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A Portfolio of Carbon Management Options

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Continuation of current trends in fossil-fuel and land use is likely to lead to significant climate change, with important adverse consequences for both natural and human systems. This has led to the investigation of various options to reduce greenhouse gas emissions or otherwise diminish the impact of human activities on the climate system. Here, we review options that can contribute to managing this problem and discuss facors that could accelerate their development, deployment, and improvement.
development, deployment, and improvement.

There is no single option available now or apparent on the horizon that will allow stabilization of radiative forcing from greenhouse gases and other atmospheric constituents. A portfolio approach will be essential.

The portfolio contains two broad options:

- Reducing sources of carbon (or carbon equivalents) to the atmosphere (e.g., reduce dependence on fossil fuels, reduce energy demand, reduce releases of other radiatively active gases, limit deforestation)
- Increasing sinks of carbon (or carbon equivalents) from the atmosphere (e.g., augment carbon uptake by the land biosphere or the oceans over what would have occurred in the absence of active management)

A variety of options could make a significant contribution in the short term. These include: changing agricultural management practice to increase carbon storage and reduce non-CO_2 gas emission; improving appliances, lighting, motors, buildings, industrial processes, and vehicles; mitigating non-CO_2 greenhouse gas emissions from industry; reforestation; and geoengineering Earth's climate with stratospheric sulfate aerosols.

Longer-term options that could make a significant contribution include separating carbon from fossil fuels and storing it in geologic reservoirs or the ocean; developing large-scale solar and wind resources with long-distance electricity transmission and/or long-distance H2 distribution and storage; ceasing net deforestation; developing energy-efficient urban and transportation systems; developing highly efficient coal technologies (e.g., integrated gasifier combined cycle, or IGCC, discussed later in this chapter); generating electricity from biomass, possibly with carbon capture and sequestration; producing transportation fuels from biomass; reducing population growth; and developing next-generation nuclear fission.

As long as we continue to use fossil fuels, there are relatively few places to put the associated carbon.

- If CO_2 is put directly into the atmosphere, about one-third stays in the atmosphere, causing climate change. Another one-third currently goes to the biosphere, but this sink will eventually saturate, leaving CO_2 to accumulate in the atmosphere, where it can cause climate to change. The remaining one-third quickly enters the ocean (and most of the increased atmospheric burden will end up in the ocean on longer timescales). This movement causes significant acidification of the biologically active surface waters before mixing and diluting in the deep ocean on timescales of centuries.
- If CO_2 is put directly into the deep ocean (through deep injection), most of it will stay there without first producing a substantial acidification of biologically more active surface waters, but risks to deep ocean biota are not well understood.
- If CO_2 is put into deep (>1 km) geological formations (through geologic sequestration) it may be effectively sequestered, but there is uncertainty about the available geological storage capacity, about how much of the injected carbon dioxide will stay in place and for how long, and what ecological and other risks may be associated if and when reservoirs leak.
- If CO_2 could be mineralized to a solid form of carbonate (or dissolved forms in the ocean), it could be effectively sequestered on geological timescales, but currently we do not know how to mineralize carbon dioxide or accelerate natural mineral weathering reactions in a cost-effective way.

In the short run (<20 years), management of emissions of non-CO_2 greenhouse gases and black carbon may hold as much or more potential to limit radiative forcing than management of carbon dioxide. Continued management of these non-CO_2 greenhouse gases and particulates will remain essential in the long run.

Management strategies must be regionally adaptive since sources, sinks, energy alternatives, and other factors vary widely around the world. In industrializing and industrialized countries, the largest sources of CO_2 are from fossil fuel. In less-industrialized countries the largest sources involve land use.

Technologies and approaches for achieving stabilization will not arise automatically though market forces. Markets can effectively convert knowledge into working solutions, but scientists do not currently have the knowledge to efficiently and effectively

stabilize radiative forcing at acceptable levels. Dramatically larger investments in basic technology research, in understanding consequences of new energy systems, and in understanding ecosystem processes will be required to produce the needed knowledge. Such investments would enable creation of essential skills and experience with innovative pilot programs for technologies and options that could be developed, deployed, and improved to facilitate climate stabilization while maintaining robust economic growth.

A Portfolio of Options

The Importance of a Portfolio Approach

Stabilizing radiative forcing from greenhouse gases and other atmospheric constituents will require massive changes in the design and operation of the energy system, in the management of forests and agriculture, and in several other important human activities. No single technology or approach will be sufficient to accomplish these changes (Hoffert et al. 1998, 2002). Successful control of greenhouse gases will thus require the development of a portfolio of options, potentially including greater efficiency in the production and use of energy; expanded use of renewable energy technologies; technologies for removing carbon from hydrocarbon fuels and sequestering it away from the atmosphere; a mixture of changes in forestry, agricultural, and land use practices; a reduction in the emissions of the non-CO_2 greenhouse gases; and other approaches, some of which are currently very controversial, such as nuclear power and certain types of "geoengineering."

A failure to adopt a portfolio approach runs the risk of dramatically increasing the cost of controls and needlessly polarizing public discourse. Thus, for example, if the proponents of carbon capture and sequestration were incorrectly to suggest that these technologies could resolve all of the problems of limiting emissions, their claims would likely alienate members of the environmental community, who tend to be strong proponents of conservation and renewables, and might impede development of an understanding of this important option. At the same time, arguments that the entire problem could be solved by expanded use of conservation and renewables fail to recognize important technical, economic, and behavioral realities and could unnecessarily confuse the public debate.

Just as a mixed portfolio of solutions will be needed, so too a portfolio approach is needed in research and development. Not every nation need make substantial investments in every technology—indeed few, if any, can afford to do so. Across the world, however, it is essential that substantial investments be made in all promising technologies since there is considerable ambiguity about which ones will ultimately prove most useful, socially acceptable, and cost-effective. Indeed, because of the high diversity across the world's nations, peoples, and ecosystems, different mixes of options are likely to prove desirable in different locations.

It is important that experts remain cognizant of the considerable uncertainties that confront this field. It *is* incumbent upon the technical community to provide leadership to maintain a wide search for options. It would be a serious mistake if work on promising options were prematurely foreclosed by incomplete expert or public understanding or by short-term political or business agendas. Developing practical hands-on experience with many different technologies is essential. Equally important is the recognition that markets are good at commercializing existing intellectual capital, but they are generally not very good at making sustained investments in the basic research needed to develop this capital. Investments in basic technology and environmental research will be crucial for providing the intellectual capital that the world will need over the next century as it grows progressively more serious about addressing this problem.

Overview of the Portfolio

Carbon emissions (C) can be represented *as* the product of gross domestic product (GDP) and carbon emissions per unit GDP (C/GDP), that is, C = GDP x (C/GDP). The growth rate of GDP today is roughly 2.5 percent per year. Stabilizing CO_2 emissions in a world whose GDP increases 2-3 percent per year requires comparable or greater percentage reductions in C/GDP. Stabilizing CO_2 concentrations ultimately requires making deep long-term cuts in CO_2 emissions (Houghton et al. 2001).

C/GDP can be expressed as the product of the amount of CO_2 (or CO_2-equivalents) emitted per unit of energy consumed (C/E) and the amount of energy consumed per unit GDP (E/GDP), that is, (C/GDP) = (C/E) x (E/GDP). Reduction in C/E can be accomplished by using renewable fuels (solar, wind, biomass, etc.), using fossil fuels with carbon sequestration, reducing C-equivalent emissions of non-CO_2 greenhouse gases, or using nuclear power or potential future sources such *as* fusion power. Reduction in E/GDP can be accomplished by developing, for example, more efficient appliances, vehicles, buildings, and industrial processes (i.e., device efficiency), and by developing, for example, urban centers that lend themselves to more efficient transportation systems (i.e., systems efficiency).

Table 5.1 shows energy system and biophysical options categorized by how quickly a significant fraction of each option's total potential could be realized (columns) and by the potential magnitude of CO_2 mitigation or its radiative equivalent (rows). This table identifies many options that we can begin deploying now and that can make a significant contribution over the coming decades. Research and development undertaken now can produce the additional options needed to stabilize climate on a longer timescale. In Table 5.2 we indicate the readiness of various options for deployment, as well the magnitude of carbon emissions that could be mitigated by each option. Furthermore, we indicate our subjective appraisal of the relative size of the research and development budget that should be allocated to each option. We believe that highest allocations should go to the most promising options that are limited now by unresolved, but tractable, scientific or technological issues (e.g., energy distribution systems that can facilitate large-scale wind and solar power, improved energy production efficiency, and fossil-fuel carbon capture

Table 5.1. Categorization of mitigation options by timescale to achieve a significant proportion of possible reductions (columns) and by potential magnitude of CO_2 equivalent impact on radiative forcing (rows)

	Rapidly deployable[a]	*Not rapidly deployable*[b]
Minor contributor ≤3%	• Biomass co-fire in coal-fired power plants • Cogeneration (smallscale distributed) • Expanded use of natural gas combined cycle • Hydropower • Wind without storage (=10% of electric grid) • Niche options: wave and tidal, geothermal, smallscale solar	• Building-integrated photovoltaics • Forest management/ fire suppression • Ocean fertilization
Major contributor >3%	• Carbon storage in agricultural soils (no-till cultivation, cover crops) • Improved appliance, lighting, and motor efficiency • Improved buildings • Improved industrial processes • Improved vehicle efficiency • Non-CO_2 gas abatement from industrial sources including coal mines, landfills, pipelines • Non-CO_2 gas abatement from agriculture including soils, animal industry • Reforestation/land restoration • Stratospheric sulfate aerosol geoengineering	• Biomass to hydrogen or electricity possibly with carbon capture and sequestration • Biomass to transportation fuel • Cessation of net deforestation • Energy-efficient urban and transportation system design • Fossil-fuel carbon separation with geologic or ocean storage • Highly efficient coal technologies (e.g., IGCC) • Large-scale solar (with H_2, long-distance transmission, storage) • Next-generation nuclear fission • Reduced population growth • Wind (with H_2, long-distance transmission, storage) • Speculative technologies (direct atmospheric scrubbing, space solar, fusion, exotic geo-engineering, bioengineering)

Note: Minor contributors are capable of contributing <0.2 PgC y^{-1}; major contributors >0.2 PgC y^{-1}. The left column represents technologies that can achieve a significant fraction of their potential within a few decades. The right column represents technologies that could be available in the coming decades if research and development begin now.

[a] A significant fraction of option's potential could be achieved within a few decades.

[b] Unlikely to achieve a significant fraction of option's potential within a few decades.

Table 5.2. Magnitude of R&D needed driven by CO_2 mitigation needs

Options	*Magnitude of Potential contribution*	*Longevity of energy source*	*Economic efficiency*	*Technical readiness*	*Relative size of preferred R & D allocation*	*Comments*
Rapidly deployable, minor potential ≤ 3% (≤ 0.2 PgC y⁻¹) and ≤ 20 years						
Biomass co-fire in coal-fired power plants	•	•••	•••	•••	•	Conversion is straightforward
Cogeneration (small-scale distributed)	•	•••	•••	•••	•	Principle obstacles are regulatory
Expanded use of natural gas combined cycle	•	••	•••	•••	•	Economic considerations are already driving adoption of this option; attractiveness depends on price and availability of natural gas
Hydropower	•	•••	≥••	•••	•	Siting, relicensing, ecosystem disruption
Wind	•	•••	≥••	•••	••	Limits imposed by dispatch in power systems, resource availability
Niche options: wave and tidal, geothermal, small-scale solar	•	•••	≤••	•••	•	
Rapidly deployable, minor potential >3% (>0.2 PgC y⁻¹) and = 20 years						
Carbon storage in agricultural soils (no-till cultivation, cover crops)	••	•	•••	•••	•	Verification, incentives, research into persistence of stored carbon; can be driven by nonclimate considerations
Improved appliance, lighting, and motor efficiency	••	••	•••	•••	••	Many possibilities, principal issue is incentives and public communication; can be driven by nonclimate considerations
Improved buildings	••	••	•••	•••	••	Zoning, codes, and construction practice are important, higher capital requirements can be driven by nonclimate considerations
Improved industrial processes	••	•••	≤•••	•••	••	Many possibilities, principal issue is incentives; can be driven by nonclimate considerations
Improved vehicle efficiency	••	••	≤•••	•••	••	Regulatory environment more important than technology; can be driven by nonclimate considerations
Non-CO_2 gas abatement from industrial sources including coal mines, landfills, pipelines	••	•	•••	•••	•	Principal issues are regulation, cost, and incentives
Non-CO_2 gas abatement from agriculture including soils, animal industry	••	•	•••	•••	•	Verification; Research on nitrogen cycling
Reforestation/land restoration	••	•	•••	•	•	Verification; land competition; win-win possibilities
Stratospheric sulfate aerosol geoengineering	•••	•••	•••	•	•	Issues of public acceptance, international law and unintended consequences

(continued)

Table 5.2. *(continued)*

Options	*Magnitude of Potential contribution*	*Longevity of energy source*	*Economic efficiency*	*Technical readiness*	*Relative size of preferred R & D allocation*	*Comments*
Not rapidly deployable, minor potential = 3% (= 0.2 PgC y⁻¹) and >20 years						
Building-integrated photovoltaics	•	•••	••	••	••	Primary research issue is system cost reduction
Forest management/fire suppression	•	•	•••	•••	•	Win-win possibilities, but potential ecological costs, enhanced long-term fire vulnerability, questions about long-term effectiveness
Ocean fertilization	•	••		•	•	Issues include public acceptance, verification, efficacy, and unintended consequences
Not rapidly deployable, minor potential > 3% (> 0.2 PgC y⁻¹) and >20 years						
Biomass to hydrogen or electricity possibly with carbon capture and sequestration	••	•••	•••	••	••	Large land requirements with potential landscape and ecological consequences; potential for negative net emissions
Cessation or possible reversal of net deforestation	••	••	•••	•••	•	Social/economic/political factors are limiting
Energy-efficient urban and transportation system design	••	••	≤•••	•••	•	Social/economic/political factors are limiting
Fossil-fuel carbon separation and transport with geologic or ocean storage	••	••	••	••	•••	Unintended consequences, leakage, public acceptance; development of cost-effective H_2 use technologies
Highly efficient coal technologies (e.g., IGCC)	••	••	••	••	•••	Need process improvements and cost reduction
Large-scale solar (with H_2, long-distance transmission, storage)	••	•••	•	•	•••	Principal research costs in low-cost cell design, energy storage, transport
Next-generation nuclear fission	••	•••	••	••	••	Principally limited by public acceptance
Reduced population growth	••	•••	•••	•••	•	Social/economic/political factors are limiting
Wind (with H_2, long-distance transmission, storage)	••	•••	••	•	•••	Principal research costs in storage and transmission not in turbine design
Speculative technologies (direct atmospheric scrubbing, space solar, fusion, exotic geoengineering, bioengineering)	•••	•••	?	•	•	

Note: Many important options have relatively low R&D needs. Description of symbols: Magnitude of potential: • = could be a minor contributor (≤ 0.2 PgC y^{-1}), •• = could be a major contributor (> 0.2 PgC y^{-1}) but inadequate to be entire solution, ••• = could be entire solution (i.e., contribute > 20 PgC y^{-1}). Longevity: • = most of potential could be exhausted this century, •• = most of potential could be exhausted over this millennium, ••• = could be sustained for many millennia. Economic efficiency as measured by cost per ton C avoided as measured against current mix of energy production: • = ≥ US$150, •• = between US$50 and US$150, ••• = < US$50 and in a few cases negative. Readiness: • = not ready, •• = ready after additional R&D, ••• = ready. R&D needs: • = modest, •• = significant, ••• = major.

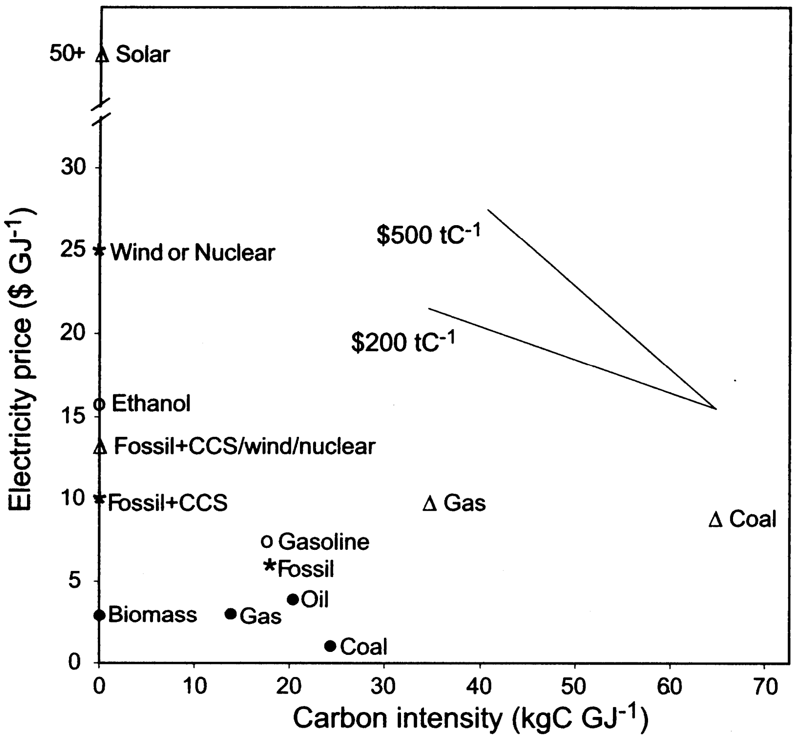

Figure 5.1. Cost of electricity presented *as* function of CO_2 emissions per unit energy produced. Lower carbon emission technologies are generally more expensive. Costs per ton of carbon avoided can be estimated from the slope of the line connecting the initial electricity generation technology to the lower carbon emission technology (redrawn from Keith and Morgan 2002). Symbols: • = primary energy, o = Liquid transportation fuel, A = electricity, * = hydrogen. CCS refers to carbon capture and storage.

and storage). Figure 5.1 illustrates estimated carbon emission avoidance costs associated with moving to lower-carbon-emissions energy systems.

In the following sections, we review opportunities to reduce energy demand, to improve energy production efficiency, to develop renewable energy sources, to capture and sequester carbon, to reduce the emissions of non-CO_2 greenhouse gases, and to mitigate climate change using fission power, geoengineering, and other options.

Demand Reduction (Conservation, Efficiency)

Energy demand can be reduced in several ways. New technology can provide the same services with lower energy inputs than were previously required (e.g., higher-mileage

automobiles, light-emitting diodes). Social preferences and industrial needs can change so that less energy *is* required to perform the mix of desired functions (e.g., reduced meat and greater vegetable content in diets, reduced use of energy-intensive transport and travel). While the population of the world *as* a whole will continue to grow in the coming decades, populations in some parts of the world have stabilized or even begun to shrink. Reduced rates of population growth result in fewer persons who must be served with a given level of energy, although the essential need for economic development in much of the world will continue to result in growing energy demand, even if the energy efficiency of these societies can be significantly increased.

There is considerable potential for progress in demand reduction. While new technology is often a necessary ingredient, regulation, pricing, tax policy, social norms, and other factors can be equally or more important.

Efficiency improvements can reduce energy demand by -1 percent per year through this century (Lightfoot and Green 2002). Thus, efficiency improvements could reduce energy demand by some few tens of percent on the timescale of several decades and could more than halve energy demand by century's end. A more extensive discussion of these options can be found in Metz et al. (2001).

Renewables and Noncarbon Energy Sources

Renewable energy sources produced by direct solar capture (photovoltaics), wind, hydro, and biomass are all forms of solar energy. Hence, all sources face a finite upper limit of available energy (Metz et al. 2001; Lightfoot and Green 2002), based on net flux density (e.g., average radiation at the ground of -200 watts per square meter [W

BIOMASS ENERGY

Biomass production is limited by the photosynthetic efficiency of conversion of solar energy, which on a canopy scale is capped at about 2-3 percent during the growing season. One must consider the phenology of the plant system, which may leave the landscape bare or sparse a considerable portion of the year, reducing annual mean photosynthetic conversion efficiency (Baldocchi and Valentini, Chapter 15, this volume). Additional energy inputs may be required for cultivation and for fertilizers in order to prevent soil degradation. Land availability is limited by competition with other needs. Furthermore, a significant portion of the terrestrial biosphere is nonarable, where scarce imported water would be needed to produce biomass.

HYDROPOWER

Hydropower produces CO_2-free energy, but this option is suitable only in selected watersheds. There are environmental costs associated with the disruption of ecosystems, fisheries, and landscapes, and silting leads to a finite reservoir life (e.g., Aswan Dam in Egypt). Moreover, when dams are situated in remote locations, there are energy transmission losses. In many industrialized countries, potential hydropower resources are already largely exploited.

WIND

All locations are not suitable for producing wind power. Wind power is a function of wind speed cubed (kinetic energy increases with wind speed squared and that energy is transported to the wind turbine at the wind speed). Best sites are near seashores (e.g., Denmark), high-wind areas in continental interiors (e.g., North Dakota), or hilltops (e.g., Altamont Pass, California). The jet stream, with energy fluxes of >10 kilowatts (kW) M^{-2}, represents a high-density resource, but one that is difficult to harvest. In isolated regions transmission losses reduce efficiencies. For many sites public acceptance is an important barrier (e.g., offshore in Cape Cod and the North Sea). Intermittency limits wind power, in the absence of energy storage and long-distance transmission technologies, to -10 percent of base load power. Wind power can potentially provide a greater fraction of total power if coupled with improved energy storage and transmission systems (e.g., hydrogen, superconducting long-distance electricity transmission). At very large scale, wind energy could begin to extract a significant portion of kinetic energy from the boundary layer and thus potentially have adverse environmental consequences.

SOLAR

Photovoltaics are increasing in efficiency, but to contribute significantly to climate stabilization, this technology must be implemented cost-effectively on a large scale. The most efficient photovoltaics from a physics perspective may not be the most efficient economically, as high-efficiency photovoltaics are expensive (Hoffert et al. 2002). Moreover, not all regions are sunny. The use of exotic materials may also be an eventual barrier to large-scale solar voltaic implementation. Because of the intermittency of solar power (and the day-night cycle), solar can only supply a major fraction of base load power if it is combined with a means of energy storage and effective transmission.

Greenhouse Gas Capture and Sequestration

LOW-CARBON USE OF FOSSIL FUEL

Hydrocarbon fuels contain both hydrogen and carbon. Today most hydrogen is made for industrial purposes by extracting it from natural gas. If a similar separation is performed on coal, and the CO_2 is not released to the atmosphere, the world's abundant supplies of coal could be used as a climate-neutral source of energy for many decades. This practice could buy time to develop new technologies that are completely independent of fossil fuels.

Carbon can be removed from coal or other fossil fuels either before, during, or after

combustion (Herzog and Drake 1996; Freund and Ormerod 1997; Metz et al. 2001). The technology for removing carbon after combustion is more developed but is likely to be less economically attractive in the long run. Although the components of carbon capture and sequestration systems exist today at commercial scale, much additional research, development, and deployment will be required both to bring the costs down and to gain essential experience.

Four different technologies have been proposed to separate CO_2 after combustion: solvent absorption, adsorption on a solid, membrane separation, and cryogenic separation. All four of these technologies are under development. The use of amine *as a* solvent for absorption of CO_2 from flue gases and its separation through steam reforming is the most mature of these technologies. Amine scrubbing *is* currently used for producing CO_2 for soft drinks, in scrubbing CO_2 from air on nuclear submarines, and in many other industrial applications including CO_2 removal from natural gas in the Norwegian Sleipner field.

Scientists are exploring various approaches to increase the concentration of CO_2 in combustion gases, and thus improve the ease with which the CO_2 can be separated. One approach is to combust the fuel in relatively pure oxygen; another idea involves combusting methane in pure oxygen and using the resulting CO_2 to drive a turbine, resulting in virtually pure CO_2 streams suitable for storage. The combustion temperatures would be far higher than techniques in use today and would pose a challenge to materials science.

Carbon can also be removed either before or during combustion. In this case, there are two basic methods for carbon capture and removal. The first involves carbon separation from the fossil energy source before combustion. For example, one technology already in a relatively mature state of development *is* steam reforming of methane (natural gas) followed by a shift reaction that results in a mixture of CO_2 and H_2. After separation, the CO_2 could be stored, while the H_2 could be used as a very clean energy carrier for electricity production in gas turbines, in fuel cells, for heat production, or in chemical uses. The main challenge is cost reduction.

The second option for CO_2 separation and capture before combustion involves coal gasification by partial oxidation to make "syngas" (mainly CO and H_2) for combined-cycle turbines. Such schemes for electricity production from coal are called integrated gasifier combined cycle (IGCC) plants and have relatively low air pollutant emissions. Today power from IGCC cogeneration plants can often be competitive with power from coal steam-electric plants with stringent air pollution controls.

IGCC technology is one example of a set of technologies that can increase the efficiency with which fossil fuel can be converted to usable energy. IGCC and more conventional technologies, such as combined cycle natural gas, achieve improved efficiency by operating at a much higher temperature, thus increasing the thermodynamic efficiency of the process. There are other ways to increase energy conversion efficiency. For example, distributed small-scale electric power generation technology is much more effi-

Table 5.3. Estimates of storage capacity of geologic reservoirs

Carbon storage reservoir	*Capacity (PgC)*
Basalt formations*	>100
Deep saline reservoirs	87-2,727
Depleted gas reservoirs	136-300
Depleted oil reservoirs	41-91
Unminable coal seams	> 20

*Estimate for Columbia River basalt only.

Sources: Herzog et al. (1997), Freund and Ormerod (1997), McGrail et al. (2002).

cient than conventional central generation technology, because in addition to generating electricity, these technologies also supply heat for space conditioning in the buildings in which they are located. Similarly, advanced engine technologies and vehicle design can achieve dramatic improvements in the efficacy with which automobiles convert fuel into kilometers traveled. Together, options for increased conversion efficiency could make major contributions to reducing greenhouse gas emissions in both the short and long term and have the additional advantage of limiting air pollution and other undesirable consequences from fossil-fuel use.

Although they are often not included in discussions of advanced coal technology and of carbon capture and separation, it is important to remember that coal mining, processing, and transport have major land-use and adverse environmental consequences that will continue to grow as the use of coal expands. A full accounting of these and other technologies' costs should be factored into evaluations of different options.

INJECTION OF CARBON DIOXIDE INTO DEEP GEOLOGICAL FORMATIONS

Once carbon dioxide has been separated from fossil fuel, it must be sequestered away from the atmosphere. On land it can be injected into a variety of deep (>1 km) geological formations. Candidates include injection into spent gas fields, injection into depleted oil fields to stimulate additional (secondary) recovery, injection into deep briny aquifers, and injection into coal beds that are too deep for economic production. Table 5.3 provides a very preliminary estimate of reservoirs capacities.

In some parts of the world, large-volume deep injection of fluids already occurs. For example, the United States already injects a mass of fluids into geologic reservoirs larger than the mass of all CO_2 produced by U.S. power plants (Wilson and Keith 2002). These fluids are principally wastewaters from municipalities and oil and gas operations (and, to a lesser extent, CO_2 for secondary oil recovery).

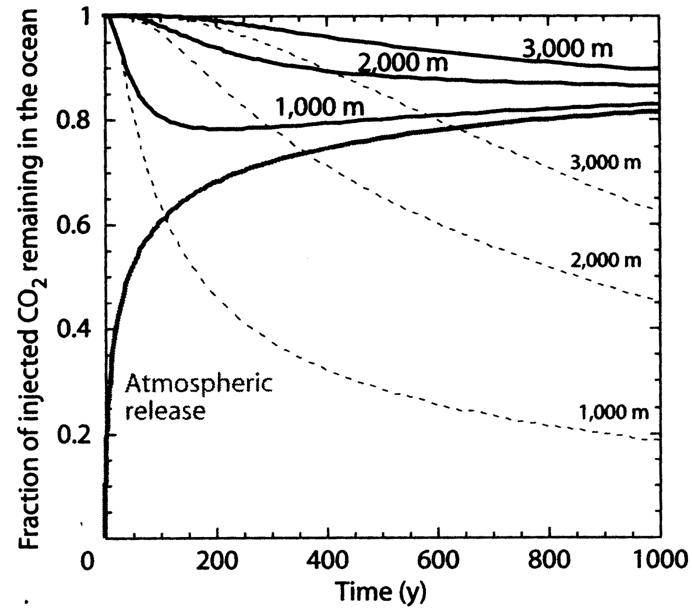

Figure 5.2. Representation of model results for direct injection of carbon into the ocean at three depths under two different boundary conditions (Caldeira et al. 2001). The solid lines represent the fraction of carbon that would be found in the ocean at any time after an initial injection at 1,000 m, 2,000 m, or 3,000 m depth. Most of the CO_2 added to the ocean through direct injection will remain in the ocean essentially forever. The dashed lines show all the carbon leaking out of the ocean on the timescale of several hundred years. This subtracts from the amounts shown in the solid lines the CO_2 that has leaked to the atmosphere but was then reabsorbed by the ocean. The solid lines represent the amount of carbon found in the ocean, but the dashed lines show the amount of CO_2 storage credited to ocean sequestration

We currently have a very limited understanding of how to accurately characterize and license geological reservoirs for CO_2, monitor possible leakage of CO_2 from reservoirs, and assess and deal with potential ecological and other risks (Wilson and Keith 2002).

DIRECT OCEANIC INJECTION OP CARBON DIOXIDE

The ocean is the principal sink for absorbing CO_2 from the atmosphere. This capacity arises from the alkalinity of seawater and the reaction of CO_2 with dissolved carbonate to form bicarbonate in the ocean waters. The ocean surface waters now absorb -25 million tons of CO_2 per day. The ocean will eventually absorb up to 85 percent of all atmospheric fossil-fuel CO_2.

Most of the CO_2 added to the ocean through direct injection will remain in the ocean over geological time periods. An important issue is how to credit ocean sequestration for carbon in the ocean, taking into account the fact that most of the CO_2 released to the atmosphere would have entered the ocean on this timescale anyway (Figure 5.2).

Total fossil fuel CO_2 emissions to the atmosphere today are -6 petagrams of carbon (PgC) y^{-1}, of which -2 PgC y^{-1} enter the ocean. If we were to permit atmospheric CO_2 levels to rise to - 600 parts per million (ppm), then surface ocean waters would experience an acidification of -0.3 pH units. If all ocean waters were to experience -0.3 pH reduction, then the quantity of CO_2 absorbed would be -1,800 PgC.[1] Thus stabilization at an atmospheric pCO_2 of -600 ppm would commit us to -1,800 PgC of ocean carbon storage.

The ultimate capacity of the ocean is large, and direct injection of CO_2 into deep (-3,000 m) ocean waters (bypassing the atmospheric step with its attendant global warming) would in theory be possible in very large quantities (Herzog et al. 2001). Technological capability for this already exists, making it a high-capacity and quickly available option. Possibilities exist for making ocean sequestration more permanent and reducing pH consequences using the dissolution of carbonate minerals; furthermore, it may be possible to use carbonate neutralization as a flue gas separation process with long-term ocean storage (Kheshgi 1995; Caldeira and Rau 2000).

Significant barriers remain, however: There are a limited number of power plants close to deep ocean waters; public acceptance may not be forthcoming; the London Convention could prohibit this option; and the impact of increased CO_2 on deep-sea ecosystems is poorly understood. Research to investigate the potential and risks of ocean storage options is an important priority.

ACCELERATED CHEMICAL WEATHERING

A basic approach to neutralizing carbon acidity is to dissolve carbonate or silicate minerals. Accelerated weathering of carbonate minerals could be used to store carbon in the ocean for tens of thousands of years (Kheshgi 1995; Caldeira and Rau 2000). Like deep ocean injection, this approach raises legal, social, and environmental issues associated with the use of the oceans as a disposal site. In contrast, accelerated weathering of silicate minerals could potentially lead to carbon storage as a solid carbonate mineral (Lackner 2002). The process is exothermic, but the kinetics are very slow. Thus, the potential for accelerated weathering to make a difference in the next 50 years must be regarded as speculative.

Potential for Abating Non-CO_2 Greenhouse Gas Sources

Non-CO_2 greenhouse gases and black carbon are responsible for about 45 percent of total anthropogenic radiative forcing (Houghton et al. 2001), a magnitude that provides substantial opportunities for abatement. These gases include CH_4, N_20, tropospheric O_3, and halocarbons (Prinn, Chapter 9, and Robertson, Chapter 29, both this volume).

The total anthropogenic flux of CH_4 is 344 Tg CH_4 y^{-1}, equivalent to 2.1 PgC_{equiv} y^{-1} (based on a 100-year GWP time horizon). About half of this flux (1.1 PgC_{equiv}) is of agricultural origin; the remainder is from energy extraction and production, industrial combustion, and landfills (Houghton et al. 2001; Robertson, Chapter 29, Table 29.3). There are multiple options for reducing the total CH_4 flux; for example, industrial sources including landfills have declined in the United States by 7 percent since 1990 largely owing to the economic value of methane recovery. If these efficiencies were applied more broadly, we might expect to achieve a 10 percent global flux reduction in the next 20 years and a 25 percent reduction in the years following.

The large agricultural CH_4 flux is mainly from enteric fermentation, rice cultivation, biomass burning, and livestock waste treatment. Current technology is available to abate 10-30 percent of emissions from confined animals via nutritional supplements, *as* is now common in U.S. feedlots and dairies. With adoption of best management practices, methane in rice can be reduced substantially; recent results suggest a potential for 50-80 percent abatement based on irrigation management and management for high yields (Robertson, Chapter 29). Likewise, technology is available now to abate most CH_4 from animal waste by storing waste in lagoons and generating power from the captured methane; such use has a net negative carbon cost. Modest abatement of these fluxes in the next 20 years and in some cases more aggressive abatement afterward, together with industrial savings, could generate a total abatement of 75 PgC_{equiv} over 100 years.

N_2O fluxes can also be mitigated. The total anthropogenic flux of N_2O is 8.1 TgN_2O-N y^{-1}, equivalent to 1.0 PgC $_{equiv}$ y^{-1}. More than 80 percent of this flux (0.9 PgC_{equiv}) is from agriculture; most of the rest is from the industrial production of adipic and nitric acids and combustion. Agricultural soils emit annually about half of the entire anthropogenic flux; waste handling in feedlots and dairies generates about 25 percent of the flux, and biomass burning and industry generates the remainder (Table 5.4).

Technology is now available to abate most of the industrial sources of N_2O, and N_20 from waste handling could be largely comitigated with CH_4 waste management abatement (as described above). Agricultural soils are more problematic; soils emit N_2O largely as a function of available soil N, and although it is easy to reduce soil N, it is difficult to do so without affecting yields. Better nitrogen placement and timing could reduce current fertilizer needs and therefore N_2O flux by perhaps 20 percent using today's technology, which is the basis for our 20-year abatement estimate (Table 5.4); further mitigation using site-specific farming technologies, varietal improvements for plant nitrogen-use efficiency, and new forms of fertilizer and nitrification inhibitors could lead to 80 percent mitigation in 20-50 years. If so, total 100-year N_2O abatement could reach 75 PgC $_{equiv}$.

Other non-CO_2 greenhouse gases, notably the halocarbons, the ozone precursors CO and NO_R, and black carbon, are also abatable. Although GWPs for the ozone precursors are at present uncertain and for black carbon unknown, best estimates suggest

Table 5.4. Potential for non-CO_2 greenhouse gas abatement and biosphere carbon storage

Gas/source	*Current flux strength ($TgC_{eg}y^{-1}$)*	*Feasible abatement rate ($TgC_{eq}\,y^{-1}$)*			*Total abatement (PgC eq/100y)*
		0-20 y	*20-100 y*	*>100 y*	
CH_4					
Industry including landfills	1,016	100	250	250	22
Agriculture					
Enteric fermentation	590	60	300	300	25
Rice cultivation	251	160	160	160	16
Biomass burning	213	20	50	50	4
Animal waste treatment	88	75	75	75	8
Total agricultural CH_4	1,142				53
Total anthropogenic CH_4	2,158				75
N_2O					
Industry, transport	165	80	130	130	12
Agriculture					
Soils	533	100	425	425	36
Animal waste treatment	266	200	250	250	24
Biomass burning	63	6	30	30	3
Total agricultural N_20	862	306	705	705	63
Total anthropogenic N_20	1,027	386	835	835	75
Other					
Halocarbons	98	10	75	90	6
Ozone precursors (CO, NO_x)	1650	150	750	1500	63
Black carbon	nd				nd
Total other gases	1748	160	825	590	69
Biosphere carbon storage					
I Agricultural soils	0	300	500	0	46
Reforestation/agroforestry					
Improved management	0	170	150	0	15
Agroforestry + afforestation	0	200	100	0	12
Cessation of deforestation	0	100	200	0	18
Total forestry		470	450	0	45
Total biosphere C storage		770	950	0	91

Note: Current flux strengths are based on Houghton et al. (2001) and other sources (see Prinn, Chapter 9; Smith, Chapter 28; and Robertson, Chapter 29; all this volume). nd = currently not determinable because of GWP uncertainty.

a total source strength >1.6 PgC_q y^1, of similar importance to CH_4 and N_20 (Prinn, Chapter 9, this volume). Mitigation potentials appear to be of a similar magnitude.

Biological Sinks and Source Reduction

FOREST MANAGEMENT AND OTHER ACTIVITIES IN THE BIOSPHERE

Forests cover 42 x 10^{12} m^2 globally (Sabine et al., Chapter 2, this volume); some 21 percent (-7 x 10^{12} m^2) can be considered managed in some direct manner. Forest carbon storage can be achieved by three principal means: (1) improve the management of currently forested areas, (2) expand the area currently forested via afforestation and agroforestry, and (3) reduce the rate of deforestation. All of these measures aim to adapt management to alter the balance between carbon fluxes into the system (photosynthesis) and fluxes out (plant and soil respiration and harvest), resulting in increased carbon stocks or avoided emissions.

Potential forest sequestration approaches 1 PgC y^{-1} (Watson et al. 2000); more realistic estimates of achievable sequestration are on the order of 0.17 PgC y^{-1} from improved management of existing forests and 0.2 PgC y^{-1} from establishment of new forests on formerly wooded and degraded lands (Watson et al. 2000). Financial costs are modest to high in Annex I countries (US$3 to $120 per ton C) and often small elsewhere (US$0.2 to $29 per ton C). Management measures to improve carbon storage in forestry include prolonging rotations, changing tree species, continuous-cover forestry, fire control, combined water storage with peat swamp afforestations, fertilization, thinning regimes, and mixed species rotations, among others. At some point management improvements will saturate forest carbon sinks; after 100 years of improved management, it is unlikely that any further net storage will occur.

Cessation of deforestation is another major means for improving biosphere carbon storage in forests. Complete cessation of the current 1.8 PgC y^{-1} is unrealistic for a variety of reasons but nevertheless offers the single largest potential for forest carbon sequestration. Tropical forests and peatlands are at particular risk. With respect to peatlands, it is important to ensure that water tables are maintained so that C continues to be sequestered, especially in the face of global warming at high latitudes.

Although reversing deforestation is a laudable goal, it will be difficult to implement, govern, or reinforce without tangible socioeconomic incentives. Verification also poses difficulties. Over the next 20 years we estimate that with proper incentives 0.1 PgC y^{-1} could be saved from deforestation, and twice this amount in the period afterward. Once the biosphere is essentially deforested, of course, this potential savings becomes nil.

Despite large attention for carbon storage measures in the political discussions before and after the Conference of the Parties in Kyoto, only a limited number of example projects are underway. Together they affect only some tens of millions of hectares. There are a number of reasons for this: (1) the biosphere inherently shows a large natural dynamic, thus creating uncertainty and risk; (2) political discussions have been lengthy and outcomes uncertain; (3) biospheric sinks will eventually saturate in the future; (4) many other aims for land management exist (food, fiber, biodiversity, water storage), and all these aims have to be met in an integrated way; and (5) a verification infrastructure must be created and maintained.

AGRICULTURAL CARBON CAPTURE IN SOILS

Some 40-90 PgC has been lost in agricultural soils since the onset of cultivation. Recapturing some portion of this carbon forms the basis for the soil carbon sequestration sink. The most optimistic estimates of soil carbon sequestration place potential rates of net carbon capture at 0.9 PgC y^{-1}, which would restore most of the lost carbon within 50-100 years; more measured estimates place the potential at 0.3-0.5 PgC y^{-1} (Smith, Chapter 28, this volume).

Soil carbon can be built through a variety of agronomic techniques, usually based on increasing plant carbon inputs, slowing soil carbon decomposition rates, or (more commonly) both. Carbon inputs can be enhanced by growing more high-biomass crops, by leaving more crop biomass to decompose in situ, by increasing belowground net primary production (NPP), and by growing cover crops during portions of the year that the soil would otherwise remain fallow. Decomposition rates can be slowed by reduceing tillage and by growing crops with low residue quality—that is, containing organic carbon that is less susceptible to microbial attack.

If financial incentives were sufficient, agronomic management for carbon storage could lead to the sequestration of 0.3 PgC y^{-1} within the first 20 years of adoption and on average 0.5 PgC y^{-1} for the following 80 years, providing a 100-year total of 46 PgC mitigation. After this period the soil sink will be essentially saturated and sequestration rates will be nil (Table 5.4).

IRON FERTILIZATION OF THE OCEAN

Sinking organic matter transports carbon from the near-surface ocean to the deep ocean. It has been suggested that the addition of trace nutrients such as iron could enhance this sinking flux and thus act *as* a way to store additional carbon in the deep ocean, where it is relatively isolated from the atmosphere. Field experiments of iron addition to the ocean have yielded convincing evidence (e.g., Coale et al. 1998) that productivity can increase several fold within weeks, and there is some evidence that export of organic matter from the surface ocean increases after both experimental and natural iron additions (Bishop et al. 2002). Theory and experimental evidence suggest, however, that most of the exported carbon will return to the surface layers within decades.

It has been suggested that iron fertilization could represent an inexpensive carbon storage option; however, widely discussed cost estimates are questionable as they typically have been based on implausible assumptions including that exported carbon has high C/Fe ratios, that all of the added organic carbon exported from the euphotic zone

is balanced by a corresponding CO_2 influx from the atmosphere, and that CO_2 taken up by the ocean through iron fertilization remains there for a long time. Model simulations involving extreme assumptions (e.g., complete phosphate utilization south of 31°S) indicate maximum sustained carbon uptake rates of < 1 PgC y^{-1} Realizable sequestration potential is likely to be much less.

Advanced Noncarbon Technologies

Advanced noncarbon technologies, such *as* nuclear fission or fusion, space solar power, and geoengineering, could potentially play an important role in dimate stabilization. Several of these technologies are controversial, in early stages of development, or both. Until an option can be shown not to be viable, however, we should work to understand the option's potential benefits and drawbacks.

NUCLEAR FISSION

Nuclear fission is an existing technology that could help stabilize dimate. In some countries (e.g., France) nuclear power generates a substantial fraction of electricity, thus displacing CO_2 emissions that might otherwise occur. Fission involves generating electricity by splitting heavy atomic nuclei, most commonly U^{235}, into lighter atomic nuclei. Present nuclear reactor technology provides CO_2-free electricity while posing unresolved problems of waste disposal and nuclear weapons proliferation. The supply of fissile material, which depends on price, *can* be extended greatly through the use of breeder reactors; however, such reactors could greatly exacerbate nuclear weapons proliferation. Fission can potentially play a large role in providing carbon-free energy, if the issues of safety, waste disposal, weapons proliferation, resource availability, and public acceptance can be adequately addressed.

NUCLEAR FUSION

Fusion involves generating electricity through the joining or fusing of light atomic nuclei to form heavier atomic nuclei. Fusion power holds the promise of a nearly inexhaustible source of climate-neutral energy It is unlikely, however, that fusion power will be commercially available in the time frame needed to stabilize climate (Hoffert et al. 2002), although it may play a role in maintaining climate stability in future centuries.

SPACE SOLAR POWER

Solar power satellites could be constructed to generate power in Earth orbit or on the moon and beam that power to the Earth (Hoffert et al. 2002). Advantages of the space environment include higher and more consistent solar fluxes (avoidance of clouds, day-night cycle, etc.). Currently, however, launch costs make this approach uneconomical. In general, space power options require very large scales before economies of scale can be realized. Furthermore, there are environmental and public health concerns.

Public resistance to beaming energy through the atmosphere to Earth's surface is likely. Space power will probably not be economically feasible during this century.

GEOENGINEERING

It has been suggested that climate change induced by anthropogenic CO_2 could be cost-effectively counteracted with geoengineering schemes designed to diminish the solar radiation incident on, or absorbed by, Earth's surface. Several schemes have been proposed; these schemes typically involve placing reflectors or other light scatterers in the stratosphere or in orbit between the Earth and Sun, diminishing the amount of solar radiation incident on the Earth (Keith 2000; Govindasamy and Caldeira 2000). Less exotic, biosphere-based geoengineering approaches are possible, although they may be impractical or expensive or have other undesirable consequences. For example, the albedo of large-scale forests could be increased through selective logging. Changing C4 grasses to C_3 grasses could partition more available energy into latent heat rather than sensible heat, thus cooling the planetary surface.

There are serious ethical, environmental, legal, technical, and political concerns associated with intentional climate modification. For example, political tensions could be heightened if countries were to undertake geoengineering efforts without first obtaining international consensus. It has been suggested that geoengineering should be researched as an emergency backup strategy in case we needed to head off a truly threatening climate change catastrophe (e.g., runaway methane hydrate degassing [see Gruber et al., Chapter 3, this volume]). Any geoengineering scheme is likely to have negative consequences, which would need to be carefully studied before any serious consideration of deployment.

Cross-Cutting Issues

The Role of Uncertainty

Although we have tried in the preceding discussion to provide some rough quantification of the potential magnitude of the contribution that may be achieved through various management options, as well as the timescale on which it may be possible to achieve these contributions, it is important to recognize that there is great uncertainty about both the cost and the efficacy of many options. We do not view these uncertainties *as* a basis for delay or inaction (Caldeira et al. 2003). The evidence of a growing problem *is* sufficiently compelling that action is clearly needed today. Economic, business, and ecological theory suggests that when faced with large uncertainty, the best option is to invest in a broad portfolio that creates a diversity of future options.

Our ability to project population, per capita GDP, political and social revolutions, and so on, is quite limited (Nakicenovic and Swart 2000). For example, the widely used IS92a scenario of the Intergovernmental Panel on Climate Change (IPCC) was technologically overoptimistic but failed to anticipate reduced CO_2 emissions associated with the end of the Soviet Union; thus the IS92a scenario overestimated year 2000 CO2 releases. Experts meeting a century ago could not have anticipated developments like world wars, jet travel, nuclear power (and its rejection in many places), the computer, and the Internet. We assume we are in an equally disadvantageous position regarding the prediction of technical, social, and political innovation likely to occur this century.

The Essential Role of Research

In contrast to other important industrial sectors, such *as* microelectronics and pharmaceuticals, which invest 10 percent or more of gross revenues in research, the energy sector has long had among the lowest research and development (R&D) investments of any major industrial sector.[2] Although concern about the need to deal with the problem of climate change has begun to spark modest increases in private and public research investment, the magnitude of those investments remains dramatically low given the magnitude of the challenge the world faces.

One of the issues that has been consistently lacking in the national and international discourse on greenhouse gas (GHG) policy has been a focus on finding ways to divert a modest portion of the large monetary flows that will be involved in any serious management program into investments into research, development, and demonstration.

Enabling Technologies

As shown in some of the comments in the right column of Table 5.2, a number of technologies, although not direct options for managing radiative forcing, will be essential for implementing some of the options we have identified. For example, if cost-effective carbon-free strategies for producing hydrogen fuel can be developed, then cost-effective strategies for compact hydrogen storage and conversion (e.g., fuel cells) become important. Similarly, energy storage technologies and/or highly efficient long-distance transmission of electric power (e.g., by superconducting cables) will be critical to making large-scale use of wind or photovoltaics a practical reality.

Barriers to Implementation

Engineers frequently adopt the view that "if we build it (so that it is cheap and effective) they will come." The reality is that large-scale technology adoption and diffusion are often much more complicated and uncertain. Even when there are no major barriers to adoption, it may take several decades or more for a new technology to become widely used because old capital stock remains economically attractive and personnel are slow to understand and appreciate the benefits of new technology. Beyond this, in many cases large vested interests have a stake in sustaining old technologies. These interests often work actively to impede the introduction of new competing technologies. Frequently regulatory or similar barriers inhibit introduction. For example, in many countries electric utilities are granted exclusive service territories, making it illegal for a private entrepreneurial company to introduce microgrid systems built on small-scale combined heat and power distributed generation (which is more energy efficient than central station power). At the same time, traditional utility companies may see little or no incentive to invest in such technology.

Social acceptability can also play an important role in the rate at which a new technology is adopted. As already noted, social concerns are often not founded on a full understanding of a technology, its strengths and weaknesses, and those of available alternatives. In such cases the professional community has an obligation to provide leadership and keep important options open for development and evaluation. But technology proponents also have a long history of arrogantly ignoring legitimate public concerns, consequently fostering a climate of mistrust and hostility that makes rational public decision making difficult or impossible.

Ancillary Benefits of CO_2 Stabilization Technologies

Probably the single greatest motivation for adopting a new technology is direct cost: If it is cheaper than existing technologies it is adopted quickly. Externalities rarely figure into private sector motivations unless encouraged with government incentives or regulatory structures. Nevertheless, a number of mitigation options have ancillary benefits that can substantially multiply their value to GHG mitigation per se.

Biosphere sequestration of carbon and mitigation of non-CO_2 fluxes are two areas that can have substantial societal value beyond GHG mitigation. Organic carbon sequestered in soil contributes to soil and hence ecosystem health, with benefits for soil and water conservation, nutrient storage, porosity, invertebrate biodiversity, plant health, and ground and surface water quality. Carbon sequestered in reestablished and regrowing forests has similar benefits for forested watersheds, in addition to abetting plant and animal biodiversity. Thus, organic carbon storage has important practical implications for drinking water quality, coastal fisheries, farmland quality, and flood protection.

Reducing the emission of non-CO_2 greenhouse gases also provides ancillary benefits. N_20 suppression through the better management of nitrogen in cropping systems will help to keep exogenous nitrogen from environmental fates other than crop yields (e.g., air pollution). At present the amount of nitrogen fixed by anthropogenic means is close to that fixed biologically; because less than half of the fertilizer applied to cropping systems is taken up by the crop and the remainder is available to cause significant environmental harm. Likewise CH_4 capture from waste handling can provide energy savings for individual farms and perhaps rural communities, and composted waste applied to soils can substitute for synthetic fertilizer, with its economic and CO_2 manufacturing cost.

Additionally, industrial capture of carbon and higher carbon use efficiency in the industrial and transport sectors will lead to the emission of fewer industrial non-CO_2 greenhouse gases. Black carbon, while not a gas, is nonetheless responsible for about 7 percent of the radiative forcing attributable to anthropogenic sources, and cleaner power generation will reduce radiative forcings from this source. Likewise, lower emissions of the ozone precursors—namely NO_x, CO, and the non-methane volatile organic carbons (NMVOCs)—will potentially reduce concentrations of tropospheric ozone, responsible for about 12 percent of total anthropogenic radiative forcing *(see* Prinn, Chapter 9, and Robertson, Chapter 29). NO_x reductions will attenuate both rainfall acidity and much of the unintentional nitrogen deposition now occurring over much of the Earth's surface (Holland et al. 1999).

Conclusions

Stabilizing climate will require massive changes in the design and operation of the energy system, in the management of forests and agriculture, and in several other important human activities. Yet we do not currently have sufficient knowledge to efficiently and effectively make the changes necessary to stabilize climate at acceptable levels.

A portfolio of options is required because no single technology or approach will be sufficient, although over time specific options may assume dominant roles. The development of expanded use of conservation and renewables is important, *as* is fossil-fuel carbon capture and sequestration. The suggestion that just one of these options could solve the entire problem, however, fails to recognize technical and economic realities. Furthermore, desirable portfolio options will vary by location. A failure to adopt a portfolio approach runs the risk of delaying implementation and dramatically increasing the cost of controls.

Technologies and approaches for achieving stabilization will not arise automatically through market forces. Markets can effectively convert knowledge into working solutions, but the needed knowledge can only be developed with dramatically larger investments in basic technology research, in efforts to understand consequences of new energy systems, and in efforts to understand ecosystem processes.

The technical community must provide leadership in a wide-ranging search for options. Incomplete expert or public understanding or short-term political or business agendas cannot be allowed to short-circuit the search for promising solutions. This search must include pilot experiments to gain hands-on experience with many different technologies and approaches. This approach would enable creation of essential skills and experience needed to develop systems of energy production and use to develop land management options, and to promote climate stabilization and vigorous economic growth.

Notes

1. 1 PgC = 10^{15} gC = 1 GtC = 1,000 TgC = 3.7 Gt CO_2 = 8.3 X 10^{13} mol C.

2. For example, the U.S. electricity industry invests on the order of 0.3 percent of gross sales in basic technology research.

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