4

Scenarios, Targets, Gaps, and Costs

Jae Edmonds, Fortunat Joos, Nebojsa Nakicenovic,
Richard G. Richels, and Jorge L. Sarmiento

The Technology "Gap"

With substantial increases in the global demand for energy services expected over the next century, energy technology holds the key to effective limitation of greenhouse gas emissions. Carbon-based fuels and their associated technologies supplied 88 percent of the world's energy in 1995. Over the coming decades, technologies that provide energy services but emit little or no CO_2 into the atmosphere will compete in the global marketplace with ever-improving carbon-emitting fossil-fuel technologies. How successfully they compete will determine future emissions.

Figure 4.1 illustrates the nature of the challenge. The middle curve depicts the carbon dioxide emissions associated with the Intergovernmental Panel on Climate Change (IPCC) central scenario, denoted IS92a. This IPCC reference case scenario is based on analysis of trends in global population, economic growth, land use, and energy systems. The underlying energy and land use changes produce carbon emissions that grow steadily throughout the century from 7 petagrams of carbon (PgC) per year in 1990 to almost 20 PgC per year in 2100.

The extent of technological improvements contained in the IS92a scenario is not always appreciated. They are substantial. To illustrate the extent of technological change incorporated in the IS92a scenario, we have computed carbon emissions that would be associated with a world having the same population and economic growth as IS92a but with energy technology held constant at its 1990 level. This calculation is not intended to be a realizable scenario but is rather intended to highlight the degree to which technologies that are expected to participate in energy systems consistent with the stabilization of greenhouse gas concentrations are already assumed to contribute. The difference between the upper and middle curves illustrates the technological improvement needed merely to achieve the IS92a emissions path with its corresponding impact on

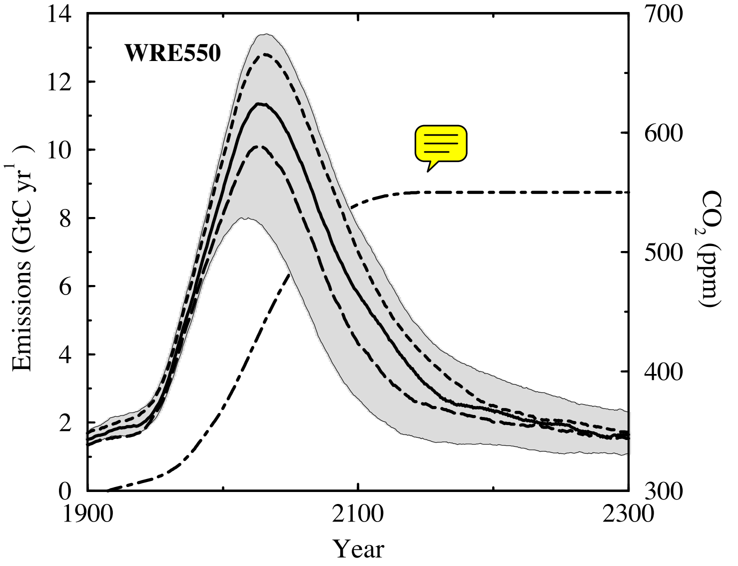

Figure 4.1. Carbon emissions, 1990–2100.

concentrations. The effects of energy intensity improvements and the deployment of non-carbon-emitting energy supply technologies are large. Power generation is 75 percent carbon free by the year 2100, and modern commercial biomass provides more energy than the combined global production of oil and gas in 1990.

Even under the advanced technology assumptions of IS92a, emissions will continue to grow. They will increase at a significantly slower rate than they would have without the technology developments envisioned by IS92a. Nevertheless, under the IS92a scenario, the concentration of carbon dioxide will rise to more than 700 parts per million (ppm) by the end of the 21st century—nearly triple the preindustrial level—and will continue rising.

The lower curve depicts an emissions path consistent with a 550-ppm concentration ceiling. This curve is depicted for illustrative purposes. While the Framework Convention on Climate Change commits the governments of the world to stabilize the concentration of greenhouse gases, it is silent as to which concentration. The concentration at which CO_2 is stabilized may turn out to be 350 ppm or 1,000 ppm.

Regardless of the concentration at which CO_2 is stabilized, the fact that CO_2 concentrations are determined by cumulative, not annual, global emissions implies that eventually global CO_2 emissions must peak and then begin a long-term, indefinite decline, as in this example.

We define the difference between carbon emissions that are anticipated to occur in a world that places no value on carbon and emissions required to stabilize at a specific concentration level as the "gap." Closing the gap means effecting a change in the technologies that are anticipated to come into use under the IS92a scenario. Substantial development of energy technologies is necessary to achieve the IS92a goals, and even greater development and deployment is needed to achieve stabilization. In the sections that follow, we explore how the size of the gap is affected by assumptions regarding (1) business as usual emissions, (2) the CO_2 concentration target, and (3) key components of the carbon cycle. We also show how the gap may be filled under alternative assumptions regarding technology cost and availability.

Scenarios

We begin by examining reference scenarios that represent the range (but not necessarily the distribution) of scenarios found in the open literature and explore the role technology plays in shaping fossil-fuel carbon emissions. The main conclusion is that scenarios are generally optimistic about future development and deployment of technologies that provide energy services without carbon emissions. Yet, as with the IS92a scenario, assumed technology improvements do not guarantee that the concentration of atmospheric CO_2 will be stabilized in any given scenario. In most instances there remains a gap between emissions in the scenario and an emissions trajectory that would stabilize CO_2 concentrations. The size of this gap depends on the CO_2 stabilization concentration and the degree to which advanced energy technologies—both supply and energy efficiency—are assumed to have already displaced carbon-emitting energy technologies.

A wide array of scenarios have been developed that explore future energy, industrial, and land use carbon emissions. One of the most recent examinations is the IPCC Special Report on Emission Scenarios (SRES) (Nakicenovic et al. 2000). This document examines scenarios published in the open literature and develops an array of new global scenarios looking forward through the 21st century. (The many scenarios contained in the SRES are organized into four major groups labeled A1, A2, B1, and B2. The characteristics of each group are discussed in Colorplate 4.) The literature is rich, containing scenarios that range from those with rapidly rising emissions to those in which emissions follow a pattern consistent with the stabilization of greenhouse gas concentrations. Some scenarios exhibit more rapid growth in emissions than IS92a, and some are slower. This range of anthropogenic CO_2 emissions for both fossil fuels and land use change is shown in Colorplate ~~5~~, from Nakicenovic et al. (2000).

~~Colorplate 6 compares future primary energy requirements across scenarios with historical development.~~ The scenarios ~~in the lower range~~ represent sustainable futures with a transition to very efficient energy use and high degrees of conservation. Generally, these are also the scenarios in which energy sources with low carbon intensity play an important role. The scenarios with higher energy requirements generally represent

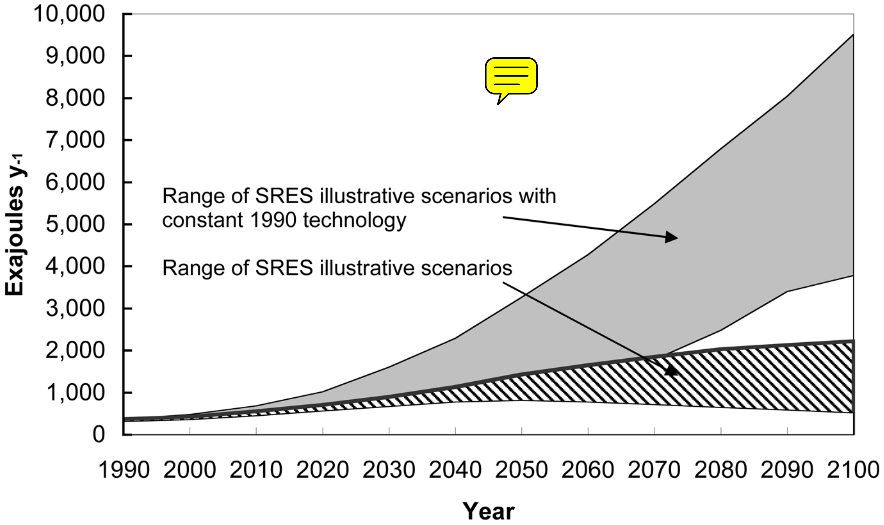

Figure 4.2. Effects of energy intensity improvements on energy demands in SRES illustrative scenarios.

futures with more rapid rates of economic growth or low rates of economic growth combined with high population.

Energy Intensity

Like the IS92 scenarios before them, all of the SRES scenarios envision substantial improvements in technology. To illustrate the magnitude of the technological change assumed to occur over the course of the 21st century in the SRES scenarios, we compute the energy requirement for each scenario, given its population and gross world product, that would be associated an energy intensity that remained unchanged from that of 1990 (see Figure 4.2).

World energy intensity is the ratio of energy to gross world product. Energy intensity improves in all SRES scenarios. That is, the amount of energy required to produce each dollar or yen or rupee of gross domestic product (GDP), after adjusting for inflation, is lower each decade than it was the decade before. Energy intensity declines as a result of many changes in the scenarios. These changes include improvements in the efficiency with which energy is used for a given process, shifts between processes, and the substitution of goods and materials with lower energy content for those with higher energy content.

Improvements in energy intensity are not new. They have been going on in some countries for a century. In the SRES scenarios, energy intensity improves at annual rates

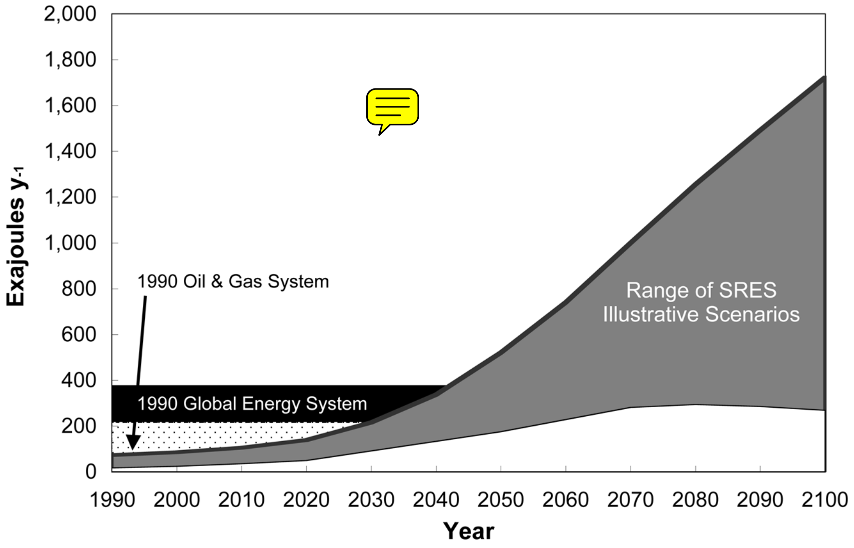

Figure 4.3. Range of non-carbon-emitting energy supply (gray) in SRES illustrative scenarios. Also shown are the magnitudes of the 1990 global energy system (black) and the 1990 global oil and gas system (hatched).

that range from less than 1 percent per year to more than 2 percent per year. By the year 2100 the cumulative effect is large. By the year 2100 primary energy demand in the SRES scenarios ranges from 55 percent to more than 90 percent lower than had no energy-intensity improvement occurred. Such is the effect of compounding.

Figure 4.2 shows the range of primary energy demands for the SRES illustrative scenarios and the corresponding range that would have been required assuming the same gross world product as in each of the SRES scenarios, but leaving energy intensity (energy per unit of gross world product) unchanged at 1990 levels. Without the improvements in energy intensity, it is hard to imagine how the global energy system could expand to produce the energy requirements of a constant-energy intensity-world. (This underscores the hypothetical nature of the constant-energy-intensity calculations and their purely illustrative character.)

Non-Carbon Energy Supply

Scenarios that consider the future evolution of global energy systems not only have significant improvements in energy intensity as a characteristic, but also envision significant increases in the deployment of non-fossil energy supply.

Figure 4.3 shows the range of deployment in the SRES illustrative scenarios for non-carbon-emitting energy (i.e., solar, wind, nuclear, and biomass). The global energy system in 1990 produced 375 exajoules (EJ) of energy. In many of the SRES illustrative sce-

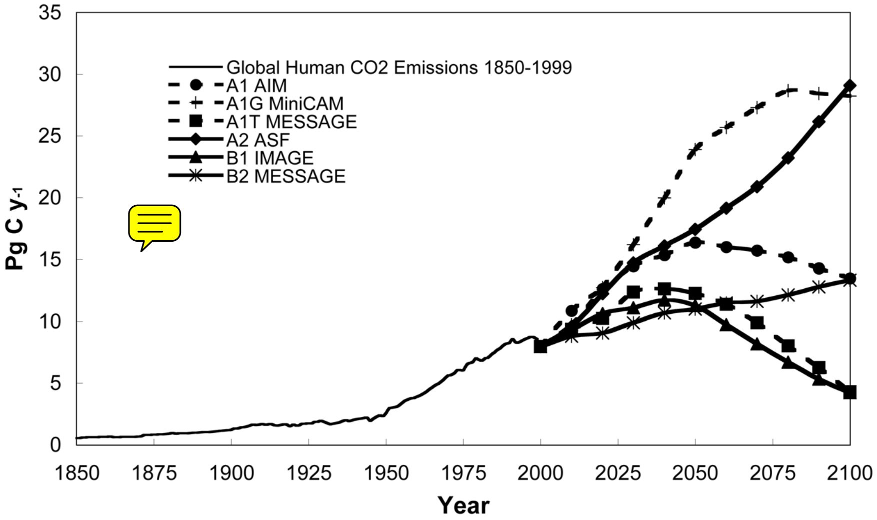

Figure 4.4. Global carbon dioxide emissions in billion tons of carbon (PgC) per year since 1850 to present and emissions trajectories for the six SRES illustrative scenarios.

narios, the deployment of non-carbon-emitting energy supply systems exceeds the size of the global energy system in 1990. In some cases the scale of the commercial biomass energy sector alone rivals or dwarfs the scale of the present global energy system.

5The Gap and CO$_2$ Stabilization

We have used the term "the gap" to refer to the difference between CO$_2$ emissions associated with reference scenarios, with their attendant technological progress, and emissions along a path that stabilizes the concentration of atmospheric CO$_2$. Historic emissions from 1850 through 1999 and the variety of SRES reference emissions paths are shown in Figure 4.4.

The Wigley, Richels, and Edmonds (1996, WRE) emissions paths (Figure 4.5) trace emissions trajectories that are consistent with stable atmospheric concentrations of CO$_2$ at five alternative levels. These paths exhibit the peak and decline pattern associated with the limit on cumulative emissions for atmospheric CO$_2$ concentrations. The higher the stabilization concentration, the later and higher is the peak in emissions. For most of the scenarios in the open literature, the dramatic advances in anticipated technology developments are insufficient to stabilize the concentration of atmospheric CO$_2$.

The magnitudes of the "gaps" between WRE trajectories for stabilization of atmospheric CO$_2$ concentrations at levels ranging from 350 ppm to 750 ppm are shown in Figure 4.6 and in Tables 4.1 and 4.2. The range of emissions reductions, relative to the

Scope 62-I.qxd 11/12/03 4:12 PM Page 83

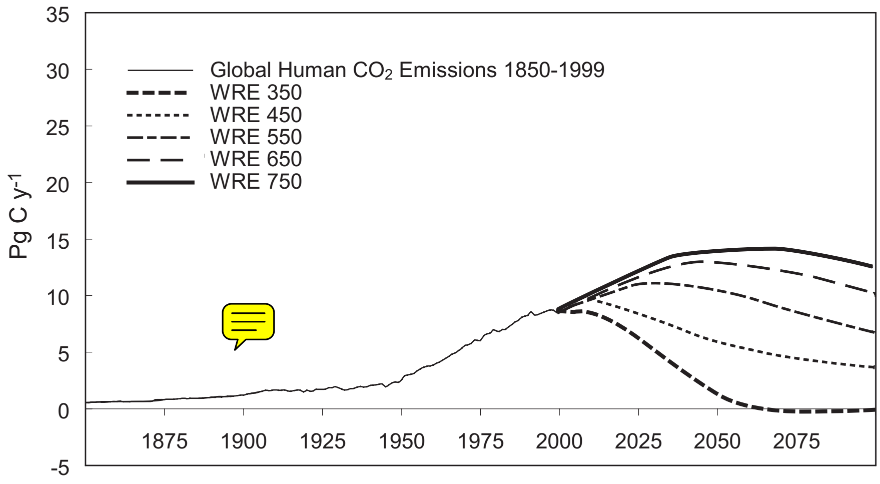

Figure 4.5. WRE CO_2 emissions trajectories for five alternative CO_2 concentrations.

reference case, that are required to attain a WRE concentration stabilization path is very wide (Figure 4.6). For some of the illustrative scenarios, events unfold in such a way as to stabilize the concentration of CO_2 at approximately 550 ppm without the need for explicit policies to limit greenhouse gas emissions. By construction, these scenarios assume that sustainable development is a priority and that policy measures ensure that non-carbon-emitting technologies are developed and deployed in preference to fossil energy technology. For most of the SRES reference scenarios, such good outcomes are not anticipated. Most of the scenarios require additional emissions reductions to stabilize the atmospheric concentration of CO_2.

Closing the Gap

Numerous mitigation measures and policies need to be invoked in the IS92a and SRES scenarios to stabilize CO_2 concentration levels. There is no unique solution to closing the gap. In fact, regardless of the reference scenario, it is never the case that a single energy technology closes the gap. In all instances the gap is closed by the deployment of a suite of energy technologies. These technologies include familiar core technologies such as energy efficiency; other energy intensity improvements; production of solar, wind, nuclear, modern commercial biomass, and other renewable energy; and changes in land use practices such as afforestation, other forest management practices, and soil carbon management. Beyond that, technologies that are only minor components in the present

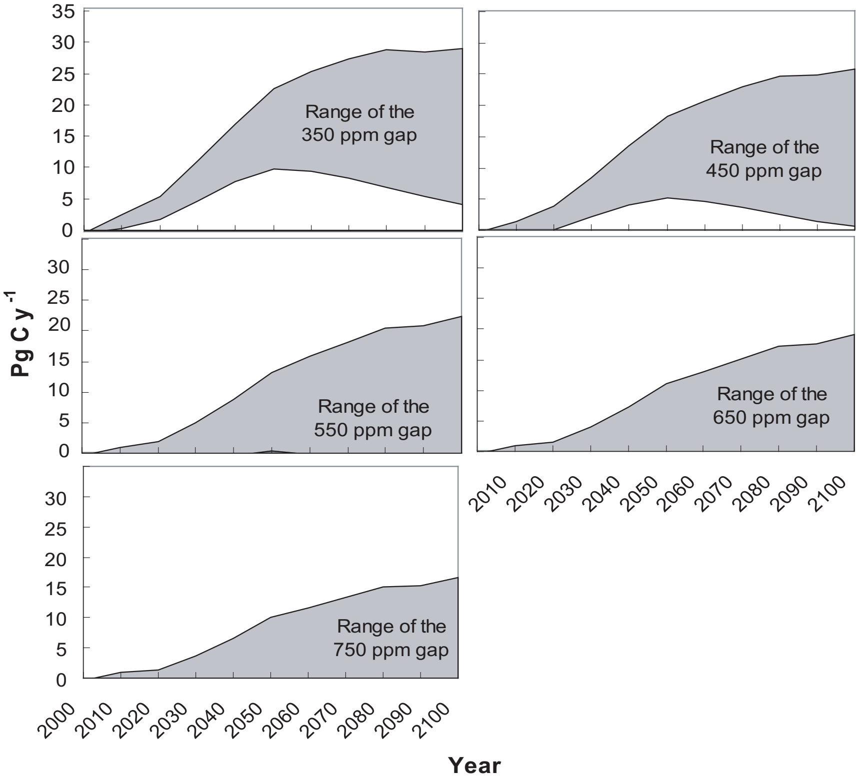

Figure 4.6. The "Gap" for five alternative CO_2 concentrations. This panel shows for five alternative CO_2 concentrations (panels a–e) the range of differences between reference emissions in the six SRES illustrative scenarios and the WRE emissions trajectory associated with stabilization of the concentration of CO_2 at the indicated level. This difference between anticipated emissions and emissions along a trajectory that stabilizes CO_2 concentrations is referred to as the "Gap."

global energy system could become major components of the global energy system in the middle and latter half of the 21st century. These technologies could include carbon capture and disposal, hydrogen and advanced transportation systems, and biotechnology.

Many issues remain to be resolved before the core technologies assumed to successfully deploy in the reference cases deploy as assumed. The development and deployment of advanced energy technologies raise other research questions.

As discussed elsewhere in this book, carbon capture and disposal could be a major technology in the 21st century. Its deployment would enable the continued employment of abundant fossil-fuel resources to provide energy services. But cost is an important

Table 4.1. The gap for the six SRES illustrative scenarios for atmospheric CO_2 concentrations ranging from 450 ppm to 750 ppm (PgC/year)

	WRE 350			*WRE 450*			*WRE 550*			*WRE 650*			*WRE 750*		
Scenario	*2020*	*2050*	*2100*	*2020*	*2050*	*2100*	*2020*	*2050*	*2100*	*2020*	*2050*	*2100*	*2020*	*2050*	*2100*
A1 AIM	5	15	13	4	10	10	2	6	7	1	4	3	1	3	1
A1G MiniCAM	6	23	28	4	18	25	2	13	21	2	11	18	1	10	16
A1TMESSAGE	3	11	4	1	6	1	NA	NA	NA	NA	NA	NA	NA	NA	NA
A2 ASF	5	16	29	3	12	25	1	7	22	1	5	19	1	4	17
B1 IMAGE	3	10	4	2	5	1	NA	NA	NA	NA	NA	NA	NA	NA	NA
B2 MESSAGE	2	10	13	0	5	10	–2	0	7	–2	–2	3	–2	–3	1

Note: NA indicates not available.

Table 4.2. The gap for the six SRES illustrative scenarios for atmospheric CO_2 concentrations ranging from 450 ppm to 750 ppm (EJ/year)

WRE 350	*WRE 450*			*WRE 550*			*WRE 650*			*WRE 750*					
Scenario	*2020*	*2050*	*2100*	*2020*	*2050*	*2100*	*2020*	*2050*	*2100*	*2020*	*2050*	*2100*	*2020*	*2050*	*2100*
A1 AIM	270	822	809	180	567	589	92	312	401	71	190	207	61	137	61
A1G MiniCAM	284	1,137	1,335	191	901	1,162	100	665	1,014	78	552	860	68	503	745
A1TMESSAGE	158	626	299	65	360	45	NA	NA	NA	NA	NA	NA	NA	NA	NA
A2 ASF	253	785	1,243	163	557	1,086	74	329	953	53	220	814	42	173	710
B1 IMAGE	166	491	200	79	262	27	NA	NA	NA	NA	NA	NA	NA	NA	NA
B2 MESSAGE	97	534	664	4	278	481	-88	21	325	-110	-101	164	-121	-154	42

Note: NA indicates not available.

question. If the cost issue is successfully addressed, or if the value of carbon is high enough, carbon capture technologies could be deployed at very large scale. Cumulative capture amounting to hundreds of billions of tons of carbon over the course of the 21st century could occur if other technology issues are addressed. Disposal is also a critical question. Many potential reservoir classes exist, including depleted oil and gas wells, deep saline reservoirs, unminable coal seams, basalt formations, and oceans. Monitoring, verification, health, safety, and local environmental issues remain to be resolved before this technology can be deployed at a large scale.

Similarly, hydrogen systems could provide a major contribution to closing the gap. Hydrogen is an energy carrier that has the attractive property of exhausting water vapor when oxidized. It can be used directly in applications ranging from space heating to electric power generation to transport. But hydrogen is not a primary energy form. It is derived either from a hydrocarbon such as a fossil fuel or biomass, or from the splitting of water, H_2O, into its constituent parts, hydrogen and oxygen, usually using electricity. The use of hydrocarbons to provide a source of hydrogen raises the question of the disposition of the carbon, and hence may require carbon capture and disposal technology to contribute to closing the gap. Hydrocarbons derived from biomass could contribute to closing the gap by providing hydrocarbon feedstocks for hydrogen production without carbon capture and disposal technology, as the carbon contained in the biomass is obtained from the atmosphere. In combination with carbon capture and disposal, biomass could provide energy with an effectively negative carbon emission. The production of hydrogen using electricity raises both the question of cost and the question of how the electricity was produced.

Once hydrogen is produced, a system must be developed and deployed to cost-effectively utilize the fuel in the provision of energy services while simultaneously providing consumer amenities, and addressing other environment, health, and safety concerns. Fuel cells attracted considerable attention in that they can convert hydrogen to electricity and heat, while producing only water vapor as exhaust. Fuel cells can be deployed in either stationary or mobile applications. Yet many questions remain to be addressed before either hydrogen systems or fuel cells are widely deployed. Economic issues loom large. The present fossil-fuel–based transportation system with the internal combustion engine has proved a highly cost-effective system for delivering transportation services. Furthermore, even if cost-competitive fuel cells are developed, they could have little or no effect on carbon emissions if they do not employ hydrogen as the fuel.

Both hydrogen and fuel cell technologies will require further research to address economic, technological, environmental, health, safety, and institutional questions.

Biotechnology could similarly play a significant part in closing the gap. Many illustrative scenarios assume that costs and performance will improve to the point where commercial biomass is a major component of the global energy system by the middle of the century. But, as with other technologies that are at an early stage of development, economic, technological, environmental, health, safety, institutional, and ethical questions abound. How is crop productivity to be improved? What other implications are implied for land use and land use emissions? Could genetically modified crops be used? How will this approach affect biodiversity?

Other biotechnology options also represent great potential contributions to closing the gap, while raising equally deep questions about technology, environmental impact, health, and safety considerations and ethics. The creation of new life forms to produce hydrogen from hydrocarbons or water, or to capture carbon from the air and store it in soils, for example, has extraordinary ethical implications in addition to technological challenges.

Technology Development and Deployment

New technologies and policies play an important role in all scenarios, including baselines and stabilization scenarios. To meet the growing need for energy services, new technologies must deliver energy services in an ever more efficient, less polluting, and less costly manner. Technological change plays an important role in this process, along with other important developments such as new institutional arrangements, adequate investments in energy, capacity building and education, or free trade to mention just a few enabling developments. The need for technological change is even greater in the stabilization cases because additional technological measures are required to close the emissions gap. Thus, numerous new and advanced energy technologies will have to be developed and deployed during the next 100 years.

Large research and development (R&D) efforts are required to deliver technologies to fill the gap in addition to delivering the reference scenarios. R&D comes in many forms, ranging from basic scientific research to technology deployment. The knowledge base upon which future technologies will emerge will be created by curiosity-driven research, applied research, research in related fields, and by learning processes that begin once technologies begin to emerge in their first applications.

New technologies historically emerge after extensive experimentation and the accumulation of knowledge through experience. Technologies typically begin their existence in niche markets and are characterized by high costs and frequently inferior performance compared with the old ones in core applications. Dedicated development often, but not always, brings improvements. In economics this process is called technological learning or learning by doing. In engineering and business, one often refers to so-called cost buy-downs along a learning curve. It is only after the costs have been reduced and performance improved that widespread diffusion can take place and old technologies can be replaced by new ones. A rich literature that describes the enormous improvements and cost reductions that can be achieved with accumulated experience and deployment of new technologies, eventually resulting in superior performance and lower costs than older competitors. Gas turbines are an example of one technology that has been developed this way. It should be mentioned that these stages in the innovation chain are not intended to be linear or sequential; it is an interactive process. R&D is always required, and niche markets for experimentation are needed to advance even the mature technologies.

The Cost of Closing the Gap

For those cases in which a gap exists—that is, for economies that are not on a course that will lead to the stabilization of CO_2 concentrations on their own—resources that would not otherwise be employed to reduce emissions must be diverted from some other human enterprise to the task of closing the gap. That is, there is an economic cost.

Many factors will determine the magnitude of that cost, including the scale of economic activity, the technical, political, and institutional ability of society to limit emissions wherever it is cheapest to do so, the set of technologies available to fill the gap, the stabilization concentration level, and the distribution of emissions in time.

The latter factor reflects the fact that cumulative, not annual, emission of carbon to the atmosphere determines atmospheric CO_2 concentrations. That is, the same concentration target can be achieved through a variety of emission pathways. This process is illustrated in Figure 4.7, which shows alternative concentration profiles leading to stabilization at 350, 450, 550, 650, and 750 ppm.

The choice of emission pathway can be thought of as a "carbon budget" allocation problem. In a first approximation, a concentration target defines an allowable amount of carbon to be emitted into the atmosphere between now and the date at which the target is to be achieved. The issue is how best to allocate the carbon budget over time.

Some insight into the characteristics of the least-cost mitigation pathway can be obtained from Weyant (2000). A group of modelers was asked to examine two alternative emission pathways for stabilizing concentrations at 450, 550, 650, and 750 ppm (see Figure 4.8). The solid and dashed lines are referred to as WG 1 and WRE, respectively denoting their source (Houghton et al. 1995; Wigley et al. 1996).

Notice that for each model, global mitigation costs are less expensive under WRE. There are several reasons why the models tend to favor a more gradual departure from their reference path. First, energy-using and energy-producing capital stock (e.g., power plants, buildings, and transport) are typically long lived. The current system was put into place based upon a particular set of expectations about the future. Large emission reductions in the near term will require accelerated replacement. This replacement is apt to be costly. There will be more opportunity for reducing emissions cheaply once the existing capital stock turns over.

Second, the models suggest that there are currently insufficient low-cost substitutes, on both the supply and demand sides of the energy sector, for deep near-term cuts in carbon emissions. With the anticipated improvements in the efficiency of energy supply, transformation, and end-use technologies, such reductions should be less expensive in the future.

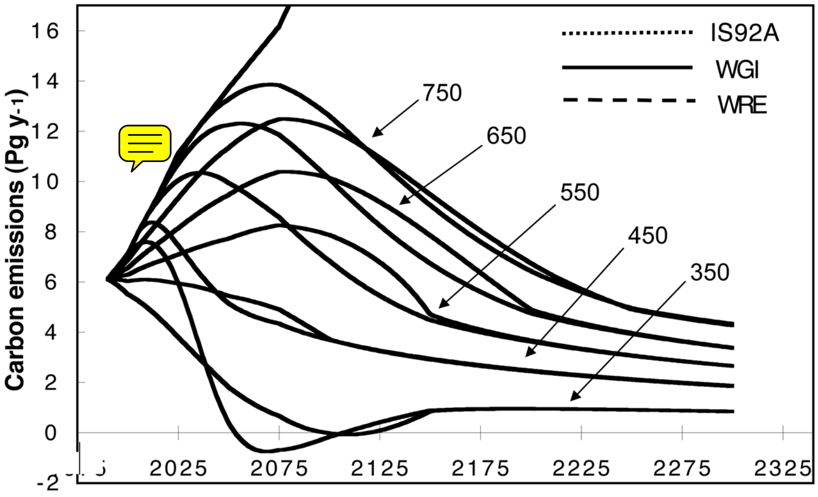

Figure 4.7. Comparison of emissions trajectories consistent with various atmospheric CO_2 concentrations. Developed by the IPCC (S350–S750) and by Wigley, Richels, and Edmonds (S350a–S750a) (Wigley et al. 1996).

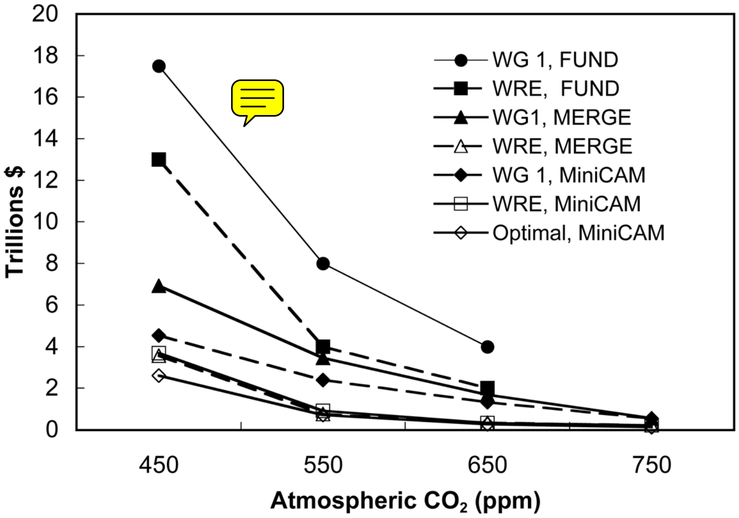

Figure 4.8. Relationship between present discounted costs for stabilizing the concentrations of CO_2 in the atmosphere at alternative levels.

Third, with the economy yielding a positive return on capital, future reductions can be made with a smaller commitment of today's resources. For example, assume a net real rate of return on capital of 5 percent per year. Further, suppose that it costs $50 to remove a ton of carbon, regardless of the year in which the reduction occurs. If we were to remove the ton today, it would cost $50. Alternatively, we could invest $19 today to have the resources to remove a ton of carbon in 2020.

The result that the lower-cost mitigation pathway tends to follow the baseline in the early years has been misconstrued by some as an argument for inaction. Wigley et al. (1996), referring to their own work, argue that this is far from the case.

> We must stress that, even from the narrow perspective of a cost effectiveness analysis, our results should not be interpreted as suggesting a "do nothing" or "wait and see" policy. First, all stabilization targets still require future capital stock to be less carbon-intensive than under a BAU scenario. As most energy production and use technologies are long-lived, this has implications for current investment decisions. Second, new supply options typically take many years to enter the marketplace. To ensure sufficient quantities of low-cost, low-carbon substitutes in the future requires a sustained commitment to research, development and demonstration today. Third, any "no regrets" measures for reducing emissions should be adopted immediately. Last, it is clear from Figure C1 that one cannot go on deferring emission reductions indefinitely, and that the need for substantial reductions in emissions is sooner the lower the concentration target.

Returning to Figure 4.8, note the "bend" in the cost curve as we move from a 550 to a 450 ppm concentration target. The reason is that even under WRE, a 450 ppm target requires an immediate departure from the baseline resulting in premature retirement of existing plant and equipment.

Finally, it should be noted that different emission pathways for achieving a given concentration target imply not only different mitigation costs, but also different benefits in terms of environmental impacts averted. These differences occur because of the differences in concentration in the years preceding the accomplishment of the target. It is therefore important to examine the environmental consequences of choosing one emission path over another.

Uncertainties in Emission Allowance from Uncertainties in the Carbon Cycle–Climate System

The integrated assessment models described in previous sections estimate the carbon emissions that result from a given scenario of economic development and population growth. These emissions are then converted into atmospheric carbon dioxide partial pressures using reduced-form carbon cycle models that do not take any uncertainties in the carbon cycle into consideration. In the flip side to these emission scenarios, the stabilization scenarios calculated by the integrated assessment models also make use of the reduced-form carbon cycle models, but now to calculate permissible emissions, which are then translated into an energy supply from fossil fuels. The aim of this section is to examine how uncertainties in the global carbon cycle might affect both the growth rate in atmospheric carbon dioxide that results from a given emission scenario and the permissible emissions that result from a given concentration stabilization scenario.

We begin our discussion with the set of stabilization scenarios shown in Figure 4.9 and a detailed breakdown of two stabilization scenarios given in Table 4.3. Because of the dependence of asymptotic atmospheric carbon dioxide on cumulative rather than annual emissions, annual carbon emissions have to peak and eventually decline well below present levels (Figure 4.9a) in order to stabilize cumulative emissions (Figure 4.9b) and thus atmospheric CO_2. This is true irrespective of the stabilization target. Note, however, that a considerable amount of emissions can continue for many decades and even centuries beyond the peak, as the deep ocean gradually comes into play as a carbon sink.

A range of processes determine carbon uptake by the ocean and the terrestrial biosphere (Prentice et al. 2001; see chapters by Friedlingstein, Le Quéré and Metzl, and Greenblatt and Sarmiento in this volume) and thus allow carbon emissions for a given stabilization pathway. Factors that influence oceanic and terrestrial storage are the increase in atmospheric CO_2, the increase in radiative forcing by CO_2 and non-CO_2 greenhouse gases (GHGs) and other agents, the sensitivity of climate to radiative forcing, and the sensitivity of carbon cycle processes to climate change (Joos et al. 2001; Leemans et al. 2002). Terrestrial carbon storage depends on past and future land use (Hurtt et al. 2002; Leemans et al. 2002; Gitz and Ciais 2003), the sensitivity of soil respiration to soil temperature and moisture changes, and changes in structure and distribution of ecosystems (Cox et al. 2000; Cramer et al. 2001; Joos et al. 2001).

The role of increasing atmospheric CO_2 and of additional nutrient input into terrestrial ecosystems (Townsend et al. 1996) in enhancing primary productivity remains controversial. Recent reviews (House et al. 2003; Houghton et al. 2003) discuss the conflicting evidence for environmental growth enhancement (see also Hättenschwiler et al. 1997; Luo et al. 1999; De Lucia et al. 1999; Caspersen et al. 2000; Joos et al. 2002; Cowling and Field 2003).

For a range of plausible assumptions, it is found that the terrestrial biosphere could act as a strong carbon source or sink during this century (Cox et al. 2000; Joos et al. 2001; Hurtt et al. 2002). The ocean's physico-chemical-driven response is to sequester carbon released into the atmosphere. The rate-limiting step is surface-to-deep mixing of excess carbon associated with typical timescales ranging from decades for the upper ocean to many centuries for the abyss (Oeschger et al. 1975). Solubility of CO_2 decreases in warming waters, tending to reduce the uptake. Other factors that can

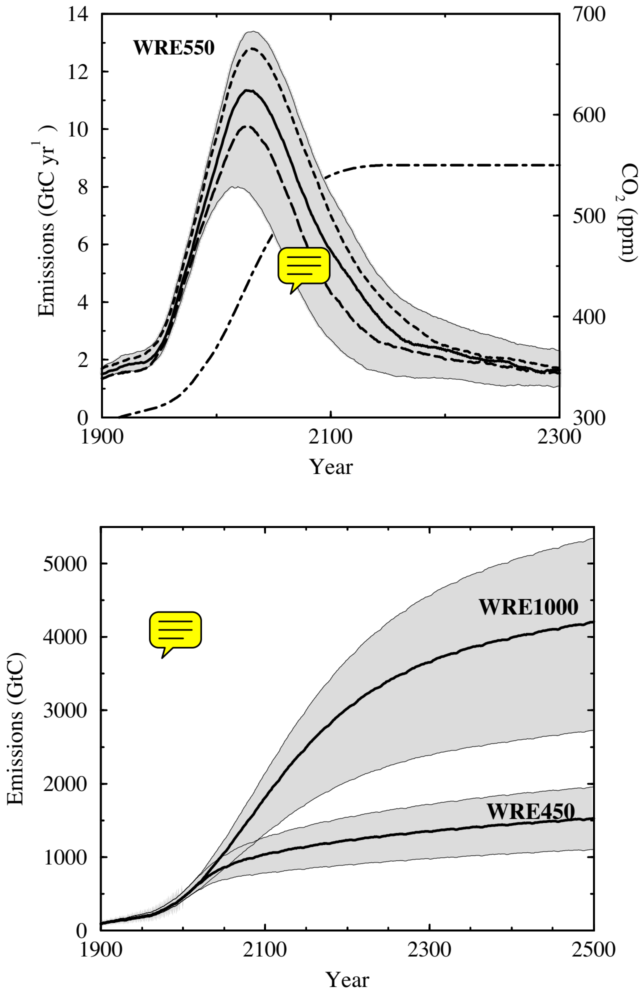

Figure 4.9. (a) Allowed carbon emission for the WRE550 pathway where atmospheric CO_2 is stabilized at 550 ppm (dot-dash line, right axis) as simulated with the Bern CC model (Joos et al. 2001). The model's climate sensitivity, expressed as equilibrium temperature increase for a doubling of atmospheric CO_2, has been varied between 0∫C (no climate feedbacks, dash), 2.5∫C (standard case, solid), and 4.5∫C (long-dash). The gray band provides an estimate of the overall uncertainty of the allowed emissions. The lower bounding has been calculated by phasing out CO_2 fertilization, the major terrestrial sink process in the model, after year 2000 and by setting slow ocean mixing rates. The upper bounding has been obtained by implementing no dependence of soil respiration rates on soil warming, thereby suppressing the major terrestrial source process in the model and by setting high ocean mixing rates. (b) Cumulative carbon emissions allowance for the two WRE stabilization pathways leading to stabilization at 450 ppm and 1,000 ppm.

Table 4.3. Allowed carbon emissions for WRE 450 and WRE 750 stabilization pathways

Pathway	*2000–2020 (20 years)*	*2020–2050 (30 years)*	*2050–2100 (50 years)*
WRE 450 stabilization pathway			
Standard	189	217	393
Bounding cases	145 to +227	136 to 268	306 to 462
Deviations due to:			
Climate feedback			
None	+21	+36	+51
High	–23	–36	–34
Ocean mixing			
Low	–17	–23	–26
High	+12	+18	+19
Land			
No CO_2 fertilization	–28	–58	–61
Temperature-independent soil respiration rates	+26	+33	+50
Bounding deviations	–44 to +38	–81 to +51	–87 to +69
WRE 750 stabilization pathway			
Standard	202	399	654
Bounding cases	155 to 235	271 to 468	396 to 801
Deviations due to:			
Climate feedback			
None	+23	+50	+111
High	–24	–40	–99
Ocean mixing			
Low	–17	–33	–57
High	+13	+24	+43
Land			
No CO_2 fertilization	–30	–96	–200
Temperature-independent soil respiration rates	+20	+45	+104
Bounding deviations	–47 to +33	–128 to +69	–259 to +147

Note: Total allowed emission in PgC for the standard and bounding cases and deviations from the standard in PgC for the other cases, as obtained with the Bern CC model. The lower bounding case is obtained by combining low ocean mixing with the phasing out of CO_2 fertilization on land after year 2000, whereas the upper bounding case results from combining high ocean mixing with soil respiration rate coefficients that remain unchanged under global warming.

influence the oceanic uptake are a slowing of the circulation in response to changed heat and freshwater fluxes into the surface ocean, and changes in marine ecosystems and their productivity in response to changes in the physical and chemical environment (Maier-Reimer et al. 1996; Sarmiento et al. 1998; Joos et al. 1999; Matear and Hirst 1999; Plattner et al. 2001). Uncertainties in projections are thus associated both with uncertainties in basic carbon cycle processes, such as the rate of surface-to-deep mixing of excess carbon or fertilization mechanisms on land, and with uncertainties in carbon cycle–climate feedbacks, including a possible collapse of the formation of North Atlantic Deep Water or dieback of extant forests.

In the following sections, we explore these uncertainties in a quantitative framework, using primarily sensitivity studies that have been carried out within the framework of IPCC with the Bern carbon cycle–climate (CC) model (Joos et al. 2001; Prentice et al. 2001), but also including recent results from two three-dimensional Earth system models (Cox et al. 2000; Friedlingstein et al. 2000). The Bern CC model links a chemistry and radiative forcing module, the HILDA box-diffusion-type ocean model, the Lund-Potsdam-Jena (LPJ) dynamic global vegetation model (Sitch et al. 2003), and a substitute of the ECHAM3/LSG AOGCM. The three-dimensional models are computationally expensive, and simulations are not available for the stabilization scenarios. Figure 4.9 and Table 4.3 illustrate how uncertainties might affect estimates of emissions for various stabilization scenarios. The cumulative upper-to-lower-limit range of these uncertainties for a standard climate response of 2.5°C warming for a CO_2 doubling is on the order of 40 percent of the standard scenario for the next 20 years, then increases to 50 percent and greater for the 2020 to 2050 and 2050 to 2100 periods, and beyond.

The largest contribution to these uncertainties in all the scenarios arises from the parameterization of land processes. The LPJ model as used for the standard scenarios given in the top row of the tables includes both a representation of the effect of CO_2 fertilization on plant growth and a conventional temperature dependence of soil respiration rates (Sitch et al. 2003). These mechanisms have opposite effects. CO_2 fertilization leads to carbon uptake for rising atmospheric CO_2 concentrations, whereas global warming leads to higher soil respiration rates and a loss of soil carbon. The extent of stimulation of carbon storage in natural ecosystems by CO_2 has been a matter of controversy, and there is no proof that the biospheric sink on the global scale (see Chapter 1) is indeed primarily due to CO_2 fertilization, as implied by the LPJ results. Other processes, such as nitrogen fertilization (Schindler and Bayley 1993; Townsend et al. 1996), climate variations (Dai and Fung 1993; McGuire et al. 2001), and forest regrowth and woody encroachment (Pacala et al. 2001; Goodale et al. 2002; see also Nabuur, Chapter 16, this volume), might be responsible for part or most of the terrestrial sink. If this were the case, then it would be unlikely that primary productivity would increase as a function of future CO_2 concentrations. A simple alternative hypothesis is that primary productivity remains close to its present level. Then the allowed carbon emissions would have to drop by a very large amount (row "no CO_2 fertilization" in tables), as the terrestrial biosphere turns into a source in the coming decades as soil carbon is lost. There is also conflicting evidence on the temperature dependence of soil and litter respiration (Trumbore et al. 1996; Giardina and Ryan 2000) over multiannual timescales. If soil and litter respiration rates are indeed independent of global warming, then carbon loss from litter and soil would be suppressed and allowed carbon emissions could be higher (row "temperature independent soil respiration rates"). Uncertainty in ocean circulation, represented in the Bern CC model by varying the ocean mixing, is also substantial, though not as great as uncertainties in land processes. Uncertainty in climate projections also translate into uncertainties in estimated carbon emission allowance. The climate feedback rows vary the equilibrium temperature for a CO_2 doubling from its standard value of 2.5°C to 0°C in the no climate feedback case and 4.5°C in the high climate feedback case. Projected temperature and precipitation changes affect photosynthesis and soil respiration rates on land and the solubility of CO_2 in the ocean. Climate change also affects vegetation dynamics, leading to forest expansion in high northern latitudes as well as to forest dieback in other regions. The results obtained with the three-dimensional Hadley and IPSL models summarized in Table 4.4 give another illustration of the climate feedback effect. Here the carbon emissions are fixed per the IPCC IS92a (Hadley) and A2 (IPSL) scenarios, and the models predict the resulting CO_2 in the atmosphere. The Hadley model land biosphere, which suffers from a massive loss of soil carbon in the climate feedback case, shifts from being a large net sink to a large net source when climate feedback is added;. As a consequence, atmospheric CO_2 climbs to almost 1,000 ppm from the non-climate feedback result of 702 ppm. This represents a difference of almost 600 PgC in the carbon sinks between the two cases. By contrast, the IPSL model, which is more similar to the Bern model in its behavior, shows a difference of only 160 PgC in the carbon sinks between the two scenarios.

As discussed in Chapter 2, there exist vulnerabilities and possible "surprises" that are not readily included in state-of-the art models or that are possible but not necessarily likely. For example, an uncertainty not considered in the projections presented by IPCC and shown here in Figure 4.9 and Table 4.3 is the possibility of a collapse of the North Atlantic Deep Water formation and its impact on oceanic and terrestrial carbon uptake (see also Joos and Prentice, Chapter 7, this volume). Since the detection of rapid abrupt climate change in Greenland ice cores, European lake sediments, and sediments in the deep Atlantic (Oeschger et al. 1984; Broecker et al. 1985; Clark et al. 2002), concerns have been expressed that the formation of North Atlantic Deep Water may cease in response to global warming (Broecker 1987; Manabe and Stouffer 1993; Stocker et al. 2001). This would imply reduced ocean heat transport to the North Atlantic region with large consequences for the climate in Europe and the Northern Hemisphere. Model results suggest that the meridional overturning circulation may be vulnerable to future changes in the hydrological cycle and in sea surface temperature (Cubasch et al. 2001) and that North Atlantic Deep Water formation may even eventually cease in

Table 4.4. Impact of climate feedback on carbon sinks and global warming in the Hadley (Cox et al. 2000) and IPSL (Friedlingstein et al. 2000) simulations

Period	*Emissions (PgC)*	*Ocean uptake (PgC)*	*Land uptake (PgC)*	*CO_2 in final year (ppm)*	*Temperature change (°C)*
HADLEY model					
With climate feedback					
2001–2020	205	58	20	457	0.45
2021–2050	397	111	–14	596	1.60
2051–2099	865	221	–182	982	2.00
No climate feedback					
2001–2020	205	42	70	409	
2021–2050	397	81	134	494	
2051–2099	865	161	258	702	
IPSL model					
With climate feedback					
2001–2020	209	67	55	409	0.5
2021–2050	464	154	102	506	0.72
2051–2100	1,128	349	209	778	1.12
No climate feedback					
2001–2020	209	66	66	399	
2021–2050	464	145	139	484	
2051–2100	1,128	336	334	701	

Note: The IS92a emission scenario is applied in the Hadley simulations, and the SRES A2 scenario in the IPSL run.

response to anthropogenic forcing (Stocker and Schmittner 1997), similar to what happened frequently during the last glacial period. However, since such ocean circulation changes, and in particular large-scale reorganizations, are highly nonlinear processes involving thresholds, there are inherent limitations to the predictability of such phenomena (Knutti and Stocker 2002). Sensitivity experiments carried out with dynamical ocean-biogeochemical models (Sarmiento and Le Quéré 1996; Joos et al. 1999; Plattner et al. 2001) show that a collapse of North Atlantic Deep Water formation has the potential to substantially reduce oceanic carbon uptake as surface-to-deep mixing is slowed considerably on century timescales (Figure 4.10).

Uncertainties in the IPCC projections of emission allowance appear to be asymmetrically distributed around the best estimates. The chance that emission allowance is overestimated is higher than that it is underestimated. One reason is that these projec-

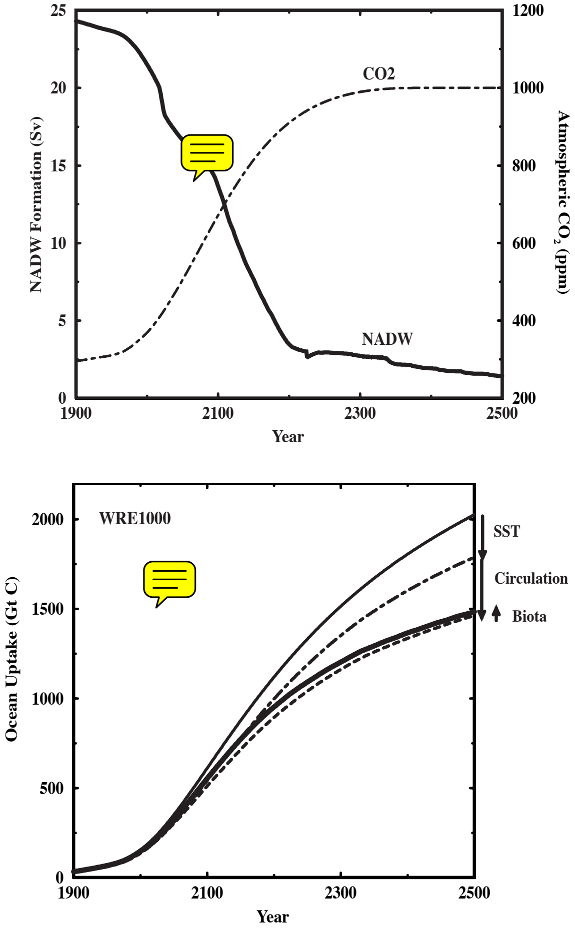

Figure 4.10. Impact of a possible collapse of the formation rate of North Atlantic Deep Water (NADW) on the oceanic carbon uptake, and hence the carbon emission allowance to meet a stabilization target (Joos et al. 1999). (a) Prescribed atmospheric CO_2 stabilization pathway (WRE1000) (dashed, right-hand scale) and the modeled decrease in NADW formation under global warming (solid). (b) Oceanic carbon uptake is reduced for the simulation with global warming and a collapse in NADW formation (solid) compared with a simulation without global warming (thin solid). The contribution of various mechanisms to the overall reduction has been quantified by additional simulations and is indicated by arrows. Only the reduction in carbon uptake due to the effect of sea surface warming on the CO_2 solubility (difference between thin solid and dash-dot , "SST") has been included in the IPCC projections. The slowed surface-to-deep ocean exchange leads to a further reduction in oceanic carbon uptake (difference between dash-dot and dash, "circulation"), whereas a more efficient nutrient utilization slightly enhances uptake of excess carbon (difference between dash and solid, "biota").

tions do not fully account for the vulnerabilities of carbon reservoirs discussed previously and in Chapter 2, most of which are positive feedbacks. Another reason is that current terrestrial models (Cramer et al. 2001; McGuire et al. 2001) include relatively strong sink mechanisms driven primarily by CO_2 fertilization. A strong sink mechanism is consistent with the traditionally high land-use emission estimates (Fearnside 2000; McGuire et al. 2001; Houghton 2003) and the contemporary carbon budget (Chapter 1). If land-use emissions (Archard et al. 2002; DeFries et al. 2002), and thus the present terrestrial sink processes, are overestimated or if the sink decreases in the near future (Hurtt et al. 2002; Cowling and Field 2003), this would have by far the largest potential impact on emission allowance of all the processes considered (Table 4.3). Yet another reason is that additional warming by non-CO_2 GHGs, not included in the IPCC stabilization pathway calculations (Prentice et al. 2001), would likely lead to reduced ocean and terrestrial carbon uptake (Joos et al. 2001).

In summary, there exist a broad range of uncertainties in the projected emission allowance for a distinct CO_2 stabilization pathway. The impacts of these uncertainties on estimates of the cost required to close the gap between no climate policy scenarios and stabilization pathways and on optimal hedging strategies need yet to be explored and is a task for future research.

Some Closing Comments

In this chapter we explored a range of scenarios for future CO_2 emissions drawing upon the extensive literature on this subject. Models of the socioeconomic system are coupled with those of the carbon cycle to determine future emissions under alternative assumptions about population and income growth, the cost and availability of existing and future energy-producing and -using technologies, and the key determinants of the carbon cycle.

Most scenarios suggest that in the absence of a constraint on emissions, atmospheric CO_2 concentrations will continue to rise well beyond current levels, highlighting a gap between business-as-usual CO_2 emissions and those required to stabilize concentrations at levels currently under consideration. To eliminate this gap will require the development and deployment of a new generation of energy.

Of course, technology development is but one of the options for dealing with global climate change. As pointed out in IPCC (2001), climate policy requires a portfolio of responses. The challenge facing today's policy makers is to arrive at a prudent hedging strategy in the face of climate-related uncertainties. Among the options are

- immediate reductions of greenhouse gas emissions,
- investments in actions to assist human and natural systems in adapting to any climate change that should occur,
- continued research to reduce uncertainties about how much change will occur and what effects it will have, and

- R&D on energy supply and end-use technologies to reduce the costs of limiting greenhouse gas emissions.

The issue is not one of "either-or" but one of finding the right blend of options. Policy makers must decide how to divide greenhouse insurance dollars among these competing needs.

Notes

1. Balanced is defined as not relying too heavily on one particular energy source, on the assumption that similar improvement rates apply to all energy supply and end use technologies.

Literature Cited

Archard, F., H. D. Eva, H. Stibig, P. Mayaux, J. Gallego, R. Richards, and J. Malingreau. 2002. Determination of deforestation rates of the world's humid tropical forest. *Science* 297:999–1002.

Archer, D., H. Kheshgi and E. Maier-Reimer. 1999. Dynamics of fossil fuel CO_2 neutralization by marine $CaCO_3$. *Global Biogeochemical Cycles* 12:259–276.

Broecker, W. S. 1987. Unpleasant surprises in the greenhouse. *Nature* 328:123–126.

Broecker, W. S., D. M. Peteet, and D. Rind. 1985. Does the ocean-atmosphere system have more than one stable mode of operation? *Nature* 315:21–25.

Caspersen, J. P., S. W. Pacala, J. C. Jenkins, G. C. Hurtt, P. R. Moorcroft, and R. A. Birdsey. 2000. Contributions of land-use history to carbon accumulation in U.S. forests. *Science* 290:1148–1151.

Clark, P. U., N. G. Pisias, T. F. Stocker, and A. J. Weaver. 2002. The role of the thermohaline circulation in abrupt climate change. *Nature* 415:863–869.

Cowling, S. A., and C. B. Field. 2003. Environmental control of leaf area production: Implication for vegetation and land-surface modeling. *Global Biogeochemical Cycles* 17, doi:10.1029/2002GB001915.

Cox, P. M., R. A. Betts, C. D. Jones, S. A. Spall, and I. J. Totterdell. 2000. Will carbon-cycle feedbacks accelerate global warming in the 21st century? *Nature* 408:184–187.

Cramer, W., A. Bondeau, F. I. Woodward, I. C. Prentice, R. A. Betts, V. Brovkin, P. M. Cox, V. Fisher, J. A. Foley, A. D. Friend, C. Kucharik, M. R. Lomas, N. Ramankutty, S. Sitch, B. Smith, A. White, and C. Young-Molling. 2001. Global response of terrestrial ecosystem structure and function to CO_2 and climate change: Results from six dynamic global vegetation models. *Global Change Biology* 7:357–373.

Cubasch, U., G. A. Meehl, G. J. Boer, R. J. Stouffer, M. Dix, A. Noda, C. A. Senior, S. Raper, and K. S. Yap. 2001. Projections of future climate change. Pp. 525–582 in *Climate change 2001: The scientific basis. Contribution of Working Group I to the third assessment report of the Intergovernmental Panel on Climate Change*, edited by J. T. Houghton, Y. Ding, D. J. Griggs, M. Noguer, P. J. van der Linden, X. Dai, K. Maskell, and C. A. Johnson. New York: Cambridge University Press.

Dai, A., and I. Y. Fung. 1993. Can climate variability contribute to the "missing" CO_2 sink? *Global Biogeochemical Cycles* 7:599–609.

DeFries, R. S., R. A. Houghton, M. C. Hansen, C. B. Field, D. Skole, and J. Townshend. 2002. Carbon emissions from tropical deforestation and regrowth based on satellite observations for the 1980s and 90s. *Proceedings of the National Academy of Sciences* 99:14256–14261.

De Lucia, E. H., J. G. Hamilton, S. L. Naidu, R. B. Thomas, J. A. Andrews, A. Finzi, M. Lavine, R. Matamala, J. E. Mohan, G. R. Hedrey, and W. H. Schlesinger. 1999. Net primary production of a forest ecosystem with experimental CO_2 enrichment. *Nature* 284:1177–1179.

Fearnside, P. M. 2000. Global warming and tropical land-use change: Greenhouse gas emissions from biomass burning, decomposition and soils in forest conversion, shifting cultivation and secondary vegetation. *Climatic Change* 46:115–158.

Friedlingstein, P., L. Bopp, P. Ciais, J.-L. Dufresne, L. Fairhead, H. LeTreut, P. Monfray, and J. Orr. 2000. Positive feedback of the carbon cycle on future climate change. *Note du Pôle de Modélisation* (Institut Pierre Simon Laplace) 19:1–15.

Giardina, C. P., and M. G. Ryan. 2000. Evidence that decomposition rates of organic carbon in mineral soil do not vary with temperature. *Nature* 404:858–861.

Gitz, V., and P. Ciais. 2003. Amplifying effects of land-use change on future atmospheric CO_2 levels. *Global Biogeochemical Cycles*, doi 10.1029/2002GB001963..

Goodale, C. L., M. J. Apps, R. A. Birdsey, C. B. Field, L. S. Heath, R. A. Houghton, J. C. Jenkins, G. H. Kohlmaier, W. Kurz, S. Liu, G.-J. Nabuurs, S. Nilsson, and A. Z. Shvidenko. 2002. Forest carbon sinks in the Northern Hemisphere. *Ecological Applications* 12:891–899.

Hättenschwiler, S., F. Miglietta, A. Raschi, and C. Körner. 1997. Morphological adjustments of mature *Quercus ilex* trees to elevated CO_2. *Acta Oecologica* 18:361–365.

Houghton, R. A. 2003. Revised estimates of the annual net flux of carbon to the atmosphere from changes in land use and land management, 1850–2000. *Tellus* 55B:378–390.

Houghton, J. T., L. G. M. Filho, J. Bruce, H. Lee, B. A. Callander, E. Haites, N. Harris, and K. Maskell, eds. 1995. *Climate change 1994: Radiative forcing of climate change and an evaluation of the IPCC IS92 emissions scenarios.* Cambridge: Cambridge University Press.

Houghton, R. A., F. Joos, and G. P. Asner. 2003. The effects of land use and management on the global carbon cycle. In *Land change science: Observing, monitoring, and understanding trajectories of change on the Earth's surface*, edited by G. Gutman. Kluwer, submitted, 2003.

House, J. I., N. Ramankutty, I. C. Prentice, M. Heimann, and R. A. Houghton. 2003. Reducing uncertainties in the global terrestrial CO_2 sink. *Tellus* 55B:345–363.

Hurtt, G. C., S. W. Pacala, P. R. Moorcroft, J. Caspersen, E. Shevliakova, R. A. Houghton, and B. Moore. 2002. Projecting the future of the U.S. carbon sink. *Proceedings of the National Academy of Sciences of the United States* 99 (3): 1389–1394.

Joos, F., G.-K. Plattner, T. F. Stocker, O. Marchal, and A. Schmittner. 1999. Global warming and marine carbon cycle feedbacks on future atmospheric CO_2. *Science* 284:464–467.

Joos, F., I. C. Prentice, S. Sitch, R. Meyer, G. Hooss, G.-K. Plattner, S. Gerber, and K. Hasselmann. 2001. Global warming feedbacks on terrestrial carbon uptake under the Intergovernmental Panel on Climate Change (IPCC) emission scenarios. *Global Biogeochemical Cycles* 15:891–907.

Joos, F., I. C. Prentice, and J. I. House. 2002. Growth enhancement due to global atmospheric change as predicted by terrestrial ecosystem models: Consistent with U.S. forest inventory data. *Global Change Biology* 8:299–303.

Knutti, R., and T. F. Stocker. 2002. Limited predictability of the future thermohaline circulation close to an instability threshold. *Journal of Climate* 15:179–186.

Leemans, R., B. Eickhout, B. Strengers, L. Bouwman, and M. Schaeffer. 2002. The consequences for the terrestrial carbon cycle of uncertainties in land use, climate and vegetation responses in the IPCC SRES scenarios. *Science in China* 45:126.

Luo, Y. Q., J. Reynolds, and Y. P. Wang. 1999. A search for predictive understanding of plant responses to elevated CO_2. *Global Change Biology* 5:143–156.

Maier-Reimer, E., U. Mikolajewicz, and A. Winguth. 1996. Future ocean uptake of CO_2: Interaction between ocean circulation and biology. *Climate Dynamics* 12:711–721.

Manabe, S., and R. J. Stouffer. 1993. Century-scale effects of increased atmospheric CO_2 on the ocean-atmosphere system. *Nature* 364:215–218.

Matear, R. J., and A. C. Hirst. 1999. Climate change feedback on the future oceanic CO_2 uptake. *Tellus* 51B (3): 722–733.

McGuire, A. D., S. Sitch, J. S. Clein, R. Dargaville, G. Esser, J. Foley, M. Heimann, F. Joos, J. Kaplan, D.W. Kicklighter, R. A. Meier, J. M. Melillo, B. Moore III, I. C. Prentice, N. Ramankutty, T. Reichenau, A. Schloss, H. Tian, L. J. Williams, and U. Wittenberg. 2001. Carbon balance of the terrestrial biosphere in the twentieth century: Analyses of CO_2, climate and land-use effects with four process-based ecosystem models. *Global Biogeochemical Cycles* 15:183–206.

Metz, B., O. Davidson, R. Swart, and J. Pan, eds. 2001. *Climate change 2001: Mitigation (The contribution of Working Group III to the third assessment report of the Intergovernmental Panel on Climate Change*). Cambridge: Cambridge University Press.

Nakicenovic, N., et al. 2000. *Special report on emissions scenarios*. Cambridge: Cambridge University Press.

Oeschger, H., U. Siegenthaler, U. Schotterer, and A. Gugelmann. 1975. A box diffusion model to study the carbon dioxide exchange in nature. *Tellus* 27:168–192.

Oeschger, H., J. Beer, U. Siegenthaler, B. Stauffer, W. Dansgaard, and C. C. Langway. 1984. Late glacial climate history from ice cores. Pp. 299–306 in *Climate processes and climate sensitivity,* edited by J. E. Hansen and T. Takahashi. Geophysical Monograph 29. Washington, D.C.: American Geophysical Union.

Pacala, S. W., G. C. Hurtt, D. Baker, P. Peylin, R. A. Houghton, R. A. Birdsey, L. Heath, E. T. Sundquist, R. F. Stallard, P. Ciais, P. Moorcroft, J. P. Caspersen, E. Shevliakova, B. Moore, G. Kohlmaier, E. Holland, M. Gloor, M. E. Harmon, S.-M. Fan, J. L. Sarmiento, C. L. Goodale, D. Schimel, and C. B. Field. 2001. Consistent land- and atmosphere-based U.S. carbon sink estimates. *Science* 292:2316–2320.

Plattner, G.-K., F. Joos, T. F. Stocker, and O. Marchal. 2001. Feedback mechanisms and sensitivities of ocean carbon uptake under global warming. *Tellus* 53B:564–592.

Prentice, I. C., G. D. Farquhar, M. J. R. Fasham, M. L. Goulden, M. Heimann, V. J. Jaramillo, H. S. Kheshgi, C. Le Quéré, R. J. Scholes, and D. W. R. Wallace. 2001. The carbon cycle and atmospheric carbon dioxide. Pp. 183–237 in *Climate change 2001: The scientific basis (Contribution of Working Group I to the third assessment report of the Intergovernmental Panel on Climate Change)*, edited by J. T. Houghton, Y. Ding, D. J. Griggs, M. Noguer, P. J. van der Linden, X. Dai, K. Maskell, and C. A. Johnson. New York: Cambridge University Press.

Sarmiento, J. L., and C. Le Quéré. 1996. Oceanic carbon dioxide uptake in a model of century-scale global warming. *Science* 274:1346–1350.

Sarmiento, J. L., T. M. C. Hughes, R. J. Stouffer, and S. Manabe. 1998. Simulated response of the ocean carbon cycle to anthropogenic climate warming. *Nature* 393:245–249.

Schimel, D., M. Grubb, F. Joos, R. K. Kaufmann, R. Moos, W. Ogana, R. Richels, and T. Wigley. 1997. *Stabilization of atmospheric greenhouse gases: Physical, biological and socio-economic implications*, edited by J. T. Houghton, L. G. Meira Filho, D. J. Griggs, and K. Maskell. IPCC Technical Paper 3. [Geneva:?] Intergovernmental Panel on Climate Change.

Schindler, W. D., and S. E. Bayley. 1993. The biosphere as an increasing sink for atmospheric carbon: Estimates from increased nitrogen deposition. *Global Biogeochemical Cycles* 7:717–733.

Sitch, S., B. Smith, I. C. Prentice, A. Arneth, A. Bondeau, W. Cramer, J. O. Kaplan, S. Levis, W. Lucht, M. T. Sykes, K. Thonicke, and S. Venevsky. 2003. Evaluation of ecosystem dynamics, plant geography and terrestrial carbon cycling in the LPJ dynamic global vegetation model. *Global Biogeochemical Cycles* 9:161–185.

Stocker, T. F., and A. Schmittner. 1997. Influence of CO_2 emission rates on the stability of the thermohaline circulation. *Nature* 388:862–865.

Stocker, T. F., G. K. C. Clarke, H. LeTreut, R. S. Lindzen, V. P. Meleshko, R. K. Mugara, T. N. Palmer, R. T. Pierrehumbert, P. J. Sellers, K. E. Trenberth, and J. Willebrand. 2001. Physical climate processes and feedbacks. Pp. 417–470 in *Climate change 2001: The scientific basis (Contribution of Working Group I to the third assessment report of the Intergovernmental Panel on Climate Change)*, edited by J. T. Houghton, Y. Ding, D. J. Griggs, M. Noguer, P. J. van der Linden, X. Dai, K. Maskell, and C. A. Johnson. New York: Cambridge University Press.

Townsend, A. R., B. H. Braswell, E. A. Holland, and J. E. Penner. 1996. Spatial, temporal patterns in terrestrial carbon storage due to the deposition of fossil fuel nitrogen. *Ecological Applications* 6:806–814.

Trumbore, S. E., O. A. Chadwick, and R. Amundson. 1996. Rapid exchange between soil carbon and atmospheric carbon dioxide driven by temperature change. *Science* 272:393–396.

Weyant. 2000. [Please complete.]

Wigley, T. M. L., R. Richels, and J. A. Edmonds. 1996. Economic and environmental choices in the stabilization of atmospheric CO_2 concentrations. *Nature* 379 (6562): 240–243.