of course, the power produced in these places could be shipped to other locations, but this means overcoming the transmission problems discussed previously.) According to a preliminary study by Wheeler (2008, p. 6), concentrated solar power is competitive with coal in Botswana at a carbon penalty of about \$35/tCO_2. Sub-Saharan Africa needs power to develop, but if it is to develop without increasing greenhouse gas emissions, this carbon penalty will have to be paid. As indicated in Table 1, this price should be paid, if not now, then in the not-too-distant future. However, the prices in Table 1 are global prices. International negotiations will need to resolve the question not only of whether the price should be paid but who should be responsible for paying it.

A more radical idea is "space solar power." This technology would use huge photovoltaic arrays to capture the sun's energy in space, convert it to direct electrical current, and then beam the electricity to Earth using microwaves or lasers. To produce this energy, solar satellites would be placed in high altitude, geosynchronous orbit, and spaced far enough apart so that at least one unit faced the sun at all times—a solution to the intermittency problem. Macauley and Shih (2007) calculate that, as compared with alternatives such as combined cycle gas turbines and wind, space solar power could be competitive in meeting incremental electricity demand by 2030 in places like California, the U.S. Midwest, Germany, and India—provided fossil fuel alternatives faced a carbon penalty of about \$15–25/tCO_2.[2] This estimate makes space solar power look very appealing, but it may be optimistic—among other things, the economics of space solar power depend on enhancements in complementary technologies, such as those that can reduce Earth-to-orbit transportation costs.

Privately funded R&D can help to improve the prospects for wind and solar power, but breakthroughs are very likely to need a sizable carbon penalty, coupled with widespread investments in complementary infrastructure and technology and basic R&D.

Nuclear Power

An expansion of nuclear energy has the potential to reduce greenhouse gas emissions significantly and within decades using proven technology. It also has disadvantages. Addressing these will require innovation and institutional changes.

The economics of nuclear power are hugely sensitive to capital costs—and, thus, to differences in construction time, plant scale and design, and utilization rates, all of which can vary from country to country. In the United States, as shown in Table 2, nuclear power can compete with coal and natural gas at a carbon penalty of just above \$27/tCO_2.[3] The economics of nuclear power have generally

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[2] Macauley and Shih (2007, p. 116) assume a penalty of 1.5–2.5 cents/kWh. They derive their estimates from Krupnick and Burtraw (1996, p. 438), who argue that a climate damage cost of one dollar per ton of CO_2 translates into one tenth of a cent per kWh. This puts the carbon penalty at about \$15–25/tCO_2.

[3] The Massachusetts Institute of Technology (2003) study shows that, at this carbon price, nuclear competes with natural gas provided the price of gas is "high" (\$6.72/MCF). When I first wrote this paper

been unattractive in developing countries, because high capital costs favor scale (most nuclear plants are at least 1,000 megawatts in size). In places with little grid capacity, and in regions with low population density, smaller plants are needed. The so-called "pebble-bed modular reactors" being developed in South Africa will be as small as 100 megawatts. This emerging technology could help to spread nuclear power if, as planned, the diseconomies of its small scale were offset by economies of mass production.

Uranium is an exhaustible resource. Just over 400 plants operate now, and according to current estimates, the quantity of reserves remaining can fuel 1,000 new reactors over the next 50 years (Massachusetts Institute of Technology, 2003). Uranium supply, however, is unlikely to limit nuclear power's expansion this century. As uranium becomes scarcer, prices will rise, creating incentives for new discoveries. Other ways can also be found to ease the supply constraint, including the reprocessing of spent fuel, construction of fast-breeder reactors, extraction of uranium from seawater, and substitution of thorium fuel.

The safety of nuclear power plants has improved. Chernobyl, site of the worst nuclear accident ever, was an early generation nuclear plant that lacked a containment structure. Three Mile Island was a more modern plant; though its reactor core melted, no radiation escaped from this facility. Newer nuclear designs incorporate passive safety features; in the event of an accident, these reactors will shut down automatically. The so-called Generation IV designs now being developed will be safer still.

Nuclear waste remains highly radioactive for thousands of years, and solutions to its long-term disposal have yet to be implemented. The obvious long-term storage solution is geological storage, either in repositories like Yucca Mountain in Nevada, several hundred meters below the Earth's surface, or in boreholes drilled several kilometers deep. So far, however, neither kind of site has been developed, anywhere. Nuclear waste has instead been stored temporarily, on site. The magnitude of the storage requirement is breathtaking. As noted by the authors of an MIT (2003, p. 10) study, "To dispose of the spent fuel from a steady state deployment of one thousand [1,000 MW] reactors of the light water type, new repository capacity equal to the nominal storage capacity of Yucca Mountain would have to be created somewhere in the world every three to four years." New technologies that "partition" and "transmute" the long-lived waste could reduce the storage burden, but these technologies have yet to be demonstrated.

Reprocessing extracted plutonium from the spent fuel, making it available in a form that can be handled easily, increases the risk of nuclear weapon proliferation. The production of fresh fuel also poses a risk to proliferation. Most nuclear power today is produced in rich countries. If nuclear power is to play a major role

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in 2008, natural gas prices in the United States were higher than this. When I revised the paper in early 2009, prices were lower. In the years since the MIT study was completed, plant construction costs have increased significantly.

in reducing greenhouse gas emissions, fast-growing poor countries will also need access to this energy source. The challenge is to facilitate access without making it easier for more and more countries to master either end of the fuel cycle. This is the purpose of the International Atomic Energy Agency's proposal to establish a fuel bank of low-enriched uranium. However, to halt proliferation, it will also be essential to reduce the incentive for states to acquire nuclear weapons, and this will require strengthening the existing nonproliferation regime.

Nuclear fusion offers a near ideal alternative to fission—or, indeed, almost any alternative energy source. At least in theory, its fuel is abundant; it poses no risk of a nuclear accident; it yields no high-level waste; and its fuel and waste pose a relatively small risk of weapons proliferation. Fusion power is also a long way from being demonstrated. A new, big science R&D project (the International Thermonuclear Experimental Reactor or ITER), currently being constructed in France, is expected to take nuclear fusion to the next stage. However, the future of fusion is speculative. It is not expected to contribute to reducing greenhouse gas emissions before 2050 (IEA, 2008, p. 306).

Substituting carbon-free energy for fossil fuels is an obvious way to reduce emissions, but each of the options considered here faces numerous obstacles. Putting a price on carbon will help, but additional policies will be needed to reduce emissions dramatically. Moreover, as we succeed in substituting carbon-free energy for fossil fuels, the price of fossil fuels will fall (all else being equal, of course), lowering the returns to incremental investments in carbon-free energy. For all these reasons, we also need to consider ways of reducing or offsetting the emissions associated with fossil fuel use.

CO_2 Capture and Sequestration

Emissions can be reduced at the power plant by removing CO_2 before it reaches the air. CO_2 can also be removed directly from the air. Table 3 summarizes the economics of, and the challenges associated with, both of these options.

Power Plant Capture and Storage

Fossil fuels can be burned without contributing to climate change if the CO_2 that would ordinarily be emitted is captured, transported, and stored somewhere other than the atmosphere. CO_2 pipelines already exist, and CO_2 can also be transported at sea by ships similar to the ones that now transport liquefied petroleum gases. There are no serious technical obstacles to CO_2 transport. The technical challenges concern capture and storage.

CO_2 capture can be done either after combustion, by removing CO_2 from the stack gases, or before combustion, by removing it from the fuel. CO_2 is already captured for certain industrial purposes, like the production of hydrogen for fertilizer manufacture (after being captured, this CO_2 is currently released into the air). Other capture techniques are only now being demonstrated. Capture involves

Table 3

CO_2 Capture and Sequestration Technologies

	Carbon capture/storage fossil fuel plants	*Land-based biomass capture/storage*	*Ocean fertilization*	*Increasing ocean alkalinity*	*Industrial air capture*
Viability	Many component technologies are proven, but plant-scale capture/storage has not been demonstrated.	No such plant yet demonstrated.	Verification difficult; would likely have to rely on models.	Not yet demonstrated.	Prototypes being developed.
Economics	\$40–90/tCO_2 or less (IEA, 2008, p. 270); \$25–\$30 (IPCC, 2005, p. 41); \$54–\$68/tCO_2 (Anderson and Newell, 2004, p. 109). Retrofits more expensive.	\$50–\$110/tCO2 (see Table 4).	\$4/tCO_2 (Kite-Powell; see note); \$5tCO_2 (Whaley; see note).	"No practical method now exists for adding alkalinity to the ocean at reasonable cost · · ·" (Stephens and Keith, 2008, p. 238).	\$135/tCO_2 (Keith, Ha-Duong, and Stolaroff, 2005); \$100–\$200/tCO_2 (Zeman and Keith, 2008); less than \$100/tCO_2 (Lackner and Sachs, 2005).
Risks/ co-benefits	Geologic storage poses local environmental risks; ocean storage may pose wide-scale risks. Leakage of stored CO_2 another risk.	Storage risks; environmental damage from shift to biomass.	Main concern is effect on ocean ecosystems.	Increased alkalinity will reduce ocean acidification, but there will also be harmful environmental consequences.	Sequestration risks.
Diffusion	Diffusion will require either standards or a high carbon price.	Diffusion will require either standards or a high carbon price.	Can be done as a project.	Can be done as a project	Can be done as a project.
Scale	Geological storage 1,690–11,100 $GtCO_2$ (IPCC, 2005, p. 31); Ocean storage 2,000–12,000 $GtCO_2$ (IPCC, 2005, p. 35).	Storage limited as above. Land another constraint.	Can sequester less than "several hundred million tons of carbon per year" (Buesseler et al., 2008, p. 162).	Because relies on ocean–atmosphere mixing, rate of CO_2 uptake very slow.	Can stabilize concentrations at virtually any level.
Governance	London Convention parties endorsed carbon storage beneath sea floor.	No major multilateral challenges.	Parties to two treaties have cautioned against large-scale fertilization.	Who decides whether this should be done, and on what scale?	Who decides the concentration level?

Note: The estimates of costs for ocean fertilization are from personal communications with Hauke Kite-Powell of the Woods Hole Oceanographic Institution and Dan Whaley of Climos. $GtCO_2$ is gigatons of carbon dioxide.

substantial economies of scale, and is appropriate only for large emitting facilities such as power plants. Existing technologies for power systems can capture about 85–95 percent of the CO_2 that is produced, but energy is needed to separate the CO_2, and so the net amount of CO_2 captured is closer to 80–90 percent (Intergovernmental Panel on Climate Change, 2005, p. 22).

The economics of capturing CO_2 from power plants depend on the type of plant used for comparison purposes (Anderson and Newell, 2004). Costs also depend on whether the plant is designed for capture and storage; retrofits are more costly than purpose-built facilities, not least because existing plants are built close to where electricity is demanded rather than where their CO_2 can be stored. China has recently been bringing on line about one new coal-fired power plant every week. None of this capacity has been added with regard to the possible need to retrofit these plants for carbon capture and storage.

CO_2 can be stored in geological formations such as oil and gas reservoirs, deep saline aquifers, and un-minable coal beds. Small amounts of CO_2 are already being sequestered in places like the Weyburn oil field in Saskatchewan and in the Utsira aquifer off the coast of Norway. When stored at depths below 800 meters, CO_2 is transformed into a liquid or supercritical state. Supercritical CO_2 is more buoyant than water and some crude oils. To ensure that this CO_2 remains trapped below ground, it must be stored in formations with impermeable cap rock. Over centuries and millennia, CO_2 stored at these depths will dissolve in water, and become denser. Over millions of years, further chemical reactions will convert the stored CO_2 into solid carbonate minerals. Sudden releases, however, are possible in the near term and may pose health and environmental risks (by displacing oxygen in the neighborhood of the release). More gradual releases are also possible and may contaminate groundwater and soils—along with allowing CO_2 to escape into the atmosphere.

There is plenty of geological storage capacity for CO_2. In recent years, emissions of CO_2 have been around 28 billion metric tons per year. Only a fraction of this amount can be captured economically from large sources, and so the capacity estimates shown in Table 3 imply that there is enough geologic storage capacity to lock away at least a century's worth of CO_2 from such sources, and probably much more than that.

The capacity of the deep ocean to store CO_2 is greater still, but the oceans are not a truly permanent solution. Ocean mixing would, over a period of centuries, return the CO_2 to the surface, where it would be released into the atmosphere very gradually (for the same reasons that the ocean's surface waters currently absorb CO_2 very slowly). Deep ocean storage would also change ocean chemistry at the injection site and, over time, as the ocean waters mixed, throughout the world's oceans. The ecological consequences of large-scale, deep ocean storage are unknown.

A final possibility is to fix CO_2 by accelerating the process of mineral carbonation using natural silicates. CO_2 stored in this way would have no chance of atmospheric release, and there is enough silicate available to store all the CO_2 we are ever likely to emit. However, this method of storage is costly (carbonization alone would cost about \$80/tCO$_2$), and mining the silicate rock would be environmentally disruptive (IPCC, 2005, p. 247; Lackner and Sachs, 2005, p. 247). Geochemical storage may only be economic, for a high enough carbon price, in regions lacking underground storage sites (Stephens and Keith, 2008).

As shown in Table 3, estimates of the costs of capturing, transporting, and storing CO$_2$ underground range from \$25/tCO$_2$ to \$90/tCO$_2$. Comparing these estimates with the carbon prices shown in Table 1, an economic case can be made either for adopting this technology very soon or later this century. No reasonable case can be made for ignoring this option. An imperative must be to learn more about this technology, including more about its costs and environmental effects. This will require investment in a significant number of demonstration projects, in addition to related basic research.

Biomass Carbon Capture and Storage

Tree planting, or "biomass carbon capture and storage," takes CO$_2$ out of the air. Unlike power plant capture and storage, tree planting need not be coupled to the energy supply system.

Biomass (including wood, forestry and crop residues, and various grasses) contains carbon and so can be converted into energy products. Since biomass growth removes CO$_2$ from the atmosphere, substitution of this form of energy for fossil fuels could potentially reduce emissions. Scaling up will be a problem, however, if biomass-for-energy crops displace food crops or result in the destruction of natural ecosystems (though these stresses could possibly be alleviated over time by advances in biotechnology, such as the development of a new strain of algae that could be used to produce a so-called "third generation" biofuel).

If biomass were used as a fuel for electricity generation with carbon capture and sequestration, biomass energy would result in *negative* net emissions. As shown in Table 3, this technology currently costs more than carbon capture and storage from fossil fuel power plants. However, as I shall explain later, energy from biomass may be able to compete, as an offset, with high-cost alternatives for reducing emissions in the transportation sector.

Ocean Fertilization

CO$_2$ can also be removed from the air by fertilizing iron-limited regions of the oceans, to stimulate phytoplankton blooms. If the produced algae (which, like any biomass, absorbs CO$_2$ in the process of photosynthesis) sink into the deep ocean, iron fertilization will remove CO$_2$ from the atmosphere. A related approach is to stimulate phytoplankton blooms by creating an upwelling of nutrients from deep water to the surface in parts of the ocean where the surface waters are low in nitrates.

The potential for this kind of air capture is limited. It would work in only a few locations; at best it could play only a small role in stabilizing concentrations. There are also practical problems, such as how to verify the amounts of CO$_2$ sequestered.

Some experiments in ocean fertilization have been conducted, but to learn more will require large-scale experiments, and these may risk harming ocean ecosystems (Buesseler et al., 2008).

Increasing Ocean Alkalinity

Another way to increase ocean uptake of CO_2 is to change the ocean's alkalinity by adding lime or bicarbonate to the ocean. As noted by Stephens and Keith (2008, p. 228), "If the alkalinity of the oceans was increased, the ocean's capacity to store dissolved inorganic carbon would increase and the associated increase in acidity would be reduced." In short, increasing ocean alkalinity could reduce atmospheric concentrations of CO_2 even as it reduced ocean acidification. The feasibility, environmental impacts, and costs of this approach are unknown, but its role in stabilizing concentrations will in any event be limited because the rate of uptake of CO_2 by the oceans is slow.

Industrial Air Capture

CO_2 can also be sucked out of the air directly, anyplace on Earth, by means of an industrial process that puts air into contact with a chemical "sorbent," such as an alkaline liquid. As shown in Table 3, the costs of industrial air capture are expected to be substantial—higher than carbon capture from fossil fuel power plants, because CO_2 is more highly concentrated in a plant's stack gases than in the air. As with all of the new technologies discussed in this paper, these cost estimates are educated guesses. Lackner and Sachs (2005) believe that, with R&D and learning by doing, the costs of air capture might fall to \$30/tCO_2.

Industrial air capture has several desirable features (Sarewitz and Nelson 2008). It would be decoupled from our energy systems, and could be located near geologic sites for long-term carbon storage and away from population areas, where land is cheap. It could also be scaled to any level. Conceivably, every other aspect of the global economy could remain unaltered, and this technology be used to sustain virtually *any* desired reduction in atmospheric levels of carbon. Pure air capture is a true "backstop technology."

Because it acts directly on reducing concentrations, industrial air capture also offers more options for the timing of investment. Pielke (forthcoming) calculates that air capture could achieve the same concentration target as has been advocated by Stern (2007), for about the same total cost as Stern projected for a scenario of emission reductions. This is because, though air capture has a high marginal cost, its use can be delayed until (for the concentration target advocated by Stern) after around 2050. Even if the intention were not to deploy this technology, it may pay for us to develop it as a hedge against future climate change risks, given its unique ability to be scaled to reduce concentrations directly. Finally, unlike emission reductions, industrial air capture could be deployed by a single country, or by a "coalition of the willing." This possibility creates an important question for governance: who should decide the level of atmospheric carbon to target?

Transportation Fuels

There are three different options for reducing CO_2 emissions in road transport: offsetting the emissions associated with using petroleum-based fuels; using new energy carriers to substitute for these fuels; and developing synthetic hydrocarbon fuels as substitutes.

Offsets

Automobile transportation can be made "carbon neutral" by offsetting vehicle emissions with air capture. The great advantage of this approach is that it avoids the need to change the transportation infrastructure. The disadvantage is cost.

Row one of Table 4 gives the cost of gasoline and row two the cost of gasoline *plus* the costs of offsetting the CO_2 emissions from gasoline consumption by industrial air capture. These costs are expressed in dollars per gigajoule, a standard unit of energy (one U.S. gallon of gasoline contains about 0.13 gigajoules of energy). The additional cost of the offset, expressed in \$/metric ton CO_2, is given in the last column of the table. Air capture is a pure add-on cost; it becomes attractive only if the price of carbon exceeds this value. Recalling the carbon price estimates reviewed in Table 1, this cost is currently not worth paying, though it could become so later this century.

Since biomass growth removes CO_2 from the air, use of biomass for electricity production coupled with carbon capture and storage could, like industrial air capture, offset the emissions from gasoline combustion. An estimate of this cost is shown in the third row of Table 4. This option is plainly cheaper than industrial air capture, but the estimates for biomass costs ignore the social costs of this option (such as for land-use change).

CO_2-Free Energy Carriers

Hydrogen can carry energy without emitting CO_2 when burned. However, hydrogen would require a new infrastructure—for production, storage, and distribution as well as for new vehicles and refueling stations. Powering cars with electricity will also require infrastructure changes—new vehicles with new energy storage systems (batteries), supported by an expanded system for recharging. Moreover, if the aim were to reduce CO_2 emissions, either of these energy carriers would have to be produced using renewable energy, nuclear power, or fossil fuels coupled with carbon capture and storage.

Estimates of the costs of these energy carriers, produced by a carbon-free process, are shown in the fourth and fifth rows of Table 4. These costs cannot be compared directly to others in the table. The estimates for hydrogen are for delivery to the vehicle. They ignore the costs of developing an on-board hydrogen storage system and energy conversion. They also ignore the efficiency advantage of fuel cells and the local environmental benefits of reductions in conventional pollutants. Similarly, the costs for electric-powered transportation ignore vehicle costs and the value of differences in

Table 4

Costs of Reducing Road Transport Emissions

	Fuel cost (per gigajoule of energy)	*Cost of avoiding emissions from gasoline (per metric ton CO_2)*
Conventional gasoline[a]	\$13–\$24/GJ	—
Gasoline offset by air capture[a,b]	\$24–\$44/GJ	\$150–300/tCO_2[c]
Gasoline offset by biomass electricity with carbon capture and storage[d]	\$16.5–\$31.5/GJ	\$ 50–110/tCO_2
Hydrogen made using fossil fuels with carbon capture and storage	\$26.5–\$41/GJ	Vehicle costs additional and will be very high.[e]
Electricity made using fossil fuels and carbon capture and storage	\$15–\$23/GJ[f]	Vehicle costs additional and will be high; additional infrastructure also required.
Synthetic fuel made from CO_2 in biomass	\$18.5–\$21/GJ	\$80/tCO_2; could be negative for high oil price.
Synthetic fuels made from atmospheric CO_2[b,g]	\$25.5–\$34/GJ	\$150–185/tCO_2

Source: Estimates in the fuel cost column are from Zeman and Keith (2008).

[a] Assumes a price of oil of \$50–100 per barrel.

[b] Assumes industrial air capture costs of \$100–\$200/tCO_2.

[c] These estimates, slightly rounded, include a 40 percent penalty for the capture and storage needed to offset the emissions associated with refining oil to produce gasoline.

[d] Assumes biomass delivered to the power plant costs \$40–\$80 per dry metric ton.

[e] According to Keith and Farrell (2003, p. 315), "Costs may exceed [\$272/tCO_2] if hydrogen cars are to match the performance of evolved conventional vehicles." Other estimates in the literature are higher than this.

[f] Includes \$1–3/GJ to use air capture to offset fugitive emissions from electricity production with carbon capture and storage.

[g] Includes capture and storage costs for the CO_2 emitted in the production of hydrogen.

vehicle characteristics, such as the number of miles that can be driven between recharges and the onboard space taken up by batteries.

The need to match a new infrastructure with a new energy carrier creates a formidable challenge. To make a transition to a "hydrogen economy," the costs of multiple components need to fall and their performance improve. Given substantial network externalities, such a transition also requires coordinating investment across the different components. An example is the well-known chicken-and-egg problem: consumers will hesitate to purchase hydrogen vehicles unless hydrogen fuel is widely available and competitively priced relative to the alternatives, while energy firms will be reluctant to build a hydrogen fuel infrastructure so long as hydrogen vehicle ownership is low.

Plug-in hybrids could serve as a transition technology. They can run on electricity and gasoline, with the electric power being recharged from the existing grid. In contrast to the all-electric car (given current battery technology), plug-in hybrids can also be driven long distances, making use of the existing refuelling infrastructure. Moreover, as more people drive plug-in hybrids, the recharging infrastructure will grow to serve this new market and vehicle manufacturers will have an incentive to improve battery performance. These developments will in turn improve the economics of moving to the all-electric car. Finally, as more countries adopt a new automobile standard, there will be incentives for more to do so (Barrett, 2005). As noted before, should the hydrogen or electric vehicle become a new global standard, the challenge will be to ensure that production of these fuels is carbon-free.

Synthetic Fuels

A different and more radical approach is to develop new kinds of hydrocarbons that can be distributed and burned using the installed base of capital—synthetic hydrocarbon fuels (Zeman and Keith, 2008).

Automobile fuels made today from biomass reduce emissions very little (relative to gasoline); some, such as corn-based ethanol, even increase emissions (Fargione, Hill, Tilman, Polasky, and Hawthorne, 2008). Advances in plant sciences and "biorefinery" manufacturing may change the economics of biofuels (Ragauskas et al., 2006), but here I focus on a different possibility—using biomass to reduce emissions by separating the carbon in biomass and combining it with hydrogen to make a synthetic hydrocarbon fuel, with the energy needed to power this process being produced from a carbon-free energy source. An estimate of the costs of this alternative is shown in the sixth row of Table 4. These values are very low, but as noted before, they exclude the social costs of biomass production (such as the displacement of food crops). On the other hand, since biomass is not used to power the fuel conversion process, less biomass (and, therefore, less land) is needed to produce a given amount of synthetic fuel as compared with ordinary biofuels.

A related approach would remove CO_2 from the air using industrial air capture and use this as a feedstock for producing a synthetic hydrocardon fuel. Essentially, the carbon would be recycled: taken out of the air to make fuel, and then put back in the air as that fuel is burned. So long as the energy that powers this system and that produces the hydrogen input is carbon free, this approach would have an advantage over gasoline offset with air capture—CO_2 would not need to be stored underground or in the oceans. The cost of this alternative is shown in the last row of Table 4.

Yet another approach is to use the new science of synthetic biology to construct microorganisms that use CO_2 as a feedstock to make "fourth-generation biofuels." These would also be compatible with the existing transportation infrastructure.

Overall, there does not yet appear to be an obvious "technological 'winner'" for the transportation sector (Zeman and Keith, 2008, p. 16). Different futures can be written for the automobile.

Systemwide Effects

I have so far considered technologies in isolation, but systemwide effects will be important. For example, if hydrogen is produced from fossil fuels at a substantial scale, the economics of carbon capture and storage will improve. This is because hydrogen production yields a stream of pure CO_2, making capture easier (Anderson and Newell, 2004, p. 115). Similarly, if the costs of producing electricity from renewable energy or nuclear energy were to fall, the economics of producing hydrogen would improve, as would the returns to R&D into the production of hydrogen by electrolysis. Hydrogen is more appealing as a fuel for maritime than for road transport, but should hydrogen be used for shipping, network effects will improve the economics of using hydrogen for road transport (Farrell, Keith, and Corbett, 2003). Finally, the intermittency problems with certain types of renewable energy like wind or solar matter less if these sources are balanced by complementary generation from hydro, the electricity output of which can be varied relatively quickly, rather than from nuclear or coal with carbon capture and storage (DeCarolis and Keith, 2006, p. 397).

These interconnections mean that early policy decisions favoring one technology, for whatever reason, may influence the evolution of the technology revolution.

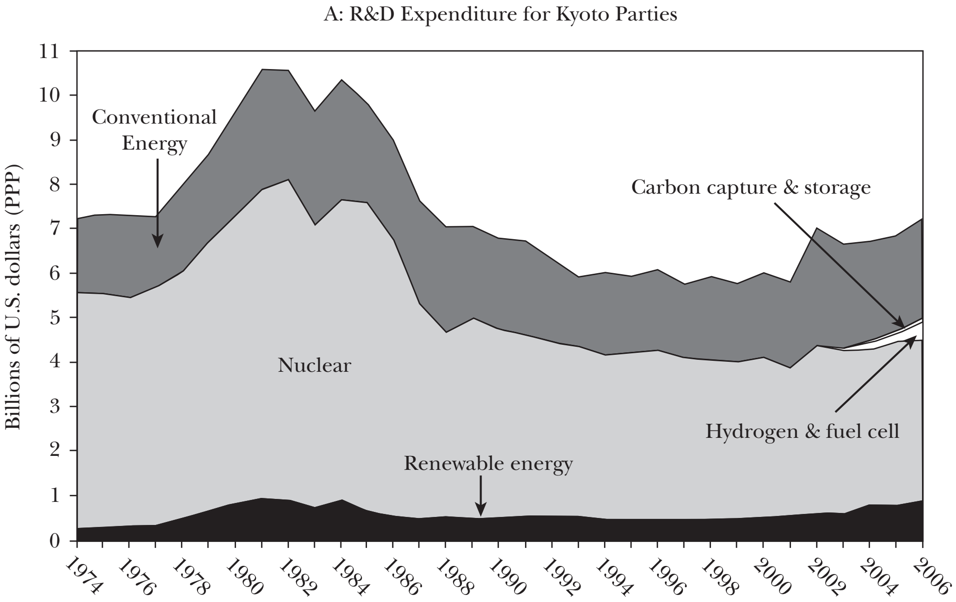
Research and Development

None of the breakthrough technologies discussed here can be brought to commercialization without substantial investment in R&D. Unfortunately, as shown in Figures 1A and 1B, energy R&D spending by the members of the International Energy Agency declined after the Framework Convention on Climate Change was negotiated in 1992 and picked up only slightly after the Kyoto Protocol was adopted in 1997. The pattern of R&D spending for parties and nonparties to Kyoto has been very similar. Only in the last few years have countries begun to invest in hydrogen, fuel cells, and carbon capture and storage. This level of R&D spending is too small to kick-start a technological revolution.

Why so little R&D? The reason is not only that the knowledge gained from government-funded R&D is a global public good, vulnerable to free riding—that is true for all types of basic knowledge. The bigger problem is that the returns to climate-related R&D depend on the prospects of that R&D leading to reductions in greenhouse gas concentrations—another global public good (Barrett, 2006). These prospects depend on governments cooperating to push up the price of carbon, and so far this effort has been largely unsuccessful. To be sure, there are several international initiatives to promote climate–technology R&D, such as the Carbon Sequestration Leadership Forum (with 21 member countries plus the European Commission) and the International Partnership for the Hydrogen Economy (17 countries plus the European Commission). But these initiatives merely coordinate national activities; they do not increase R&D funding. The ITER (International Thermonuclear Experimental Reactor) project, noted previously, is different; it does involve international financing; but ITER will yield substantial benefits unrelated to climate change.

If a better post-Kyoto agreement is not adopted, the incentives to develop and

Figure 1
Energy R&D Expenditure



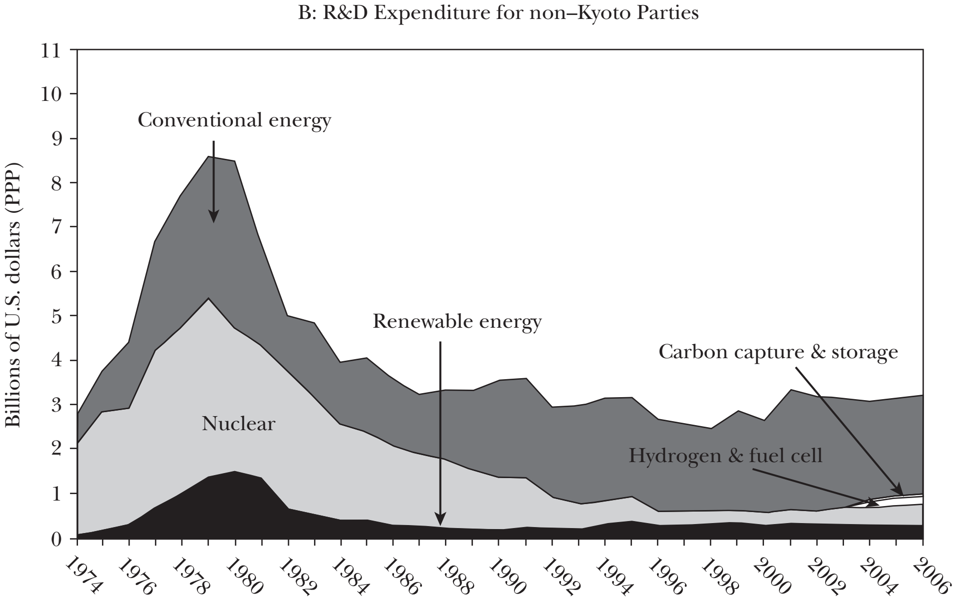
diffuse many of the technologies discussed in this paper will remain weak. The consequences of that failure will be greater climate change, which will stimulate innovation in areas that can *substitute* for mitigation. These areas are adaptation and geoengineering.

Adaptation

Much adaptation to climate change will be done "automatically" by the market. Other forms of adaptation will involve the supply of local public goods, like dikes, an augmented Thames Barrier, and so on. The incentives for countries to adapt, and to innovate for adaptation, will become very powerful as the effects of climate change appear and become magnified. Indeed, the possibility of adapting to climate change reduces somewhat the incentives to decrease carbon emissions.

Poor countries are especially vulnerable to climate change. This is partly because of their geography (Mendelsohn, Dinar, and Williams, 2006). It is also because they lack the private and public sector institutions that would help them adapt to climate change. One area requiring innovation is agriculture. The Consultative Group on International Agricultural Research has already begun undertaking research that could reduce future vulnerability dramatically. Examples include heat-tolerant crops, "drought-escaping" rice (varieties that can grow over a shorter cycle), and "waterproof" rice (varieties that survive prolonged flooding).

Figure 1—continued



Source: ⟨http://www.iea.org/RDD/TableViewer/tableView.aspx?ReportId=1⟩.
Note: Kyoto parties are Austria, Belgium, Canada, Czech Republic (excluded for lack of data), Denmark, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Japan, South Korea, Luxembourg, the Netherlands, New Zealand, Norway, Portugal, Spain, Sweden, Switzerland, and the United Kingdom. Kyoto nonparties are Australia (which became a party in late 2007), Turkey, and the United States. "Conventional energy" R&D includes energy efficiency, fossil fuels (other than carbon capture and storage), and electricity R&D. "Nuclear" includes fission and fusion. "Renewable energy" includes hydropower, solar, wind, ocean, and bioenergy. "PPP" is purchasing power parity.

These and other innovations will help to reduce the damages from climate change, but there remains a potential for climate change to widen existing inequalities between rich and poor countries.

Geoengineering

It is also possible to compensate for the effect of rising concentrations on temperature. One possibility is to increase the reflectivity of the Earth's surface—for example, by painting roofs white or by planting "shiny crops."[4] Another possibility, with a greater potential to change global temperature, is to reduce the amount of solar radiation that strikes the Earth—that is, to create a planetary parasol.

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[4] Though tree planning removes CO_2 from the atmosphere (resulting in cooling), trees grown in snow-covered tundra areas may reduce reflectivity (resulting in warming). What matters is the net effect on temperature.

This could be done at low altitude by "seeding" clouds over the oceans with seawater spray, which would whiten clouds and so increase their reflectivity (their "albedo"). The sea spray could be produced by unmanned, ocean-going vessels, propelled by vertical spinning cylinders that act like sails, with the movement of the ships creating the power needed to produce the spray. Satellites could measure the reflectivity of the clouds, allowing the amount of spray to be varied to maintain the desired level of solar deflection. Preliminary calculations suggest that a fleet of 1,500 vessels could offset the warming effect of a doubling in CO_2 concentrations. Though the proposal is still at the drawing board stage, the economics of this proposal are astonishing. According to the designers of this concept, the fleet of vessels needed to offset the effects of a doubling in CO_2 concentrations would only cost around $4 billion (Salter, Sortino, and Latham, 2008).

The geoengineering proposal that has attracted the most attention so far involves projecting sunlight-deflecting sulfate particles into the stratosphere. The operation would essentially mimic a volcanic eruption, which is known to have a cooling effect. Sulfates are already resident in the stratosphere. To offset the warming associated with a doubling in CO_2 concentrations, the amount of sulfates would have to increase 15–30 times (Rasch, 2008). (This multiple may seem high, but it is a very small increase relative to the amount of sulfur in the troposphere.) There are a number of ways to deliver sulfates to the stratosphere: by artillery shells, rockets, high-flying jets, or even hoses tethered to balloons. To maximize the time that the sulfate particles stay in the air, and to create a uniform cooling effect, the particles should be released over the equator. If the intention were to cool only the Arctic, particles could be scattered in the higher latitudes of the northern hemisphere (Caldeira and Wood, 2008).

Again, the economics of this form of geoengineering seem incredible (Barrett, 2008). Upon reviewing the options in depth, the National Academy of Sciences Panel on Policy Implications of Greenhouse Warming (1992, p. 452, 454) calculated that adding stratospheric aerosol dust to the stratosphere would cost just pennies per ton of CO_2 mitigated. Crutzen (2006) thinks the costs would be perhaps $25–$50 billion per year to offset the effects of a doubling in CO_2 concentrations, but other estimates are lower (Barrett, 2008).

It seems clear that, relative to stabilizing carbon dioxide concentrations, geoengineering is so cheap that cost will not be a major consideration (Keith, 2000, p. 263). So, why not use one of these schemes and forsake the attempt to limit atmospheric concentrations? A number of risks need to be considered: geoengineering would not address the related environmental problem of "ocean acidification"; stratospheric aerosols could destroy ozone; the cooling effect of geoengineering may not preserve the existing spatial distribution of climate; and a geoengineering experiment may have other effects, as yet unimagined. On the other hand, since particles will last at most a few years in the stratosphere (and sea spray only a few days), the geoengineering experiment could be turned off relatively quickly should its effects prove harmful overall.

A crucial feature of geoengineering is that it could be undertaken unilaterally. Indeed, given this technology's low cost, a single country may have the incentive to deploy it unilaterally. This makes its provision attractive. It may also create a potential for conflict.

It is important to distinguish "gradual" from "abrupt and catastrophic" climate change. Gradual climate change may produce winners and losers over the next century. Cline (2007), for example, estimates that a 3°C mean global temperature increase by around the year 2080 would lower India's agricultural capacity by nearly one-third while increasing capacity in China, Russia, and the United States by perhaps 6 to 8 percent. If India were to deploy geoengineering to avert a local catastrophe, these other countries might complain or intervene militarily or launch a countervailing geoengineering effort to *warm* the Earth. Over longer periods of time, even gradual climate change would be harmful all around—melting of the Greenland Ice Sheet, for example, would increase sea level by about 7 meters over a millennium. Abrupt climate change, such as a collapse of the West Antarctic Ice Sheet, though unlikely, would have more serious consequences. Should our efforts to limit concentrations fail, or should rapid change occur despite emissions being curtailed sharply, geoengineering may seem worth the risk. Either way, it would seem prudent to be prepared for these possible futures, which is why R&D into geoengineering should begin now. Given the sensitivity around this technology, this R&D should be undertaken cooperatively and openly.

Conclusions

Stabilizing atmospheric concentrations will require fundamental and comprehensive changes in technology. Market incentives are insufficient to bring about this revolution, and governments generally have weak incentives to intervene unilaterally. International cooperation is needed to set a carbon penalty, to increase R&D spending, to make complementary investments, to coordinate in establishing standards, and to govern the use of new technologies.

Many different technologies can help to limit atmospheric concentrations, each with its own advantages and disadvantages, some more speculative than others, and some depending more than others on international cooperation succeeding. It is a cliché, but true, to say that there is no silver bullet solution to the climate problem.

Adaptation and geoengineering do not depend on international cooperation in the same way as the other technological options, but they pose other problems. The different abilities of countries to adapt to climate change may widen existing inequalities. The use of geoengineering may stimulate new international tensions and will not remove all environmental risks. Indeed, it will likely create new ones.

Climate change is already underway, and our global institutions and world technology base are starting to co-evolve with it. Given the uncertainties over how quickly and in what ways this mixture of climate, institutions, and technology will change, a wise policy approach would be to assure that investment is spread over a wide portfolio of possible approaches, some that can be used relatively quickly, some that will not be available until later, and some that are kept in reserve as the twenty-first century unfolds.

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References

Anderson, Kevin, and Alice Bows. 2008. "Reframing the Climate Change Challenge in Light of Post-2000 Emission Trends." *Philosophical Transactions of the Royal Society A: Mathematical, Physical, and Engineering Sciences,* 366(1882).

Anderson, Soren, and Richard Newell. 2004. "Prospects for Carbon Capture and Storage Technologies." *Annual Review of the Environment and Resources,* vol. 29, pp. 109–142.

Arrow, Kenneth J., Linda Cohen, Paul A. David, Robert W. Hahn, Charles Kolstad, Lee Lane, W. David Montgomery, Richard R. Nelson, Roger Noll, and Anne E. Smith. 2008. "A Statement on the Appropriate Role for Research and Development in Climate Policy." AEI Center for Regulatory and Market Studies, Related Publication 08-12.

Barrett, Scott. 2005. *Environment and Statecraft: The Strategy of Environmental Treaty-Making.* Paperback edition. Oxford: Oxford University Press.

Barrett, Scott. 2006. "Climate Treaties and 'Breakthrough' Technologies." *American Economic Review,* 96(2): 22–25.

Barrett, Scott. 2008. "The Incredible Economics of Geoengineering." *Environmental and Resource Economics,* 39(1): 45–54.

Buesseler, Ken Ol et. al. 2008. "Ocean Fertilization—Moving Forward in a Sea of Uncertainty." *Science,* 319(5860): 162.

Caldeira, Ken, and Lowell Wood. 2008. "Global and Arctic Climate Engineering: Numerical Model Studies." *Philosophical Transactions of the Royal Society A,* 366(1882).

Cline, William R. 2007. *Global Warming and Agriculture: Impact Estimates by Country.* Washington, DC: Peterson Institute for International Economics. Available at: http://www.cgdev.org/content/publications/detail/14090.

Crutzen, Paul J. 2006. "Albedo Enhancement by Stratospheric Sulfur Injections: A Contribution to Resolve a Policy Dilemma?" *Climatic Change,* 77(3–4): 211–19.

DeCarolis, Joseph F., and David W. Keith. 2006. "The Economics of Large-Scale Wind Power in a Carbon Constrained World." *Energy Policy,* 34(4): 395–410.

Fargione, Joseph, Jason Hill, David Tilman, Stephen Polasky, and Peter Hawthorne. 2008. "Land Clearing and the Biofuel Carbon Debt." *Science,* 319(5867): 1235–38.

Farrell, Alexander E., David W. Keith, and James J. Corbett. 2003. "A Strategy for Introducing Hydrogen into Transportation." *Energy Policy,* 31(13): 1357–67.

Hoffert, Martin I. et al. 2002. "Advanced Technology Paths to Global Climate Stability: Energy for a Greenhouse Planet." *Science,* 298(5595): 981–7.

International Energy Agency (IEA). 2008. *Energy Technology Perspectives in Support of the G8 Plan of Action: Scenarios and Strategies to 2050.* Paris: International Energy Agency.

Intergovernmental Panel on Climate Change (IPCC). 2005. *Carbon Dioxide Capture and Storage,* Technical Summary. Available at: http://www.ipcc.ch/ipccreports/srccs.htm.

Intergovernmental Panel on Climate Change (IPCC). 2007. *Climate Change 2007: Synthesis Report, Summary for Policymakers.* http://www.ipcc.ch/pdf/assessment-report/ar4/syr/ar4_syr_spm.pdf.

Keith, David W. 2000. "Geoengineering the

Climate: History and Prospect." *Annual Review of Energy and Environment,* vol. 25, pp 245–84.

Keith, David W., and Alexander E. Farrell. 2003. "Rethinking Hydrogen Cars." *Science,* July 18, vol. 301, pp. 315–6.

Keith, David W., Minh Ha-Duong, and Joshuah K. Stolaroff. 2005. "Climate Strategy with CO_2 Capture from the Air." *Climatic Change,* 74(1–3): 17–45.

Krupnick, Alan J., and Dallas Burtraw. 1996. "The Social Costs of Electricity: Do the Numbers Add Up?" *Resource and Energy Economics,* 18(4): 423–66.

Lackner, Klaus S., and Jeffrey D. Sachs. 2005. "A Robust Strategy for Sustainable Energy." *Brookings Papers on Economic Activity,* no. 2, pp 215–84.

Macauley, Molly K., and Jhih-Shyang Shih. 2007. "Satellite Solar Power: Renewed Interest in an Age of Climate Change?" *Space Policy,* 23(2): 108–120.

Massachusetts Institute of Technology (MIT). 2003. *The Future of Nuclear Power.* http://web.mit.edu/nuclearpower/.

Mendelsohn, Robert, Ariel Dinar, and Larry Williams. 2006. "The Distributional Impact of Climate Change on Rich and Poor Countries." *Environment and Development Economics,* 11(2): 159–178.

Nordhaus, William. 2008. *A Question of Balance: Weighing the Options on Global Warming Policies.* New Haven: Yale University Press.

Panel on Policy Implications of Greenhouse Warming. 1992. *Policy Implications of Greenhouse Warming: Mitigation, Adaptation, and the Science Base.* Washington, DC: National Academy Press.

Pielke, Roger A., Jr. Forthcoming. "An Idealized Assessment of the Economics of Air Capture of Carbon Dioxide in Mitigation Policy." *Environmental Science and Policy.*

Ragauskas, Arthur J. et al. 2006. "The Path Forward for Biofuels and Biomaterials." *Science,* 311(5760): 484–89.

Rasch, Philip J., Simone Tilmes, Richard P. Turco, Alan Robock, Luke Oman, Chih-Chieh Chen, Georgiy L. Stenchikov, and Rolando R. Garcia. 2008. "An Overview of Geoengineering of Climate Using Stratospheric Sulphate Aerosols." *Philosophical Transactions of the Royal Society A: Mathematical, Physical, and Engineering Sciences,* 366(1856).

Roberts, Bryan W., David H. Shepard, Ken Caldeira, M. Elizabeth Cannon, David G. Eccles, Albert J. Grenier, and Jonathan F. Freidin. 2007. "Harnessing High-Altitude Wind Power." *IEEE Transactions on Energy Conversion,* 22(1): 136–144.

Salter, Stephen, Graham Sortino, and John Latham. 2008. "Sea-Going Hardware for the Cloud Albedo Method of Reversing Global Warming." *Philosophical Transactions of the Royal Society A,* 366(1882).

Sarewitz, Daniel, and Richard Nelson. 2008. "Three Rules for Technological Fixes." *Nature,* December 18, pp. 871–72.

Stern, Nicholas. 2007. *The Economics of Climate Change: The Stern Review.* Cambridge: Cambridge University Press.

Stephens, Jennie C., and David W. Keith. 2008. "Assessing Geochemical Carbon Management." *Climatic Change,* 90(3): 217–42.

Wheeler, David. 2008. "Crossroads at Mmamabula: Will the World Bank Choose the Clean Energy Path?" Center for Global Development Working Paper 140.

Zeman, Frank S., and David W. Keith. 2008. "Carbon Neutral Hydrocarbons." *Philosophical Transactions of the Royal Society A.* Available at http://journals.royalsociety.org/content/b336222382663v17/.

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7. D.L. Greene, P.R. Boudreaux, D.J. Dean, W. Fulkerson, A.L. Gaddis, R.L. Graham, R.L. Graves, J.L. Hopson, P. Hughes, M.V. Lapsa. 2010. The importance of advancing technology to America's energy goals. *Energy Policy* **38**:8, 3886-3890. [CrossRef]
8. Scott Barrett, Michael Toman. 2010. Contrasting Future Paths for an Evolving Global Climate Regime. *Global Policy* **1**:1, 64-74. [CrossRef]
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