S t a n f o r d   U n i v e r s i t y

C I S A C

Center for International Security and Cooperation

The Center for International Security and Cooperation, part of Stanford University's Institute for International Studies, is a multidisciplinary community dedicated to research and training in the field of international security. The Center brings together scholars, policymakers, scientists, area specialists, members of the business community, and other experts to examine a wide range of international security issues.

Center for International Security and Cooperation
Stanford University
Encina Hall
Stanford, California 94305-6165

(415) 723-9625

http://www.stanford.edu/group/CISAC/

Climate Change and the Transformation of World Energy Supply

Steve Fetter

May 1999

Steve Fetter, a 1996–97 Science Fellow at CISAC, is an associate professor in the School of Public Affairs at the University of Maryland and director of the environmental policy specialization. A physicist by training, his research interests include nuclear arms control and nonproliferation and climate change and world energy supply.

The Center is grateful to Carnegie Corporation of New York for supporting this research.

ISBN 0-935371-54-0

Contents

Climate Change and the Transformation of World Energy Supply

Steve Fetter

Introduction

In December 1997, world attention turned to Kyoto, Japan, where parties to the Framework Convention on Climate Change (FCCC) negotiated a protocol to reduce the greenhouse-gas emissions of the industrialized countries by 5 percent below 1990 levels over the next ten to fifteen years.[1] The agreement has been attacked from both sides. Environmental groups assert that much deeper reductions are urgently needed. Opponents claim that the proposed reductions are either unnecessary or premature, would curtail economic growth, or would be unfair or ineffective without similar commitments by developing countries.

Both groups overstate the importance of near-term reductions in emissions. The modest reductions called for by the Kyoto agreement are a sensible first step, but only if they are part of a larger and longer-term strategy. Indeed, near-term reductions can be counterproductive if they are not implemented in a manner that is consistent with a long-term strategy to stabilize greenhouse-gas concentrations.

The centerpiece of any long-term strategy to limit climate change is a transformation in world energy supply in which traditional fossil fuels are replaced by energy sources that do not emit carbon dioxide. This transformation must begin in earnest in the next ten to twenty years, and must be largely complete by 2050. Today, however, all carbon-free energy sources have serious economic, technological, or environmental drawbacks. If economically competitive and environmentally attractive substitutes are not widely available in the first half of the next century, it will be impossible to stabilize greenhouse-gas concentrations at acceptable levels. The most urgent need today—more urgent than immediate reductions in emissions—is a broad-based program of energy research and development aimed at eliminating these drawbacks.

This report outlines the changes in energy supply that will be required over the next fifty years. I describe the ultimate objective of controls on greenhouse-gas emissions and set a stabilization target for greenhouse-gas concentrations that is designed to achieve this objective. I translate this target into limits on the emission of carbon dioxide and the burning of fossil fuels over the next century, and estimate requirements for carbon-free energy supply over this period. Finally, I describe options for achieving this transformation in world energy supply and outline near-term research and development priorities.

In briefest summary, an equivalent doubling of carbon dioxide is the highest stabilization target that can be justified given what we know about the sensitivity of climate to increased greenhouse-gas concentrations and the impacts of climate change. In order to stabilize greenhouse gases at this level, traditional fossil fuels could supply no more energy in 2050 than they supply today. Global energy consumption is expected to double or triple over the next fifty years, however, driven by increases in population and per-capita income in developing countries. The amount of energy supplied by carbon-free sources must therefore grow by a factor of ten to twenty during the next half century, from 15 percent of commercial energy supply to 60 to 80 percent.

Only five energy sources are capable of providing a substantial fraction of this non-carbon supply: solar, fission, "decarbonized" fossil fuels, and, to a lesser extent, biomass and wind. Other potential sources are either too limited (hydro-, tidal power, and hot-water geothermal), too expensive (ocean thermal and wave energy), or too immature (fusion and hot-rock geothermal) to make a substantial contribution by 2050. Each of the five major alternatives currently has significant technical, economic, and/or environmental handicaps. Solar is benign but expensive, and would require massive energy storage or intercontinental transmission. Fission can produce electricity at competitive prices today, but suffers from public-acceptance problems related to the risks of accidents, waste disposal, and the spread of nuclear weapons. Coal is cheap and abundant, but the cost and environmental impact of capturing, transporting, and disposing of the carbon dioxide could be unacceptably high. Biomass has the potential to supply low-cost portable fuels, but energy crops could compete with food production and the preservation of natural ecosystems. Wind is economically competitive in certain areas, but attractive sites are limited.

The most urgent need, therefore, is an intensive program of research and development to address these shortcomings, and thereby ensure that abundant, inexpensive, and acceptable substitutes will be available worldwide when they are needed. Unfortunately, current energy research and development programs, in the United States and worldwide, are woefully inadequate in scope and in scale to meet this challenge. A doubling or tripling in energy R&D can easily be justified based on the need to avoid dangerous changes in climate, as well as the desire to avoid air pollution and to protect against disruptions in energy supply. As a modest step to correcting the deficiency of energy R&D, I would propose instituting a tax of $1 per ton of carbon, with the proceeds directed to a fund for carbon-free energy R&D. A tax of $1 per ton would raise fossil-fuel prices by only about 1 percent, while having the potential to avoid much larger taxes—or even larger climate-change damages—in the not-too-distant future.

Climate Change

It is useful to begin with a brief review of the science of climate change. In equilibrium, Earth absorbs solar energy at an average rate of 235 watts per square meter (W/m^2) and radiates infrared energy into space at an equal rate. Because the average rates of absorption and emission are equal, no energy accumulates in the climate system and the average temperature is stable. Objects that absorb and emit energy at this rate have a temperature of about –20 °C.[2] If the atmosphere was transparent to infrared energy, this would be the average surface temperature of Earth.

In fact, the average surface temperature is much warmer—about 15 °C. This is because certain gases in the atmosphere—"greenhouse gases"—absorb and reradiate most of the infrared energy emitted by the surface. The trapping or recycling of infrared energy increases the temperature of the atmosphere and oceans to the point where the flow of infrared energy to space equals the absorption of solar energy. This "greenhouse effect" keeps the surface of Earth 35 °C warmer than it otherwise would be.

The gas responsible for most of the natural greenhouse warming is water vapor.[3] The atmosphere also contains other trace greenhouse gases, including carbon dioxide, methane, and nitrous oxide, that contribute to this warming. Human activities—particularly fossil-fuel burning and agriculture—have resulted in significant increases in the concentrations of these trace gases over the last century. The concentration of carbon dioxide has risen by 30 percent, from about 280 parts per million by volume (ppmv) to over 360 ppmv today, and the concentration of methane has more than doubled. As the concentrations of greenhouse gases rise so will the rate at which infrared energy is absorbed by the atmosphere, and the surface temperature will increase until the balance between the rates of energy absorption and emission is restored.

The existence of the greenhouse effect is not in dispute. The debate is over how climate will respond to an enhanced greenhouse effect. The climate system is enormously complicated, and there are very large uncertainties in our understanding of how most climate variables would respond to increases in greenhouse-gas concentrations. Estimates of the average long-term temperature change that would accompany a doubling of carbon dioxide vary from less than 1.5 °C to more than 4.5 °C, with a best estimate of 2.5 °C.[4] The wide range is due largely to uncertainties about how cloud cover, ocean currents, and vegetation would change as the atmosphere warms.

There is much more to climate change than a long-term increase in global-average temperature. Changes in other climate variables—for example, precipitation, evaporation, cloud cover, and wind velocity—may be of greater consequence than changes in temperature, and changes in regional climate are more important than changes in global averages. For example, global precipitation is predicted to increase by 5 to 15 percent under a doubling of carbon dioxide, but some regions, such as the middle of North America, could become drier because of even greater increases in evaporation.[5] In addition, changes in the variability of climate are often more important than changes in average climate. For example, the incidence of drought and violent storms could increase even while average precipitation remains constant. Predicted changes in global-average surface temperature should be thought of as a shorthand reference for the myriad changes in climate—in space and in time—that would be associated with this change in temperature.

The Climate Convention

In response to concerns that increasing concentrations of greenhouse gases might lead to harmful changes in climate, the Framework Convention on Climate Change (FCCC) was negotiated in Rio de Janeiro in 1992. The objective of the Convention is stated in Article 2:

> The ultimate objective of this Convention…is to achieve…stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time-frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner.[6]

The Convention does not specify the stabilization level that would "prevent dangerous anthropogenic interference with the climate system." A committee of scientists—the Intergovernmental Panel on Climate Change (IPCC)—was established to advise the Parties on this and related questions. In 1995, the IPCC completed its "Second Assessment"—a massive, three-volume report that summarizes nearly everything that is known about climate change.[7] The report focuses on the changes in climate and related impacts that would result from a doubling of carbon dioxide concentrations and the costs of mitigating such changes. It is up to the Parties to use this information to formulate policies that would achieve the goal of the Convention.

How Much Climate Change Is "Dangerous"?

The Convention did not set a stabilization target, but it did state broad principles for determining what the target should be. The target should be set so as to (1) prevent dangerous interference with the climate system, within a time frame sufficient to (2) allow ecosystems to adapt, (3) ensure that food production is not threatened, and (4) enable sustainable economic development. Below I review the available evidence on each of these points.

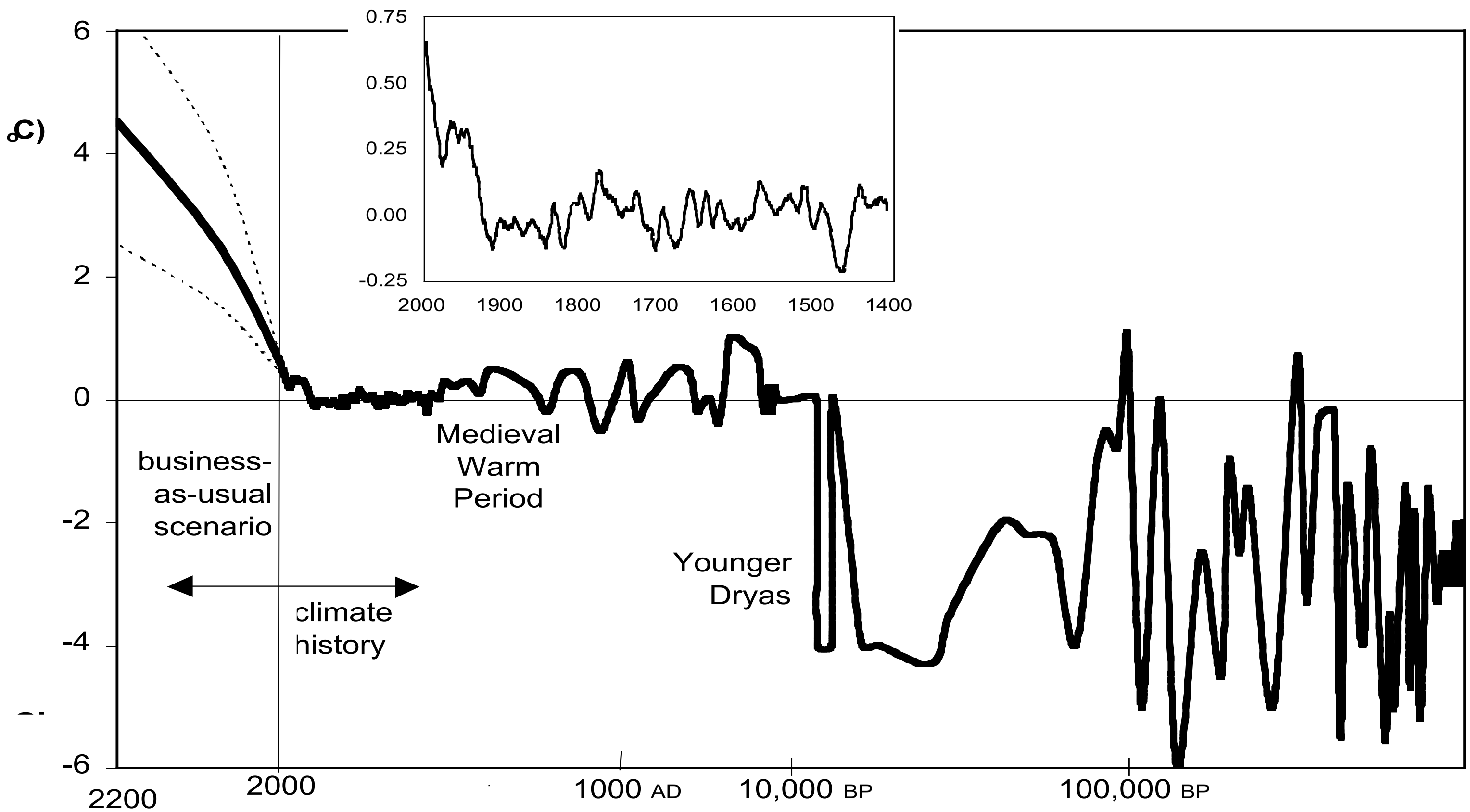
Interference with the Climate System

Past climates provide useful benchmarks for interpreting the significance of projected changes in climate, and the degree to which such changes would represent "dangerous interference" with the climate system. Figure 1 shows, in a schematic way, how the average temperature of Earth has varied over the last million years. Also shown are estimates of future changes in temperature expected in a "business-as-usual" scenario, in which greenhouse-gas concentrations reach an equivalent doubling of carbon dioxide by 2070 and continue to increase thereafter. Several features of this temperature history deserve attention.

First, global-average temperature has increased by about 0.5 °C over the last seventy years, consistent with estimates based on the increase in greenhouse gases during this period.[8] This warming has been accompanied by the retreat of mountain glaciers, a 1 percent increase in precipitation over land, an increase in cloud cover, and a 10 to 25 cm rise in sea level—all of which are consistent with predictions based on an enhanced greenhouse effect.[9] The last decade is the warmest period since at least 1400,[10] and one of the warmest in the last ten thousand years.

Second, average temperature has been relatively stable for the last ten thousand years, with variations of about 1 °C. This period of stable climate coincides with the development of agriculture and human civilization. However, even these relatively small variations in global-

Figure 1. Variations in average surface temperature over the last million years.



Sources: 1 million years BP to AD 1400: C.K. Folland, T.R. Karl, and K.Y.A. Vinnikov, "Observed Climate Variations and Change," in J.T. Houghton, G.J. Jenkins, and J.J. Ephraums, eds., *Climate Change: The IPCC Scientific Assessment* (Cambridge: Cambridge University Press, 1990), p. 202; AD 1400 to 1850: Michael E. Mann, Raymond S. Bradley, and Malcolm K. Hughes, "Global-scale Temperature Patterns and Climate Forcing over the Past Six Centuries," *Nature* 392 (23 April 1998), pp. 779–787, http://www.ngdc.noaa.gov/paleo/pubs/mann1998/frames.htm; AD 1850 to 1998: J. Hansen, R. Ruedy, Mki. Sato, and R. Reynolds, "Global Surface Air Temperature in 1995: Return to Pre-Pinatubo Level," *Geophysical Research Letters* 23 (1996), pp. 1665–1668, http://www.giss.nasa.gov/data/gistemp; AD 2000 to 2200: M. Hulme, S.C.B. Raper, and T.M.L. Wigely, "An Integrated Framework to Address Climate Change (ESCAPE) and Further Developments of the Global and Regional Climate Models (MAGICC)," *Energy Policy* 23 (1995), pp. 347–355, assuming a total radiative forcing in 1990 of 1.32 W/m^2 and a climate sensitivity of 1.5 to 4.5 ϒC, for the range of IS92 scenarios.

average temperature were associated with significant changes in regional climate that had important consequences for ecosystems and human societies. For example, during the Holocene Optimum four to six thousand years ago, when global-average temperature was about 1 °C higher than at present, forest boundaries were shifted up to 250 kilometers, the tropics were wetter and experienced catastrophic floods four to ten times greater than those witnessed today, and temperate latitudes were significantly drier.[11] During the Medieval Warm Period between A.D. 1100 and 1300, when temperatures in Europe were about 1 °C higher than at present, the Vikings colonized Greenland and wheat was grown as far north as the Arctic Circle. The subsequent cool period known as the "Little Ice Age," when average temperatures in Europe and China were 0.5 to 1 °C lower than at present, was accompanied by violent storms and floods, crop failures, widespread famine, and devastating epidemics.[12]

Third, over the last two million years the climate has oscillated between long ice ages and shorter interglacial periods, with a period of about one hundred thousand years. During the last ice age, average temperature and sea level were about 5 °C and 120 meters lower than at present; during the last interglacial period, temperature and sea level were about 2 °C and 5 meters higher than at present. These changes in temperature, which were accompanied by dramatic shifts in the distribution of vegetation, are comparable in magnitude to that which would accompany a doubling of the carbon dioxide concentration.

Glacial periods are correlated with variations in Earth's orbit, which change the amount of summer sunshine received by the poles.[13] These variations in sunshine are too small, by themselves, to account for the observed changes in climate. There must exist feedback mechanisms in the climate system—for example, changes in the biosphere or ocean currents—that amplified the warming, shifting the climate system from one equilibrium state (a cold state) to another equilibrium state (a warm state) and back again. The sensitivity of the climate system to modest variations in sunshine should make us wary about its sensitivity to changes caused by increased greenhouse-gas concentrations.

Fourth, past shifts in climate sometimes have been very rapid. For example, as Earth emerged from the last ice age 13,000 years ago, the climate suddenly returned to ice-age conditions; 1,300 years later, a warming in the Arctic of 5 to 10 °C occurred over several decades or less, after which the current warm climate has prevailed.[14] These temperature shifts, although accentuated in the polar regions, were global events, and were accompanied by dramatic changes in precipitation and wind patterns.

It is thought that these rapid shifts in climate may have been caused by a switching on or off of the North Atlantic thermohaline circulation, which today transports huge quantities of heat northward, keeping Europe much warmer than other regions at the same latitude. This current is driven by the sinking of salty water near Greenland and Iceland, allowing warm water to flow much farther north than it otherwise would. The rapid warming at the end of the last ice age might have caused a large influx of fresh water into the North Atlantic, either from melting ice or increased precipitation, diluting the salty surface waters and causing the thermohaline circulation to collapse.

Whatever caused the rapid changes in climate at the end of the last ice age, these episodes alert us to the possibility that rapid, large-scale changes in climate might be triggered if greenhouse-gas concentrations increase beyond some threshold. Models indicate that the threshold for a collapse of the thermohaline circulation might be as low as an equivalent doubling of carbon dioxide.[15] Such an event, if it happened today, would have devastating effects on global agriculture and human civilization.[16]

Ecosystem Adaptation

Ecosystems—communities of plant and animal species—are adapted to the climates in which they are found. If climate changes, the geographical distribution of ecosystems will change as species migrate to areas where the climate has become favorable to their existence, and as existing species are displaced by those better suited to the new climate of an area.

The Climate Convention states that greenhouse gases should be stabilized in a manner that would allow ecosystems to "adapt naturally," but it is unclear what this means. On the one hand, almost any change in climate will cause lasting disruptions in some ecosystems and the extinction of some species. On the other hand, ecosystems have been adapting to changes in climate for eons, although this has involved widespread changes in the distribution of vegetation and, occasionally, mass extinctions. A reasonable interpretation of the Convention might be that climate change should not cause major changes in the distribution of ecosystems, or that the rate of climate change should not exceed the capacity of most species to migrate naturally to favorable climates, and therefore should not result in the creation of large "dead zones" in which existing vegetation has died before species better adapted to the new climate could take its place.

Again, useful benchmarks are provided by the response of the biosphere to past changes in climate. Following the last ice age, tree species migrated northward at rates of 4 to 200 kilometers per century.[17] Since average temperature decreases as one moves north by about 1 °C per 150 kilometers, a warming of 1 to 2.5 °C per century—the range of forecasts for an equivalent doubling of carbon dioxide over the next century—would imply a migration rate of 150 to 400 kilometers per century. Most plant species would not be able to keep pace with this rate of change.

The effects of climate change on ecosystems also can be estimated with computer models, although existing models are crude and can predict only steady-state conditions, and they ignore species interactions.[18] In general, an increase in carbon-dioxide concentrations and associated increases in temperature and precipitation should promote plant growth, except in areas where the additional precipitation does not compensate for the increase in evaporation. Under the climate conditions predicted for a doubling of carbon dioxide concentrations, models indicate that present-day vegetation patterns would change over 20 to 40 percent of the world's surface area. Current vegetation boundaries would shift by 300 to 1,000 kilometers, with an overall expansion in the area of temperate and tropical forests.[19] In addition, rising sea levels would cause wetlands to be lost at a faster rate than new wetlands would be created.

Food Production

As noted above, climate changes associated with relatively small changes in average temperature caused widespread disruptions in agriculture hundreds of years ago. The capacity of human societies to modify agricultural practices in response to changes in climate has increased greatly since that time, particularly in developed countries. One study concluded that, under the climate conditions predicted for a doubling of carbon dioxide, total world grain production would decline up to 5 percent, compared with what it would have been in 2060 without climate change.[20] This assumed only a modest level of adaptation (changes in crop variety and shifts in planting dates). With a greater degree of adaptation (changes in crops and additional irrigation), the study concluded that global harvests could be maintained at no-climate-change levels.

This optimistic assessment must be qualified in several ways, however. First, the study predicted that, although global grain output might remain fairly constant, the output of certain regions could decrease significantly. In the case where global output decreased by up to 5 percent, for example, production in developing countries dropped 9 to 12 percent while the output of industrialized countries increased 4 to 14 percent. Unless there are reliable mechanisms to transfer grain, severe shortages could arise in developing countries in such a scenario. Second, projected agricultural productivity was based on seasonal averages of temperature and precipitation; the effect of possible increases in climate variability (e.g., storms and drought) was not evaluated. Third, impact studies generally focus on the steady-state situation, after a new climate state has been established, or assume that the transition from the old to the new climate will be gradual. Possible disruptions caused by sudden shifts in climate have not been examined. It would take only one year of widespread crop failures to wipe out global grain reserves.[21]

Economic Development

Article 2 of the Climate Convention also states that greenhouse gases should be stabilized in a way that enables "economic development to proceed in a sustainable manner." Much attention has been given to the economic costs of climate change and of mitigating greenhouse-gas emissions. Most of this work has not focused on the question of "sustainable development" per se, but on traditional economic measures of the costs of climate change.

Monetary cost is an aggregate measure that includes many factors that contribute to individual and social well-being. Most studies of the economic impact of climate change have included costs associated with sea-level rise, forest and fishery losses, and changes in agriculture, energy demand, hurricane damage, and water supply—all of which can be estimated with reference to market prices. Although a few studies have attempted to monetize certain non-market impacts, such the value of ecosystem and species loss, air and water pollution, and human death, illness, and discomfort,[22] they miss more than they capture. In addition, cost studies generally have not considered the effects of possible increases in climate variability or rapid changes in climate.

With these caveats in mind, the expected cost of impacts associated with a 2.5 °C average temperature increase is estimated at 1 to 2 percent of gross domestic product (GDP) for developed countries, 2 to 9 percent for developing countries, and about 2 percent for the world as a whole.[23] For comparison, 2 percent of current gross world product (GWP) is about $500 billion per year. For some countries, such as low-lying islands, losses could be a much greater percentage of GDP. Including unquantified non-market costs could increase these estimates substantially.

The costs cited above are best estimates for a single set of equilibrium climate conditions. There is, however, great uncertainty in these estimates. Climate might change rapidly or become more variable, or changes in climate might have unforeseen and costly impacts. In a poll of nineteen experts conducted by Nordhaus, best guesses of the cost of a 3° warming by 2090 centered around 2 percent of GWP, but ranged from 0 to 20 percent.[24] Half of the experts believed that there is at least a 10 percent chance that total costs would be greater than 6 percent of GWP. Estimates increased for a faster or larger warming. The average respondent believed that costs would triple if the temperature increase doubled (i.e., 6 instead of 3 °C by 2090), with the probability of a "climate disaster" (costs greater than 25 percent of GWP) growing by a factor of ten, to 5 percent.

How Sensitive Is Climate?

Greenhouse gases warm the atmosphere by absorbing infrared radiation. If everything about the climate system could be held constant except temperature—cloud cover, water vapor, sea ice, ocean current, vegetation, and so forth—a doubling of the carbon dioxide concentration would cause the average surface temperature to increase by 1.2 °C. About this there is no scientific dispute. But the initial warming triggers numerous other changes in the climate system, some that amplify the warming (positive feedback mechanisms) and others that diminish it (negative feedbacks). For example, higher surface temperatures will result in more evaporation, increasing the concentration of water vapor and the absorption of infrared radiation. In most models, this "water-vapor feedback" roughly doubles the warming of the carbon dioxide alone. Clouds, which both reflect sunlight and absorb infrared radiation, could provide either a net positive or negative feedback, depending on how the amount of different types of clouds would change as Earth warms. Other important feedback mechanisms include changes in snow and ice cover (which affects the amount of sunlight absorbed), in the growth and decay of vegetation (which affects the atmospheric concentrations of carbon dioxide and methane), and in ocean circulation (which affects the global transport of heat energy). Some potentially important feedback mechanisms have not been adequately quantified or incorporated into models.

Three-dimensional computer models of the climate system—"general circulation models" (GCMs)—are used to predict the changes in climate that would result from an increase in carbon-dioxide concentrations, taking into account various feedback mechanisms. The long-term (i.e., equilibrium) increase in global-average surface temperature that would result from a doubling of the carbon dioxide concentration, DT_{2x}, is often referred to as the "climate sensitivity" of a model.

Table 1 summarizes the range of values for DT_{2x} given by seven of the most sophisticated GCMs. Most of the variation in DT_{2x} can be traced to differences in how clouds are modeled, which indicates that an improved understanding of cloud formation is critical to narrowing the uncertainties. Also shown in Table 1 is the collective judgment of the IPCC (unchanged since 1990) and the results of a poll of experts. Note that the expert judgments have a somewhat lower best estimate and a larger range of uncertainty. Each of these sources indicates that there is a small but significant chance that the climate sensitivity could be as high as 4.5 °C.

Table 1. The climate sensitivity (equilibrium temperature change from a doubling of CO_2) estimated by 7 GCMs, the IPCC, and a poll of 16 climate scientists.

Estimate	Climate Sensitivity, ΔT_{2x} (°C) Median	Range
7 GCMs	3.5	2.1 – 4.6
IPCC	2.5	1.5 – 4.5
16 experts	2.8	1.0 – 5.5

Sources: J.T. Houghton, et al., *Climate Change 1995: The Science of Climate Change* (Cambridge: Cambridge University Press, 1996), p. 34, 298–299; M. Granger Morgan and David W. Keith, "Subjective Judgments by Climate Experts," *Environmental Science and Technology*, Vol. 29, No. 10 (1995), pp. 468–476. Range for experts is the median of the 5th and 95th percentiles.

The climate sensitivity refers to the increase in temperature over the long term, which may take hundreds of years to realize fully. The rate of temperature increase depends on the rate at which carbon-dioxide concentrations increase. Most GCM experiments assume an increase of 1 percent per year for carbon dioxide, which gives rates of temperature increase of 1.7 to 5 °C per century, depending on climate sensitivity.[25] If carbon-dioxide concentrations stabilize at a doubling by about 2100, models indicate that average temperature would increase by 1 to 2.5 °C over the next century.

Defining a Stabilization Target

The Kyoto Protocol limits the rate of emission of greenhouse gases by certain countries. At some point, limits on emissions will have to be linked to an agreed "stabilization target" or cap on the atmospheric concentrations of greenhouse gases. Rather than set limits for each gas, the stabilization target probably will be given as an equivalent concentration of carbon dioxide, with other greenhouse gases, such as methane and nitrous oxide, accounted for by estimating the concentration of carbon dioxide that would have about the same effect on climate. But how will the stabilization target be chosen?

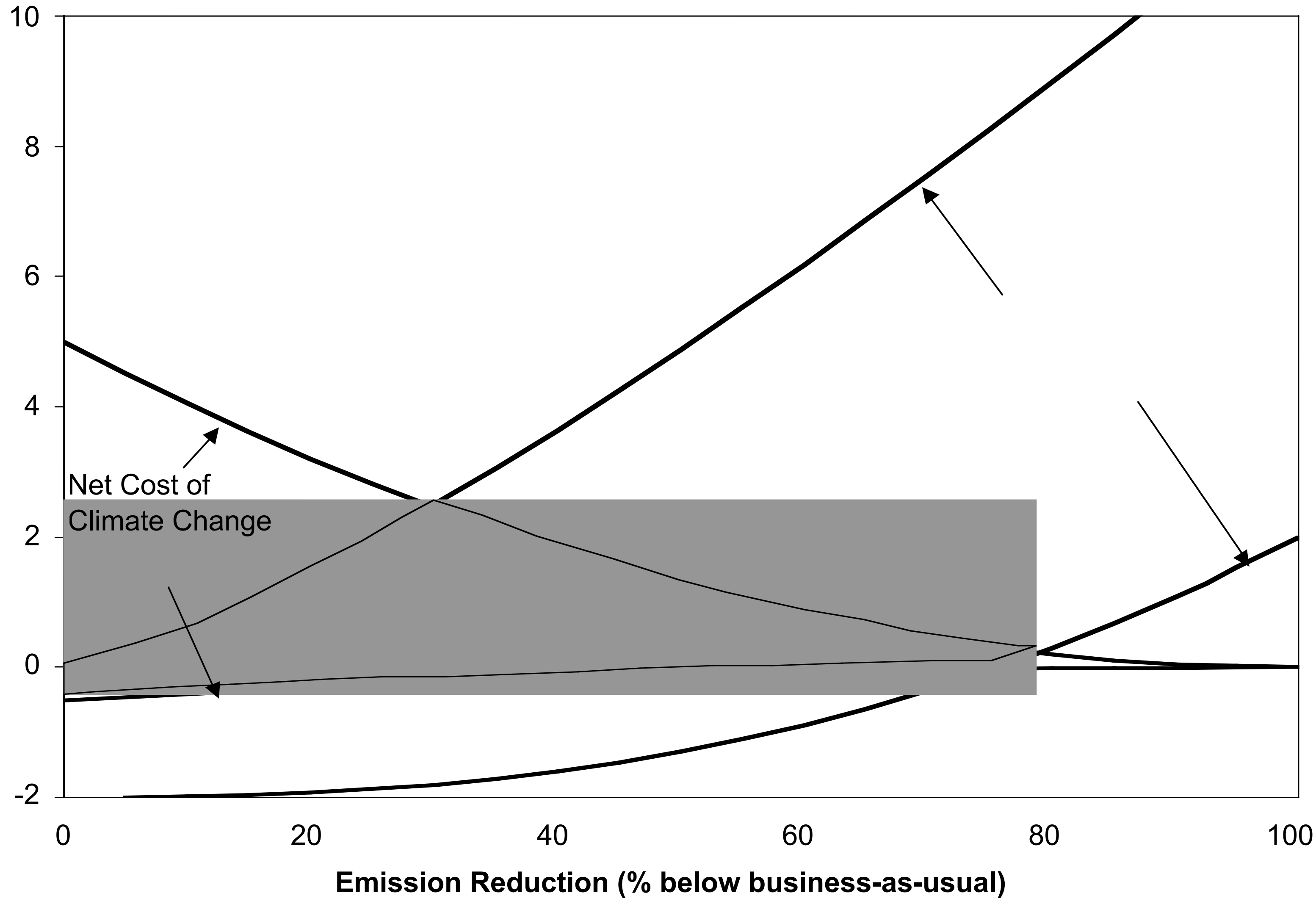
The Cost-Benefit Approach

Many analysts favor the use of cost-benefit methods to determine the stabilization target.[26] In this approach, the optimal rate of emission at a given time is achieved when the marginal benefit of reduced emissions is equal to the marginal cost of reducing emissions. Benefits include the net present value of climate-change impacts that would be avoided, as well as other benefits of reduced emissions (such as reductions in air pollution and acid deposition). Costs would be due mostly to the higher energy prices that would be necessary to reduce consumption of fossil fuels.

The cost-benefit approach suffers from two serious problems. The first is that equalizing costs and benefits is not the objective of the FCCC, and probably would not achieve that objective.[27] The second problem is practical: it is impossible to determine the benefits and costs of emission controls with any accuracy. The changes in climate that would result from a given set of greenhouse-gas concentrations and the impacts on human and natural systems that would result from a given change in climate are highly uncertain. Even if changes in climate and associated impacts were specified precisely, it would be extremely difficult to attach accurate monetary value to impacts on environmental goods and services. And even if all impacts could be monetized, the uneven geographical and temporal distribution of costs and benefits would be problematic. Some developing nations could be very seriously affected—even destroyed—by changes in climate; should these costs be weighed equally with costs in industrialized countries, even when the former would result in much greater suffering? At what rate should future costs and benefits be discounted?

Figure 2 illustrates the practical problem with cost-benefit analysis. Estimates of the costs and benefits of a given reduction in emissions cover so large a range that this approach offers little guidance to policymakers. Depending on one's assumptions, either massive or minimal reductions can be justified. The computations rely on so many assumptions and parameters, most of which are highly uncertain, that it is impossible to say which, if any, of these estimates are more credible. Nor is there any reason to believe that this approach will yield substantially more coherent results in the foreseeable future.

Figure 2. The application of cost-benefit analysis to climate change: estimated costs and benefits cover such a wide range that the optimum level of control is impossible to determine.



Standards-Setting Approach

An alternative approach is to select a stabilization target that would be likely to achieve the objective laid out in Article 2 of the FCCC, based on expert review of the available scientific evidence. Once this goal is set, cost-benefit techniques could be used to chart the least-cost path to achieving the goal. As scientific evidence accumulates about climate change and its impacts, the stabilization target could be revised.

This approach is conceptually similar to that used in setting other environmental and public-health standards, in which a maximum level of risk is set and standards are developed to ensure that this level of risk will not be exceeded. If there is uncertainty about the risk from a given level of exposure, conservative values are chosen so that the probability that the maximum risk would be exceeded is low (e.g., 5 percent).

Under this type of approach, it would be very difficult to justify a stabilization target greater than an equivalent doubling of carbon dioxide. If climate sensitivity is near the upper end of current estimates, stabilization at this level would result in an increase in average temperature of as much as 4.5 °C, and 2.5 °C over the next century. In this case, significant changes would be certain and the risk of catastrophe would be substantial. Even the "best estimate" climate sensitivity—an equilibrium increase of 2.5 °C and an increase of 1.5 °C over the next century—would entail a significant risk of "dangerous interference" with the climate system. Given what we know today, an equivalent doubling is the highest stabilization target that can be justified under Article 2 of the Climate Convention. Several parties to the FCCC, including the European Union, have also expressed this view.[28]

The stabilization target can be expressed in terms of the "instantaneous radiative forcing," or the change in the energy balance of the climate system that would result from an instantaneous change in greenhouse-gas concentrations. For carbon dioxide, the relationship between radiative forcing, ΔF_{CO_2}, and concentration, C, is given by

$$\Delta F_{CO_2} = 6.3 \log_e(C/C_0) \quad W/m^2 \qquad (1)$$

where C_0 is the preindustrial concentration of carbon dioxide (about 280 ppmv). A doubling of carbon dioxide produces a radiative forcing of 4.4 watts per square meter (W/m^2). An "equivalent doubling" of carbon dioxide is any set of concentrations of greenhouse gases that produce a combined radiative forcing of 4.4 W/m^2. The "equivalent carbon dioxide concentration," C_{eq}, is given by:

$$C_{eq} = C_0 e^{\Delta F/6.3} \qquad (2)$$

where ΔF is the total radiative forcing due to all greenhouse gases.

Over the last 150 years, deforestation and the burning of fossil fuels have increased the concentration of carbon dioxide from about 280 to 363 ppmv, producing a radiative forcing of 1.6 W/m^2. The total radiative forcing, including contributions from other long-lived greenhouse gases, is 2.6 W/m^2, which is equivalent to a carbon-dioxide concentration of about 420 ppmv.[29] Thus, we already are halfway toward an equivalent doubling of carbon dioxide.

Limits on Fossil-Fuel Emissions

The goal of the Climate Convention is to stabilize the concentration of greenhouse gases at a level that would prevent dangerous interference with the climate system. Although it is important to stabilize the concentrations of all greenhouse gases, including methane, nitrous oxide, and halocarbons, I will focus on carbon dioxide because it is the largest contributor to the enhanced greenhouse effect. I will further restrict my focus to fossil-fuel CO_2 emissions, because these represent 80 percent of all emissions. and because the use of fossil fuels is easier to regulate and monitor than most other activities that generate greenhouse gases. In order to translate a stabilization target into limits on the emission of carbon dioxide from the burning of fossil fuels, we must subtract the long-term contribution of other greenhouse gases, determine the emission pathway that would lead to stabilization at the desired level, and account for emissions of carbon dioxide from sources other than fossil fuels.

Other Greenhouse Gases

Increased concentrations of other greenhouse gases—methane, nitrous oxide, and halocarbons—currently produce a combined radiative forcing of about 0.9 W/m^2, compared with 1.6 W/m^2 for carbon dioxide. Below I estimate the long-term concentrations and radiative forcings of these other gases, in the context of an effort to stabilize greenhouse-gas concentrations at an equivalent doubling. The long-term effect of ozone and aerosols can be ignored in this context.[30]

Methane. Methane is the second-most-important greenhouse gas affected by human activity. Concentrations of methane have risen from a preindustrial level of 0.7 ppmv to 1.76 ppmv in 1997, contributing a radiative forcing of about 0.5 W/m^2. About 70 percent of current emissions are anthropogenic, of which about 75 percent is due to agriculture and waste disposal and 25 percent is due to fossil fuels.[31]

Strategies exist for reducing methane emissions from most identified sources, but the practical potential for reductions is limited. Fossil-fuel-related emissions could be reduced substantially, but population and economic growth are likely to increase agricultural and waste-related emissions despite abatement efforts. For example, the largest source of methane emissions—domestic livestock—could be reduced by up to 40 percent through improvements in feeding and manure management.[32] The population of Earth is expected to double, however, and the average diet will include more meat as incomes rise in developing countries. The resulting increase in the number of animals will more than offset any decrease in emissions per animal, leading to a net increase in methane emissions from this source.

Natural emissions of methane could increase or decrease as carbon dioxide concentrations and temperatures rise, depending on changes in soil moisture. Methane concentrations nearly doubled at the end of the last ice age as ice sheets melted and the area covered by wetlands grew. One study estimates that natural emissions could increase by up to 40 percent if carbon dioxide concentrations double.[33] The release of methane from ocean hydrates also has the potential to increase natural emissions in response to climate change.[34]

If emissions remained constant at today's level, methane concentration and radiative forcing would stabilize in forty years at about 1.9 ppmv and 0.55 W/m^2, respectively.[35] In reference scenarios developed by the IPCC—that is, scenarios that assume no policies to reduce greenhouse-gas emissions—methane concentrations in 2100 range from 2.1 to 4.7 ppmv, corresponding to radiative forcings of 0.6 to 1.4 W/m^2.[36] Taking into account the various sources of uncertainty, a program of emission reductions might be able to limit long-term concentrations of methane to 1.4 to 2.6 ppmv, corresponding to a radiative forcing of 0.55 ± 0.2 W/m^2.[37]

Nitrous oxide. Concentrations of nitrous oxide have risen from a preindustrial level of 0.28 ppmv to 0.32 ppmv in 1997, contributing a radiative forcing of about 0.16 W/m^2. As with methane, anthropogenic emissions are mostly related to agriculture: animal wastes, fertilizers, the clearing of forests, and the burning of crop residues. The potential for reductions is likewise similar to that for methane.[38]

If emissions remained constant at today's level, nitrous oxide concentration and radiative forcing would increase to about 0.4 ppmv and 0.45 W/m^2 over a period of several hundred years.[39] In reference scenarios developed by the IPCC, nitrous oxide concentrations in 2100 range from 0.39 to 0.43 ppmv, at which point they are still rising steadily.[40] Taking into account the various uncertainties, nitrous oxide concentrations might be limited over the long term to 0.34 to 0.46 ppmv, corresponding to a radiative forcing of 0.45 ± 0.2 W/m^2.[41]

Halocarbons. Halocarbons—carbon compounds containing fluorine, chlorine, bromine, or iodine—also contribute to greenhouse warming. The most common halocarbons are chlorfluorocarbons (CFCs), which cause stratospheric ozone depletion. Although the Montreal Protocol and its Amendments will lead to a phaseout of substances containing chlorine and bromine, their residence times are so long that significant concentrations will remain in the atmosphere for over a hundred years. In addition, many CFC substitutes, as well as a number of other unregulated substances, are greenhouse gases.

Today, the radiative forcing from halocarbons is about 0.28 W/m^2.[42] Reference scenarios developed by the IPCC result in a radiative forcing of 0.3 to 0.4 W/m^2 for halocarbons in 2100.[43] Here we will assume a long-term forcing of 0.3 ± 0.1 W/m^2 in the context of efforts to stabilize greenhouse gases at an equivalent doubling.

Summary. The above discussion is summarized in Table 2. Even if vigorous efforts are made to reduce emissions of methane, nitrous oxide, and halocarbons, these gases are likely to contribute a radiative forcing of 1.3 ± 0.4 W/m^2 in the period 2100 to 2200. If greenhouse-gas concentrations are to be stabilized at an equivalent doubling (i.e., a radiative forcing of 4.4 W/m^2), the forcing due to carbon dioxide must be limited to 3.1 ± 0.4 W/m^2. The corresponding carbon dioxide concentration is 460 ± 30 ppmv. At current growth rates, such concentrations would be attained in forty to eighty years.

Table 2. The limit on the carbon dioxide concentration for stabilization at an equivalent doubling, after subtracting the long-term radiative forcing from methane, nitrous oxide, and halocarbons.

Gas	Concentration (ppmv)	Radiative Forcing (W/m^2)
Stabilization target (equivalent CO_2)	560	4.4
Methane	2.0 ± 0.6	0.55 ± 0.2
Nitrous oxide	0.4 ± 0.06	0.45 ± 0.2
Halocarbons	—	0.3 ± 0.1
Limit on CO_2	460 ± 30	3.1 ± 0.4

Carbon Emissions

Carbon dioxide emitted into the atmosphere is absorbed by the oceans and by plants on timescales ranging from months to centuries. Over the first few decades, about half of the emitted carbon dioxide is absorbed by the surface layer of the oceans and by the growth of additional vegetation in response to increased carbon-dioxide concentrations. The deep oceans absorb most of the remaining excess carbon dioxide over a period of several thousand years.

Carbon-cycle models, which simulate these processes, can be used to predict the carbon-dioxide concentrations that would result from a given set of emissions. In an inverse mode, these models can be used to estimate the rates of emission that would lead to stabilization at a given carbon-dioxide concentration. Table 3 gives estimates of the rate of emission that would stabilize carbon-dioxide concentrations at 460 ± 30 ppmv in the period 2100 to 2150.[44] The error in these estimates includes uncertainties in modeling and in model parameters, as well as uncertainties in the rate at which stabilization is achieved.[45]

Table 3. Anthropogenic carbon emissions for stabilization of CO_2 concentration at 460 ± 30 ppmv (an equivalent doubling.)

Year	Anthropogenic Carbon Emissions (GtC/yr)	Cumulative Emissions since 1995 (GtC)
1995	7.5 ± 0.9	0
2025	8.9 ± 2.1	270 ± 50
2050	6.0 ± 2.2	460 ± 100
2075	4.4 ± 2.0	590 ± 150
2100	3.3 ± 1.5	680 ± 200
2150	2.1 ± 1.0	810 ± 260

Source: T.M.L. Wigely, "Balancing the Carbon Budget: Implications for Projections of Future Carbon Dioxide Concentration Changes," *Tellus*, Vol. 45B, pp. 405–425. Values are adjusted to represent median of ten carbon-cycle models. Uncertainties represent approximate 90-percent confidence intervals, and include uncertainties in the stabilized CO_2 concentration and rate of CO_2 increase with time, in rate of CO_2 uptake by the biosphere and oceans, and variations between models.

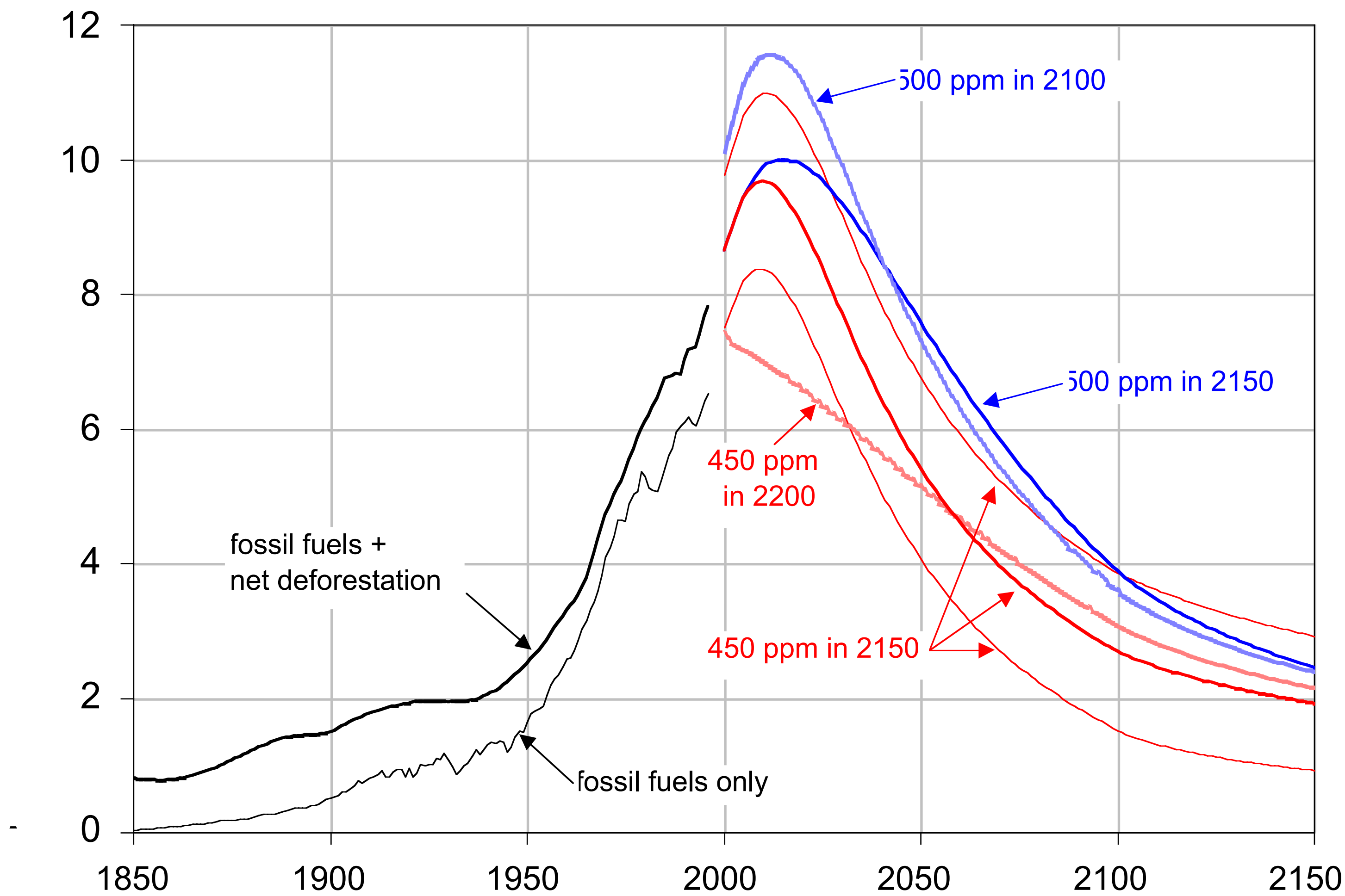
These results are given in graphical form in Figure 3, for stabilization at 450 and 500 ppmv. Also shown are emissions for a more gradual approach to 450 ppmv and for a more rapid approach to 500 ppmv.[46] Two features of this figure are particularly worthy of attention.

First, carbon-dioxide emissions must peak no later than 2020 for stabilization at an equivalent doubling. This conclusion is insensitive to the many assumptions and uncertainties mentioned above. After peaking, carbon-dioxide emissions must decline to levels below the current rate of emission by 2050, and to no more than half that rate by 2100.

Second, the stabilized concentration of carbon dioxide is determined primarily by rates of emission in the second half of the next century. A slower approach to stabilization would require immediate reductions in emissions, but would allow only slightly higher emissions over the long term. Conversely, a more rapid approach to stabilization would permit much higher emissions in the near term at the expense of slightly lower emissions over the long term. The total amount of carbon dioxide that can be emitted over the next 100 to 150 years is greater for a more-rapid approach to stabilization because near-term carbon emissions will largely be absorbed by the oceans and the biosphere by the time stabilization is achieved. In other words, emissions can be allowed to increase substantially over the next ten to twenty years, as long as they are reduced below the current level by 2050.[47]

This observation has policy implications. The stabilization target can, to a first approximation, be translated into a target for the rate of carbon emissions in 2050. Reductions in emissions over the next ten or twenty years are important only insofar as they help achieve the target in 2050. In general, it is probably better to invest money in future reductions (via energy research and development) than to pay for costly reductions today.[48]

Figure 3. Historical emissions of carbon from fossil-fuel burning and land-use changes, and emission pathways that stabilize carbon dioxide concentrations at 450 and 500 ppmv in the period 2100 to 2200.



Source: Author's calculations based on results from the model described in T.M.L. Wigley, "Balancing the Carbon Budget: Implications for Projections of Future Carbon Dioxide Concentration Changes, *Tellus*, Vol. 45B, pp. 405–425.

Non-fossil-fuel Carbon Emissions

Anthropogenic carbon-dioxide emissions are due mostly to fossil-fuel burning, but deforestation, cement manufacture, and climate feedbacks also could make significant contributions. In order to estimate the amount of carbon dioxide that could be released from fossil-fuel burning, we must account for emissions from these other sources. Unfortunately, the uncertainties in emissions from land-use and climate changes are very large.

Land-use changes. During the 1980s, it is estimated that tropical deforestation released an average of 1.6 billion tons[49] of carbon per year (GtC/yr) and that regrowth of temperate forests absorbed 0.5 GtC/yr, for a net rate of emission of 1.1 ± 0.7 GtC/yr.[50] Future emissions are a matter of speculation. Reference scenarios developed by the IPCC and others assume rates ranging from 0 to 4 GtC/yr in 2050, with a median of about 1 GtC/yr.[51] On the other hand, scenarios that include policies to slow tropical deforestation and implement reforestation programs result in a net uptake of carbon of 0.3 to 2.2 GtC/yr in 2050.[52] Most of these scenarios converge on near-zero net emission rates in 2100, because the potential for either deforestation or reforestation would by then have been largely exhausted.

Even in the context of stabilizing carbon-dioxide concentrations, policies to curtail tropical deforestation and promote reforestation are unlikely to be entirely successful or unsuccessful. I therefore assume intermediate values here, which are given in Table 4.

Climate feedbacks. As noted above, carbon storage should increase as plant growth is stimulated by higher carbon-dioxide concentrations. This negative feedback effect is incorporated into carbon-cycle models and is reflected in the results presented in Figure 3. For stabilization at 460 ppmv, the CO_2-fertilization effect is expected to increase terrestrial carbon storage by 180 ± 140 GtC over the next 150 years.[53]

Changes in temperature and soil moisture will also lead to changes in carbon storage, although the magnitude—and even the direction—of this effect is highly uncertain. Ice core records show a strong positive correlation between carbon-dioxide concentration and temperature over the last two hundred thousand years. In this case, changes in CO_2 concentration were a consequence rather than a cause of climate change, with changes in CO_2 lagging changes in temperature by about a thousand years. The increase in global-average temperature of roughly 5 °C at the end of the last ice age was accompanied by an increase in atmospheric CO_2 of 80 ppmv or 170 GtC. Since terrestrial carbon storage also increased during this period, the additional carbon dioxide must have come from the oceans.

Future changes in climate could lead either to a net emission or absorption of carbon dioxide by the biosphere, depending on the nature and the rate of climate change and rate at which plants adapt to those changes. For example, large amounts of carbon dioxide could be emitted if mature forests die before they are replaced by new forests, if higher temperatures promote the decay of dead organic materials at high latitudes, or if drier conditions increase the frequency of forest fire. It is estimated that such processes could release up to 240 GtC over the next century, at rates of up to 3 GtC/yr.[54] On the other hand, a warmer, wetter climate might result in the expansion of tropical and boreal forests, leading to a net absorption of up to 100 GtC over several hundred years.[55]

Ecological models that include both fertilization and climate effects indicate that carbon storage will increase in response to a doubling of CO_2, but by less than would be expected from fertilization alone. For example, one model indicates that equilibrium carbon storage would be increased by 360 GtC from a doubling of CO_2 alone, but by only 290 GtC if the predicted climate changes that would accompany a doubling of CO_2 were included; another model predicts transient changes from 1860 to 2070 of 490 GtC with CO_2 only and 310 GtC with both CO_2 and climate change.[56] In other words, including climate change reduced carbon storage by 70 GtC in the first case and 180 GtC in the second. I will assume that climate feedbacks from an equivalent doubling will reduce terrestrial carbon storage by 70 ± 100 GtC over the next 150 years, a range that includes most estimates.

Cement manufacture. One-half ton of carbon dioxide is released during the production of a ton of cement, as calcium carbonate is converted into lime. In 1995, cement manufacture released 0.2 GtC. By 2050, this could be expected to increase to 0.5 GtC/yr, based on expected growth in population and per-capita income. The growth of cement manufacture should slow thereafter, as population stabilizes and per-capita demand saturates.

Table 4 summarizes rough estimates of non-fossil emissions of carbon dioxide over the next century, in the context of stabilizing greenhouse-gas concentrations at an equivalent doubling.

Table 4. Non-fossil-fuel emissions of carbon dioxide from deforestation, climate feedbacks, and cement production, for stabilization at an equivalent doubling.

	Non-fossil CO_2 Emissions (GtC/yr)				Cumulative
Year	Net Deforestation	Climate Feedbacks	Cement Production	Total	since 1995 (GtC)
1995	1.1 ± 0.7	—	0.2	1.3 ± 0.7	0
2025	0.5 ± 1	0.2 ± 0.3	0.4 ± 0.1	1.1 ± 1	40 ± 30
2050	0.2 ± 1	0.4 ± 0.6	0.5 ± 0.15	1.1 ± 1	60 ± 50
2075	–0.2 ± 1	0.5 ± 0.7	0.55 ± 0.2	0.7 ± 1	90 ± 80
2100	–0.5 ± 0.5	0.5 ± 0.7	0.6 ± 0.2	0.6 ± 1	100 ± 110
2150	0.0 ± 0.5	0.5 ± 0.7	0.7 ± 0.2	1.2 ± 1	150 ± 150

Sources: Values based on literature review in J. Leggett, W.J. Pepper, and R.J. Swart, "Emissions Scenarios for the IPCC: An Update," in J.T. Houghton, B.A. Callander, and S.K. Varney, eds., *Climate Change 1992* (Cambridge: Cambridge University Press, 1992), p. 89, 91 and J.M. Melillo, I.S. Prentice, G.D. Farquhar, E.-D. Schulze, O.E. Sala, "Terrestrial Biotic Responses to Environmental Change and Feedbacks to Climate, in J.T. Houghton, et al., eds., *Climate Change 1995* (Cambridge: Cambridge University Press, 1996), pp. 464–466.

Fossil-Fuel Emissions

Emissions of carbon dioxide from fossil-fuel burning have risen steadily over the last half century, from about 1.4 GtC in 1945 to 6.2 GtC in 1995—an average growth rate of 3 percent per year.[57] Including net deforestation and cement production, total anthropogenic emissions were about 7.5 ± 0.9 GtC in 1995.

In order to stabilize greenhouse-gas concentrations at an equivalent doubling, fossil-fuel emissions of carbon dioxide must be limited to the difference between the values given for total emissions in Table 3 and those given for non-fossil emissions in Table 4; the results are given in Table 5. For example, fossil-fuel carbon emissions must be reduced to 4.9 ± 2.6 GtC/

yr by 2050. For comparison, global fossil-fuel emissions first reached 4.9 GtC/yr in 1976. Given projected population increases, this will be equal to a global average of about 0.5 tC/yr per capita in 2050—a level of fossil-fuel emissions that has not been seen since the end of World War II.

Table 5. Limits on future fossil-fuel carbon emissions and energy consumption, for stabilization of greenhouse-gas concentrations at an equivalent doubling.

	Fossil-fuel Carbon Emissions		Fossil-fuel Energy Consumption	
Year	Annual (GtC/yr)	Cumulative (GtC)	Annual (EJ/yr)	Cumulative (EJ)
1995	6.2 ± 0.5	0	329	0
2025	7.8 ± 2.3	230 ± 60	430 ± 130	12,000 ± 3,000
2050	4.9 ± 2.6	400 ± 110	270 ± 140	22,000 ± 6,000
2075	3.7 ± 2.3	500 ± 170	210 ± 130	27,000 ± 9,000
2100	2.7 ± 1.7	580 ± 230	150 ± 90	32,000 ± 13,000
2150	0.9 ± 1.3	660 ± 300	50 ± 70	36,000 ± 17,000

Sources: Tables 3 and 4. Energy consumption assumes 18 ± 1 MtC per EJ of fossil energy in 2025 and thereafter.

Limits on carbon emissions can be translated into limits on fossil-fuel consumption. About 25 million metric tons of carbon is released as CO_2 for every exajoule of coal energy released (25 MtC/EJ); the corresponding values for oil and gas are 20 and 15 MtC/EJ, respectively.[58] With the current mix of fossil fuels (30 percent coal, 45 percent oil, 25 percent gas), the average is about 19 MtC/EJ of fossil energy. This might fall as low as 17 MtC/EJ in the future, particularly if carbon taxes make natural gas more economically attractive relative to coal. Here I adopt the value 18 ± 1 MtC/EJ for emissions after 2025. As shown in Table 5, fossil-fuel energy consumption would be limited to about 270 EJ in 2050 and 150 EJ in 2100, compared with 320 EJ in 1995.

Fossil-Fuel Resources

These limits on fossil-fuel carbon emissions can be compared to the amount of oil, gas, and coal that could be extracted from the earth. Table 6 gives rough estimates of the energy and carbon content of recoverable fossil-fuel resources, as well as the amount that already has been consumed. Conventional oil and gas resources contain about 350 GtC. The burning of all oil and gas resources would not be sufficient, by itself, to raise the carbon dioxide concentration of the atmosphere above the stabilization target. Oil and gas are relatively inexpensive, convenient, and clean energy sources. Unless low-cost oil and gas resources are much larger than is now believed, they probably should be fully exploited, even under a climate-stabilization regime.

Table 6. Historical consumption and recoverable resources of fossil fuels.

	Consumption, 1765–1995		Recoverable Resources	
	(EJ)	(GtC)	(EJ)	(GtC)
Oil	4,800	90	$10{,}000^{+10{,}000}_{-2{,}000}$	200^{+200}_{-40}
Gas	2,100	29	$10{,}000^{+13{,}000}_{-2{,}500}$	150^{+200}_{-40}
Coal	5,300	131	$100{,}000^{+150{,}000}_{-50{,}000}$	$2{,}500^{+4000}_{-1000}$
Methane hydrate and oil shale	—	—	~2,000,000	~40,000
Total	12,200	250	~2,000,000	~40,000

Sources: G. Marland, R. J. Andres, T. A. Boden, C. Johnston, and A. Brenkert, "Global, Regional, and National CO_2 Emission Estimates from Fossil Fuel Burning, Cement Production, and Gas Flaring: 1751–1995" (revised January 1998; available at http://cdiac.esd.ornl.gov/ndps/ndp030.html); C.D. Masters, E.D. Attanasi, and D.H. Root, "World Petroleum Assessment and Analysis," in *Proceedings of the 14th World Petroleum Congress*, Vol. V (Chichester, UK: John Wiley and Sons, 1994), pp. 529–541 (summary at http://dr.cr.usgs.gov/fs145-97/intro.htm); World Energy Council and International Institute for Applied Systems Analysis, *Global Energy Perspectives to 2050 and Beyond* (London: World Energy Council, 1995), p. 36 (summary at http://www.wec.co.uk/energy.htm); and others.

Coal, however, is a different matter. The amount of recoverable coal is two to ten times larger than the amount necessary to double carbon-dioxide concentrations. If we assume that essentially all conventional oil and gas resources will be consumed within the next 100 to 150 years, then only about 300 GtC of carbon could be released from coal burning over this period—5 to 10 percent of the recoverable resource.[59] If, on the other hand, we could use coal in a manner that does not release carbon dioxide into the atmosphere, coal could meet world energy needs for more than a century.

Huge resources of unconventional fossil fuels—methane hydrates and oil shales—also exist. Today, these resources generally cannot be extracted at costs that would be competitive with conventional fossil fuels. As technology improves and the cost of conventional fuels rises, hydrates and shales could become economically attractive and virtually unlimited sources of energy. Obviously, this would be possible only if the release of carbon dioxide from such fuels could be prevented.

Future Energy Consumption

The results in Table 5 show that, in order to stabilize greenhouse-gas concentrations at an equivalent doubling, the rate at which fossil fuels are burned must return to today's rate in about forty years (thirty to eighty years if one takes into account the numerous uncertainties).[60] In a certain sense this is comforting, because it indicates that major reductions would not be required for many decades. Indeed, if global emissions could be held constant at today's levels, reductions would not be required for fifty or more years.

The crux of the problem is that energy consumption will double or triple over the next half century, driven primarily by increases in population and per-capita income in developing countries. Today, fossil fuels supply about 85 percent of primary commercial energy consumption.[61] If we are to stabilize greenhouse-gas concentrations at an equivalent doubling, fossil-fuel burning could account for only 20 to 40 percent of energy consumption fifty years from now. Energy sources that do not emit carbon dioxide would have to grow by a factor of ten to twenty during this period—equal to an average growth rate of about 5 percent per year for fifty years.

To describe in more detail the required shift in energy supply, we need forecasts of future energy consumption. It is extraordinarily difficult to develop reliable long-term projections of global energy consumption. Imagine attempting in 1900 to forecast energy consumption today. Population grew nearly fourfold in this time period, economic activity expanded by a factor of 18, and commercial energy consumption increased by a factor of 20. Technologies that account for the majority of today's energy consumption—automobiles, airplanes, and electric appliances of all types—were only dimly perceived a century ago.

The best way to understand energy use is through a detailed accounting of human activities and the energy consumed in supporting them. This can be formulated as follows:

$$\textit{energy use} = \sum_i \left\{ P_i \cdot \sum_j \left[\frac{\textit{activity}_j}{\textit{person}} \right] \cdot \left[\frac{\textit{energy}}{\textit{activity}_j} \right] \right\} \qquad (3)$$

Evaluating this expression requires estimates of the population of each region, Pi, the average per-capita level of the various energy-consuming activities, and the average amount of energy consumed per unit of each activity. Activities are often divided into four major categories: industrial, commercial, residential, and transportation. Industrial activities include the production of aluminum, paper, and chlorine; commercial and residential activities include heating, cooling, and lighting; and transportation activities include passenger and freight transport. Energy use per unit of activity is measured in gigajoules per kilogram of aluminum or gigajoules per vehicle-kilometer or tonne-kilometer of road, rail, sea, or air transport.

Although equation 3 is valuable in understanding past energy consumption,[62] this approach is less useful for thinking about energy consumption far into the future. We simply have no way of knowing the levels or even the types of energy-consuming activities that people will engage in fifty or one hundred years hence, much less the amount of energy that will be used in these activities.

Energy-Consumption Scenarios

Because of the impossibility of predicting the future in such detail, calculations of long-term energy consumption are usually referred to as "scenarios" rather than as "forecasts" or "projections." A scenario is an "if, then" statement about the future rather than a prediction: it calculates energy consumption for a given set of assumptions about the evolution of population, economics, technology, and policy. The range of plausible assumptions in each of these areas is fairly broad, particularly as one looks farther into the future, so it should not be surprising that scenarios produce a wide range of future energy consumptions.

Scenarios of future energy consumption most often are produced using models of the global economy. These models use economic measures of human activity, such as per-capita GDP, together with estimates of "energy intensity," or the amount of energy required to produce a dollar of economic product. Economic activity and energy intensity are often divided and subdivided into various sectors. Energy consumption can be thought of as the product of population, per-capita GDP, and energy intensity:

$$energy\ use = \sum_i P_i \cdot \left[\frac{GDP}{person}\right]_i \cdot \left[\frac{energy}{GDP}\right]_i \qquad (4)$$

It follows from equation 4 that the growth rate of energy use can be represented as the sum of the growth rates of population, per-capita GDP, and energy intensity:[63]

$$r_{energy} = r_{pop} + r_{gdppc} + r_{ei} \qquad (5)$$

The standard set of assumptions is that, between 1995 and 2050, population will grow at an average rate of about 1 percent per year, per-capita GDP will grow by 1.5 percent per year, and energy intensity will decrease by about 1 percent per year. Under these assumptions, energy consumption would grow at a rate of 1.5 percent per year, resulting in a factor of 2.3 increase, from 382 EJ/yr in 1995 to about 900 EJ/yr in 2050. Relatively small changes in these rates can produce large changes in consumption. For example, if each of these growth rates was just 0.2 percent per year lower or higher, energy consumption in 2050 would range from 600 to 1200 EJ/yr.

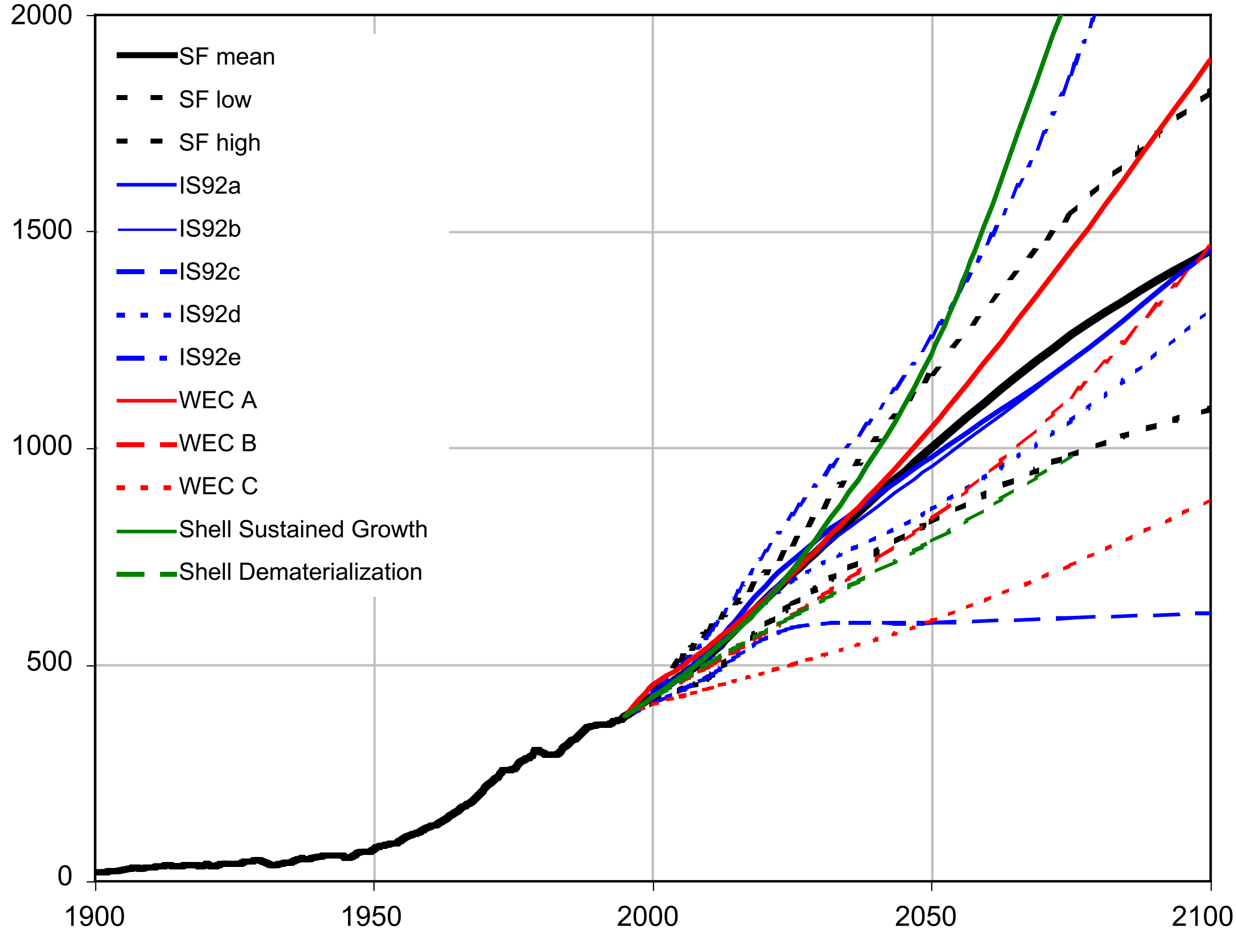
Figure 4 compares ten scenarios of world primary energy consumption prepared by the IPCC, the International Institute for Applied Systems Analysis and the World Energy Council (WEC), and Shell.[64] Except for the "WEC C" scenario, these are "reference" scenarios—that is, they assume no special policy action to reduce energy consumption or carbon-dioxide emissions. All scenarios do, however, take into account expected improvements in energy efficiency and price increases caused by the depletion of oil and gas resources. Estimates of world primary energy consumption in the reference scenarios range from 600 to nearly 1300 EJ/yr in 2050. The wide range is due to uncertainties in population forecasts, in future rates of regional economic growth, and the decline of energy intensity.

Population

Table 7 summarizes the results of world population projections by the World Bank, the United Nations, the International Institute of Applied Systems Analysis, and the U.S. Bureau of the Census. As with energy consumption, these projections usually are referred to as "scenarios"—they are simply the result of a particular set of assumptions about the evolution of fertility and morality rates.

Two features of this table are notable. First, the central projections of world population are remarkably similar, even one hundred years or more into the future. This reflects an underlying consensus about the fertility and mortality scenarios that are considered most likely. In each case, world population is projected to double by 2100. Most of the increase occurs before 2050, when population is expected to reach 9.4 to 9.9 billion, with nearly all of this growth occurring in developing countries. Seven of the ten energy-consumption sce-

Figure 4. Scenarios of future world commercial primary energy consumption by Fetter (SF), the Intergovernmental Panel on Climate Change (IS92), the International Institute of Applied Systems Analysis and the World Energy Council (WEC), and Shell Oil.



Sources: Steve Fetter, Climate Change and the Transformation in World Energy Supply (to be published); J. Leggett, W.J. Pepper, and R.J. Swart, "Emission Scenarios for IPCC: An Update," in J.T. Houghton, B.A. Callander and S.K. Varney, eds., *Climate Change 1992: The Supplementary Report to the IPCC Scientific Assessment* (Cambridge: Cambridge University Press, 1992); World Energy Council and International Institute of Applied Systems Analysis, *Global Energy Perspectives to 2050 and Beyond* (London: WEC, 1995); and Shell International Ltd., *The Evolution of the World's Energy Systems* (London: Shell International, 1996).

Table 7. World population scenarios by the Word Bank, the United Nations, the International Institute of Applied Systems Analysis (IIASA), and the U.S. Bureau of the Census (USBC) for central or best-guess fertility and mortality rates. Also given is the decrease or increase from the central value for alternative fertility scenarios.

	World Population (billions)						
Year	World Bank		United Nations		IIASA		USBC
1995	5.69		5.69		5.70		5.69
2025	8.1	–0.5 +0.2	8.0	±0.6	8.3	±0.7	7.9
2050	9.6	–1.0 +0.5	9.4	–1.7 +1.8	9.9	–2.1 +2.5	9.4
2075	10.5	–1.4 +0.9	10.0	–3.3 +4.1	10.6	–3.8 +5.3	—
2100	11.0	–1.6 +1.3	10.4	–4.8 +7.1	10.4	–5.2 +8.6	—
2150	11.4	–1.7 +1.4	10.8	–7.3 +16	—		—

Sources: Eduard Bos, My T. Vu, Ernest Massiah, Rodolfo A. Bulatao, *World Population Projections* (Baltimore: The Johns Hopkins University Press, 1994); United Nations, Department of Economic and Social Affairs, *World Population Projections to 2150* (New York: United Nations, 1998); Wolfgang Lutz, ed., *The Future Population of the World: What Can We Assume Today?* Revised and Updated Edition (London: Earthscan, 1997); U.S. Bureau of the Census, "Total Midyear Population for the World: 1950–2050," updated 15 June 1998.

narios in Figure 4 (all except for IS92c, IS92d, and IS92f) use population projections that are close to the central values given here.

Second, long-term population projections are very sensitive to assumptions about fertility. For the range of plausible fertility scenarios, world population in 2050 could be as low as 7.7 billion or as high as 12.4 billion. By 2100, population could be a factor of two lower or higher than the central estimates. This range of population estimates is produced by long-term average fertility rates that vary from about 1.5 to 2.5 births per woman. Two of the energy-consumption scenarios (IS92c and IS92d) assume populations at the bottom end of the range (6.4 billion in 2100). At the other end of the spectrum, IS92f assumes a world population of 17.6 billion in 2100. Overall, uncertainty about population is responsible for about half of the uncertainty in future energy consumption.

Per-capita Income

In most scenarios, projected growth rates of per-capita GDP are based on recent (post–World War II) experience, during which the average growth rate has been about 2 percent per year.[65] Growth has been uneven, however, with five-year averages as high as 10 percent per year in countries experiencing rapid industrialization and as low as –10 percent per year in countries undergoing painful transitions. In the early 1990s, China and the former Soviet Union were examples of these opposite trends. Over the forty-year period from 1950 to 1990, per-capita growth rates varied from a low of 1.2 percent per year in Africa to a high of 5 percent per year in Japan.

The energy-consumption scenarios in figure 4 assume average growth rates of per-capita GDP ranging from 1.0 to 2.3 percent per year over the period 1990 to 2100, with a central value of about 1.5 percent per year. These rates are not high when compared with the average growth rate since 1950, but they are greater than the average from 1820 to 1950 of about 0.9 percent per year.[66]

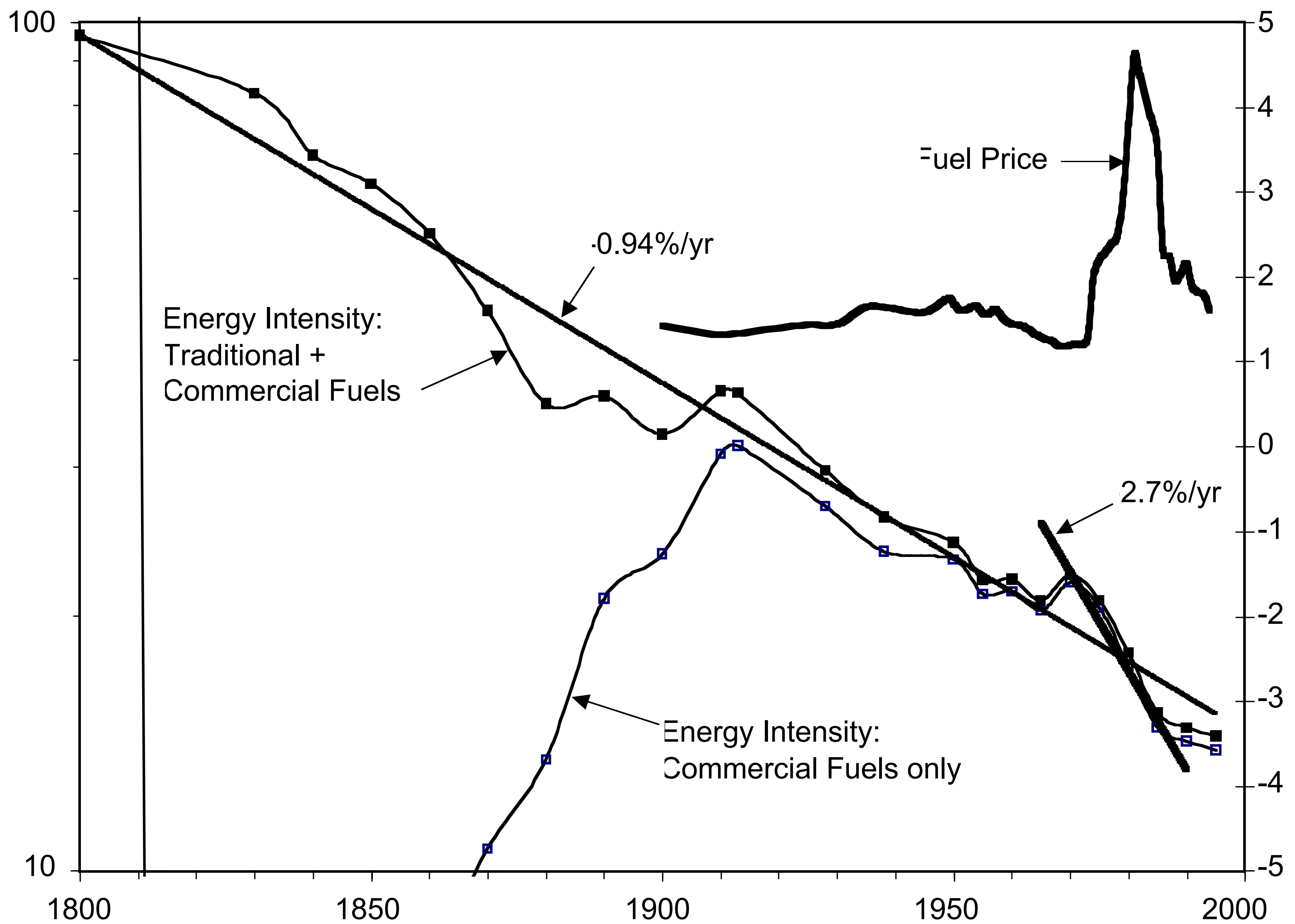
Seemingly modest growth rates of 1 to 2 percent per year lead to substantial increases—by a factor of three to seven—when compounded over one hundred years. The standard assumption that per-capita incomes will grow steadily for a century or more, even in wealthy countries, should be more open to debate. One published scenario shows annual per-capita incomes in the United States rising from $25,000 today to more than $100,000 by 2100 and $200,000 by 2200; in China, incomes are assumed to rise from about $500 today to $40,000 by 2100 and $160,000 by 2200.[67] If average incomes of $100,000 or $200,000 per year are possible for a population of 10 or more billion people, the nature of consumption might be far different than would be indicated by a simple extrapolation of current trends. Rich societies might use additional productivity gains to improve their welfare through activities that use little or no money or energy (e.g., reading, gardening, playing with children, meditating, etc.), rather than increase their income to afford more of what money can buy. Decreases in energy intensity account for these effects to some extent, but if per-capita GDP is assumed to grow at a rate which is greater than the rate at which energy intensity decreases—which is true for nearly all published scenarios—then per-capita energy use would continue to grow. It seems more plausible that demand for energy would saturate as incomes rise, and that growth in consumption might cease or decline at incomes not too far above current U.S. levels. Indeed, the historical evolution of per-capita energy consumption in various countries shows that commercial energy consumption begins to saturate at incomes above $10,000 per capita.[68]

Energy Intensity

Energy intensity is affected primarily by energy prices and technological innovation. Higher prices curtail energy consumption by raising the price of energy-intensive goods and services, resulting in shifts in economic structure and social behavior, and stimulating the development of more energy-efficient products and processes. Even in the absence of higher prices, however, technological innovation lowers energy intensities. Although U.S. energy prices have been constant or declining during most of this century, energy intensity has decreased at an average rate of about 1 percent per year. This rate of decrease jumped to nearly 3 percent per year in the wake of the price increases of the 1970s, when oil and coal prices roughly tripled (see Figure 5). For the world as a whole, energy intensity declined at a rate of about 0.5 percent per year between 1950 and 1990, but by only about 0.2 percent per year from 1820 to 1950.[69] The reference scenarios shown in Figure 4 assume rates of decline ranging from 0.7 to 1.1 percent per year.

Energy prices have a strong effect on energy intensity, but prices are extremely difficult to predict over the long term, particularly for technologies that are not now mature, such as photovoltaics. This problem is particularly prominent when forecasting the increase in price or the tax that would be necessary to decrease the consumption of fossil fuels to a certain level. The most important consideration in such calculations is the future price of carbon-free

Figure 5. Energy intensity and composite fuel price in North America.



alternatives.[70] If twenty or thirty years from now the price of such alternatives is close to or less than the price of traditional fossil fuels, the problem of stabilizing carbon emissions will be solved easily and naturally. This underscores the critical importance of research and development on carbon-free energy technologies.

Energy intensity is also affected by policies that generate or ameliorate market imperfections. These imperfections result from a combination of price distortions, monopolistic behavior by utilities, and insufficient information or faulty decisionmaking by consumers. So-called "bottom-up" studies, which calculate the lowest-cost method of providing energy services, have shown that energy consumption could be reduced by 20 to 50 percent in a decade or two at no net cost through changes in habits (e.g., using white roofing materials) and adopting energy-saving technologies (e.g., replacing incandescent bulbs with fluorescents).[71] Policies to make energy markets work better, through a combination of education, taxes and fees, and energy-efficiency standards, could result in significantly lower energy intensities.

A Simple Method

The scenarios discussed above were generated with computer models that require numerous assumptions about the future growth and structure of regional economies, the pace of technological innovation, the size of energy resources, and the price and substitutability of various fuels. Equivalent results for total energy use can be produced simply by extrapolating historical growth rates of per-capita energy use. Although extrapolations are simplistic and have little explanatory power, detailed models requiring hundreds of parameters may produce results that are no more accurate.

Energy use is the product of a region's population and per-capita energy use, E_i:

$$energy\ use = \sum_i P_i \cdot E_i \qquad (6)$$

In 1995, per-capita commercial energy consumption ranged from 12 GJ in India to 360 GJ in the United States.[72] In the past, the growth rate of per-capita commercial energy consumption in most countries has decreased steadily with increasing per-capita consumption. At low levels of per-capita commercial energy use (less than 1 GJ/yr), growth rates have been high (5–10%/yr); at intermediate levels (∪10 GJ/yr), growth has been moderate (3–5%/yr); and at high levels (>100 GJ/yr), growth has been slow (0–3%/yr). This suggests that per-capita demand for energy saturates, and that at some point growth may cease.

The steady decline in growth rate with increasing consumption can be modeled as follows:[73]

$$E(t) = E_\infty \left(\frac{E_0}{E_\infty} \right)^{e^{-t/\tau}} \qquad (7)$$

where E_0 is the per-capita energy consumption at some initial time, E(t) is per-capita consumption t years later, $E_\times$ is the level at which consumption saturates, and τ is a constant that describes the rate at which the saturation level is achieved. Table 8 gives values of $E_\times$ and τ for various regions based on historical data.[74] Figure 6 shows that there is reasonably good agreement between equation 7 and the historical experience, particularly if one ignores periods in which a region suffered from war or economic collapse (e.g., Europe during World

War I and World War II; Japan during World War II; Eastern Europe and the former Soviet Union after 1990).

Table 8. Values of parameters in equation 7, fit to historical data for ten world regions.

Region	τ (yr)	E_∞ (GJ_p/yr)
North America	50	450
Eastern Europe/FSU	70	300
Pacific OECD	45	250
Western Europe	75	225
Middle East	30	200
Latin America	65	150
India	130	150
Other Asia	70	150
China	40	125
Africa	90	100

Figure 6. Per-capita commercial energy consumption by region, and the best-fit line given by equation 7 and table 8.

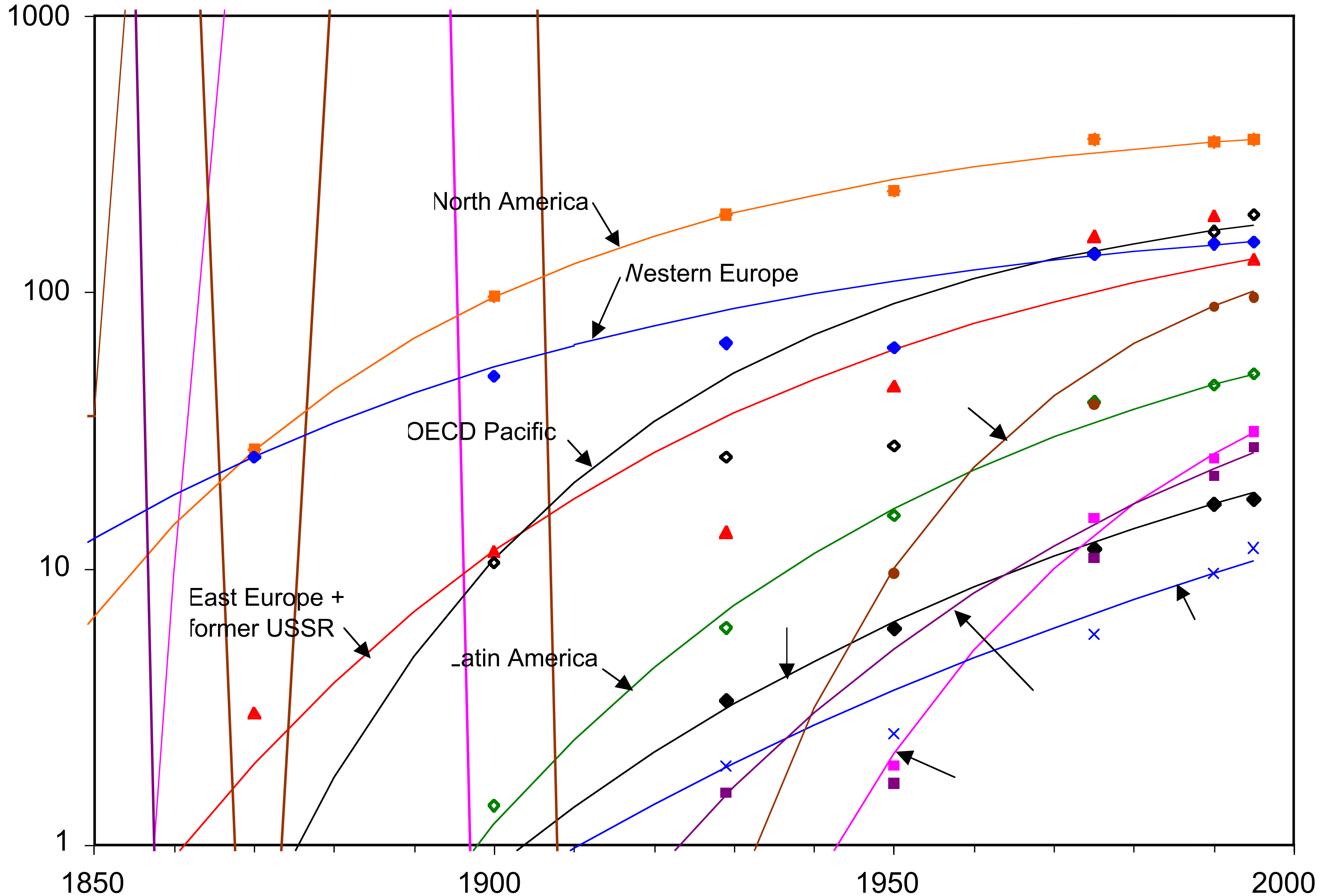


Table 9 gives estimates of future energy consumption based on equation 7 using population projections by the World Bank.[75] As shown in Figure 4, the results of this simple model approximate well the range of values given by more sophisticated models.

Table 9. Future world primary commercial energy supply, limit on traditional fossil supply for stabilization at an equivalent doubling of carbon dioxide, required carbon-free energy supply (or demand reductions), and average growth rate of carbon-free supply.

	Commercial Primary Energy Supply (EJ_p/yr)			Growth of Carbon-free Supply (%/yr)	
Year	Total	Limit on Fossil Fuels	Carbon-free Supply	since 1995	prev. 25 yr
1995	382	329	52.9	2.1	5.7
2025	710 ± 130	430 ± 130	280 ± 180	$5.7^{+1.8}_{-3.6}$	5.7
2050	1000 ± 220	270 ± 140	730 ± 260	$4.9^{+0.6}_{-0.9}$	3.9
2075	1250 ± 600	210 ± 130	1040 ± 610	$3.8^{+0.6}_{-1.1}$	1.4
2100	1450^{+1300}_{-700}	150 ± 90	1300^{+1300}_{-710}	3.1 ± 0.6	1.0
2150	1700^{+2000}_{-800}	50 ± 70	1650^{+2000}_{-800}	2.2 ± 0.5	1.0

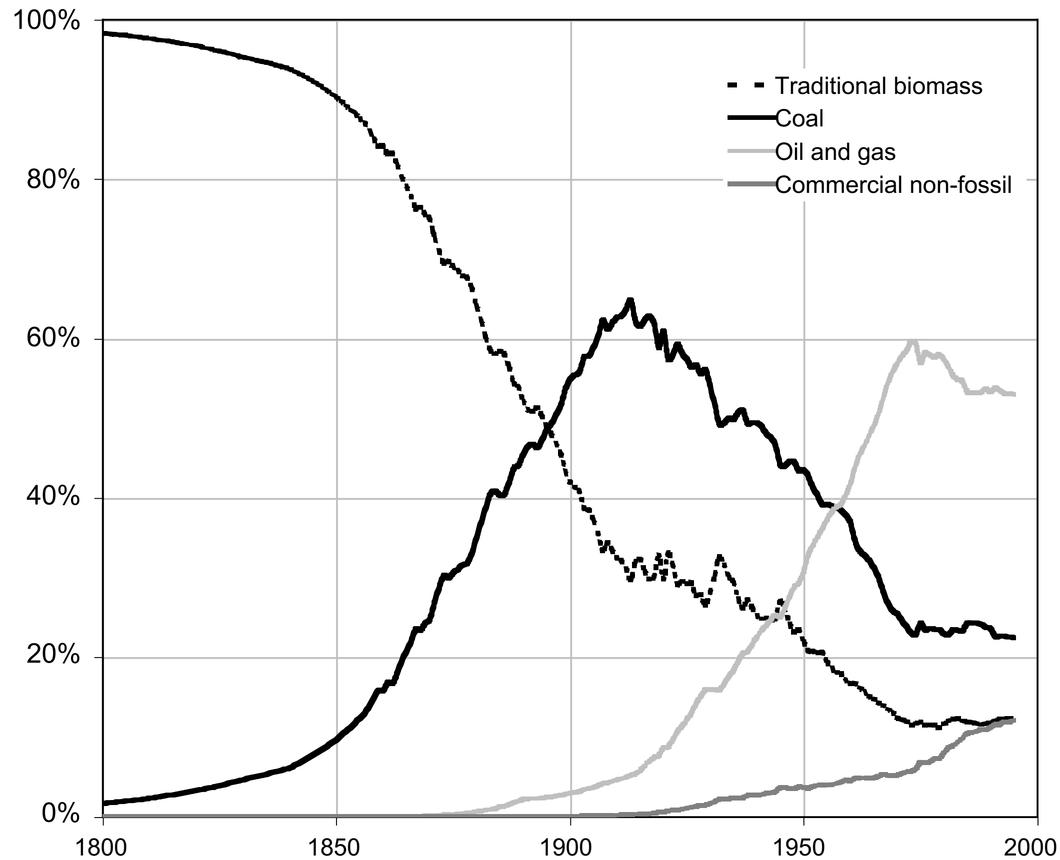
Carbon-free Energy Supply

By subtracting limits on fossil-fuel supply from total energy demand, we derive requirements for non-carbon-emitting energy supply or market interventions to reduce energy demand. These are given in Table 9 for stabilization at an equivalent doubling of carbon dioxide. Note that the supply of carbon-free energy must grow from 53 EJ/yr in 1995 to 500–1000 EJ/yr by 2050—an average growth rate of 4 to 5.5 percent per year over this period.

The implications of this scenario for world energy supply are profound. Today, fossil fuels supply 86 percent of commercial energy supply. If greenhouse gases are to be stabilized at an equivalent doubling, traditional fossil fuels can supply no more energy in 2050 than they supply today, even while total energy use doubles or triples. Carbon-free sources must grow from 14 percent of total commercial supply to 60–80 percent of total supply in 2050.

The transition to carbon-free sources will be the third transformation in world energy supply. The first shift, from firewood to coal, took place from 1850 to 1900. The second shift, from coal to oil and gas, occurred from 1925 to 1975. As shown in Figure 7, it took about fifty years for coal and for oil/gas to go from 10 to 60 percent of total supply. The third major shift, from fossil fuels to carbon-free sources, will occur from 2000 to 2050—if we decide to take seriously the goal of preventing dangerous climate change.

Figure 7. Share of energy consumption by type of fuel.



Demand Reduction

As noted above, the energy-consumption scenarios in Figure 4 (with the exception of the "WEC C" scenario) assume no policy interventions to reduce energy consumption or carbon-dioxide emissions. In these reference scenarios, consumption is determined by the expected growth in population, economic activity, and energy intensity. Total energy consumption, and the requirement for carbon-free energy supply, could, however, be reduced by interventions in energy markets. These interventions could take the form of taxes on fossil fuels, subsidies for carbon-free sources or energy-efficiency improvements, emission quotas or tradable permits, or energy-efficiency standards.

Economists generally prefer carbon taxes as the most straightforward and efficient intervention. In theory, the tax would be adjusted until carbon emissions fell to the desired level.

By increasing fuel prices, carbon taxes reduce overall demand for energy and stimulate shifts from high-carbon sources, such as coal, to low- or no-carbon sources, such as natural gas, fission, and solar. If carbon-tax revenues are used to lower other taxes, the negative effect of high energy prices on economic growth can be minimized. The fact that carbon taxes would reduce other effects on human health and the environment, such as air pollution and acid rain, further minimizes their negative economic impact.[76]

Over the long term, the tax required to achieve a given emission target depends primarily on the relative prices of high-carbon and low/no-carbon sources. If the price difference is small, the tax will be low; if the price difference is large, the tax will be high. Depending on assumptions about the costs of various mitigation options, models indicate that a tax of $100 to $500 per ton of carbon ($/tC) would be needed by 2050 to reduce CO_2 emissions to levels consistent with stabilization at an equivalent doubling.[77] Commercial energy consumption would be 30 to 50 percent lower in 2050 than it would be without the carbon tax, and the required carbon-free energy supply would be two to three times smaller.[78]

Table 10 shows the effect that a carbon tax of $100/tC would have on the price of coal, oil, and gas delivered to U.S. utilities, and on the price of electricity generated from these fuels. A tax of $100/tC would triple the current price of coal, increase the price of oil and gas by two-thirds, increase the price of electricity by 15 to 30 percent, and add $0.24 per gallon to the price of gasoline. For comparison, existing energy taxes in OECD countries are equivalent to $70/tC, ranging from $30/tC in the United States to $230/tC in France, and from $0/tC for coal to $150 for oil.[79] If global emissions are 5 GtC/yr, a tax of $100/tC would raise $500 billion per year in tax revenue—perhaps half a percent of gross world product in 2050.

Table 10. The effect of a $100/tC tax on the price of coal, heavy fuel oil, and natural gas delivered to U.S. utilities, and on electricity generated using these fuels.

	Coal	Oil	Gas
Average 1997 price ($/GJ)	1.2	2.7	2.6
Cost of $100/tC tax ($/GJ)*	2.5	2.0	1.5
Increase over 1997 price (%)	200	70	60
Cost of $100/tC tax (¢/kWh)†	2.6	1.8	1.3
Increase over average 1997 retail price of 8.5 ¢/kWh (%)	30	20	15

*Assuming emission factors of 25, 20, and 15 kgC/GJ for coal, oil, and gas (lower heating value).
†Assuming average efficiencies of 35, 40, and 42 percent for coal, oil, and gas (lower heating value).
Source: Energy Information Agency, "U.S. Energy Prices," available at http://www.eia.gov/emeu/steo/pub/4tab.htm.

A tax of \$100/tC to \$200/tC tax need not have a strong negative effect on economic growth, particularly if the tax were phased in slowly and the revenues were recycled efficiently. It seems unlikely, however, that most governments would be willing or able to impose taxes of this magnitude any time soon. Although polls indicate that a large majority of Americans believe that steps should be taken to address the problem of climate change, most would be unwilling to accept a carbon tax greater than about \$40/tC.[80] In the near term, we should focus on accelerating energy research and development, with the goal of making carbon-free energy sources cheaper and more acceptable. The cost of intensifying research and development is small compared with taxes, and the payoffs potentially are very large. In the next section, we turn to the question of which sources are the most promising targets for enhanced R&D.

Carbon-free Energy Sources

A very large expansion in the supply of energy by sources that do not emit carbon dioxide will be required in order to achieve the goal of the Climate Convention. Today, only two carbon-free sources—hydropower and nuclear fission—produce significant amounts of energy, with each accounting for about 26 EJ or 7 percent of commercial primary energy in 1995. Traditional biomass fuels provide 50 to 60 EJ/yr, but much of this is supplied by fuelwood that is harvested in an unsustainable manner, resulting in a net release of carbon dioxide. Non-fossil energy supply has been growing recently at only about 2 percent per year—much less than the 5-percent-per-year rate needed to stabilize greenhouse-gas concentrations at an equivalent doubling. We will need 500 EJ_p/yr of carbon-free energy by 2050. Where will this energy come from?

The list of potential sources is long: hydro, fission, fusion, biomass, geothermal, solar, wind, ocean (tidal, wave, and thermal), and "decarbonized" fossil fuels. Unfortunately, each of these sources has significant technical, economic, and/or environmental drawbacks that must be overcome if it is to supply a substantial fraction of world energy supply. Although it is impossible to predict which source or combination of sources will prevail, it is possible to say which will *not*. As discussed below, hydro, geothermal, ocean, and fusion energy almost certainly will not supply a large fraction of world energy before 2050. The sources with the greatest potential in this time period are nuclear fission, solar photovoltaic, decarbonized fossil fuels, and, to a lesser extent, wind and commercial biomass. Table 11 summarizes the current and potential contributions of various carbon-free energy sources.

Table 11. Current and potential contributions of carbon-free energy sources to world primary energy supply.

Energy Source	Primary Energy Production (EJ_p/yr) 1995	Potential by 2025	Long-term Potential: Economic	Long-term Potential: Technical	Natural flow (EJ_p/yr) or resource (EJ_p)
UNLIKELY TO REPRESENT SUBSTANTIAL FRACTION OF 2050 SUPPLY					
Hydroelectric	26.7	35–55	50–100	130–170	400
Geothermal	0.6	2–4	5–20	20–100	10,000,000
Ocean	0.006	0–0.5	1–5	5–10	2,000,000
Nuclear fusion	0	0	?	?	>4,000,000,000
POSSIBLE MAJOR ENERGY SOURCES					
Biomass	≈60	50–100	100–500	100–500	2,000
Nuclear fission	25.0	20–60	500+	500+	10,000,000
Solar	0.2		?	500+	3,000,000
Wind	0.08	1–10	50–150	250	40,000
Decarbonized fossil	0		?	500+	250,000

Sources: Nebojsa Nakicenovic, "Energy Primer," in Robert T. Watson, Marufu C. Zinyowera, and Richard H. Moss, *Climate Change 1995: Impacts, Adaptations and Mitigation of Climate Change* (Cambridge: Cambridge University Press, 1996); Energy Information Agency, *International Energy Annual 1996* (Washington, DC: U.S. Department of Energy, 1998), available at ftp://eia.doe.gov/pub/pdf/international/021996.pdf; and author's estimates.

Sources Unlikely to Make a Major Contribution

Hydropower

Hydropower currently is the largest non-fossil source of commercial energy. In 1995, hydro produced 2500 terawatt-hours (TWh) of electricity—21 percent of global electricity production and 7 percent of primary energy.[81] Global hydroelectric production experienced strong growth from 1900 to 1970, but growth has slowed to about 2 percent per year over the last decade. Future expansion is limited by the availability of economically attractive sites and, increasingly, by concerns about the environmental and social impacts of dams.

Table 12 gives estimates of the theoretical hydroelectric production of major world regions, together with estimates of the amount that could be exploited from a purely technical point of view, without regard to environmental considerations or detailed economic analysis. The historical experience in the United States, Europe, and Japan, where hydroelectric production has leveled off, indicates that 40 to 65 percent of the technical potential ultimately could be exploited. Global hydro production might therefore increase to 6,000–12,000 TWh/yr, or roughly 50 to 100 EJ_p/yr—one-tenth of the carbon-free supply required by 2050.

Table 12. Estimated theoretical and technically realizable potential of hydropower, 1995 production, and the ratio of 1995 production to technical potential.

Region	Theoretical Potential (TWh/yr)	Technical Potential (TWh/yr)	1995 Production (TWh)	Production / Potential (%)
North America	6200	970–3100	642	21–66
Latin America	5700	3500–3800	507	13–14
Western Europe	3000	910–1200	479	40–53
Eastern Europe, former USSR	5000	2400–4000	292	7–12
Africa	10000	1200–3100	56	2– 5
Japan, Australia, New Zealand	1500	330– 550	124	23–38
Other Asia	16500	4000–5000	387	8–10
Total	48000	15000–19000	2487	13–17

Sources: Jose Roberto Moreira and Alan Douglas Poole, "Hydropower and Its Constraints," in Thomas B. Johansson, Henry Kelly, Amulya K.N. Reddy, and Robert H. Williams, *Renewable Energy: Sources for Fuels and Electricity* (Washington, DC: Island Press, 1993); Energy Information Agency, *International Energy Annual 1996* (Washington, DC: U.S. Department of Energy, 1998); available at ftp://ftp.eia.doe.gov/pub/pdf/international/021996.pdf.

Geothermal Energy

An enormous amount of heat—nearly 10 trillion EJ—is stored in the earth's core from its formation 4.5 billion years ago, and from the decay of radioactive isotopes in the core. More than 10 million EJ lies within a within a few kilometers of the surface, and is theoretically accessible using current drilling technology. Because of the low thermal conductivity of rock, heat flow to the surface is very small—about 1000 EJ/yr, or 0.06 W/m^2. The temperature of accessible rock generally is below the boiling point of water, making it difficult to extract heat energy economically. However, near tectonic plate boundaries molten rock from the core comes much closer to the surface, making the overlaying rock and any water trapped therein much hotter. Regions of concentrated, high-temperature water and steam ("hydrothermal" reservoirs) in shallow rock are far more easily exploited for electricity production, but they represent less than 0.1 percent of the total geothermal resource.

Before 1960, only Italy produced electricity with geothermal energy. Geothermal saw rapid growth in the early 1980s, as twenty countries built geothermal power plants. More recently growth has tapered off to about 5 percent per year. In 1995, geothermal contributed about 0.6 EJ to world primary energy supply—40 TWh of electricity and about 0.15 EJ of direct-use heat.[82] Nearly all of this was extracted from high-temperature hydrothermal reservoirs. If growth continues at 5 percent per year, geothermal might supply 2–4 EJ_p/yr by 2025, and perhaps 10 EJ_p/yr in 2050.

Geothermal is often incorrectly described as a "renewable" energy source. Because heat is withdrawn from the surrounding rock much faster than it is replenished by conduction from below, it is for all practical purposes an exhaustible resource, like coal or oil. The total amount of heat that could be extracted from high-temperature hydrothermal reservoirs is on the order of 5,000 EJ_p—less than oil or gas resources. If one-fifth of this could be extracted economically over a period of one hundred years, the average rate of supply would be only 10 EJ_p/yr.[83] Thus, hydrothermal energy will never be an important global energy source.

The amount of heat stored in hydrothermal reservoirs is tiny compared with the amount stored in hot, dry rock. The problem is bringing that energy to the surface in a useful form and at an acceptable price. The basic concept is to drill two parallel wells several kilometers deep into the rock and to fracture the rock between the wells. Water injected down one well is forced through the fissures in the hot rock and pumped to the surface via the other well. The technology is in the experimental stage and commercial feasibility seems far away. Drilling to the required depths is expensive, but the most difficult problem is to create a stable fracture network of the proper size and porosity.[84] Otherwise pumping requirements or water losses can be unacceptably high or the rock can cool off too quickly. Even if these technical problems can be solved, long-term tests would be required before commercialization could begin. For these reasons, it seems unlikely that hot-rock geothermal will produce significant amounts of energy before 2025.

Ocean Energy

Large amounts of energy are stored in the oceans in tides, waves, and in heat.[85] As with hot-rock geothermal, the problem is extracting this energy economically. Ocean energy is hampered by high capital costs, by the difficulty of maintaining equipment in corrosive marine environments and protecting it from storms, by low energy densities, conversion efficiencies, and/or capacity factors, and by geographic constraints that put most of the resource far from population centers. For these and other reasons, the oceans are unlikely to become a significant source of commercial energy for the foreseeable future.

Tides. Tides are created primarily by differences in the gravitational attraction of the moon on the oceans. The average tidal range in the open ocean is only about half a meter, but this can be amplified to as much as 10 to 15 meters in funnel-shaped estuaries. Tidal energy is harnessed by building a dam across an estuary having a large tidal range. Because of its similarity to hydropower, the technology is fairly mature. Several small tidal-power facilities currently are in operation, producing about 0.6 TWh/yr of electricity (0.006 EJ_p/yr).[86] The total amount of energy dissipated by tides worldwide is over 200 EJ_p/yr, but only a small fraction—5 to 10 EJ_p/yr—occurs at sites that are technically exploitable (i.e., with a mean tidal range greater than 3 meters). Of this, perhaps 10 to 50 percent could be exploited at reasonable cost. The desire to avoid adverse impacts on the ecology of estuaries could further limit the development of tidal power.

Waves. Technology to extract energy from ocean waves is still in the experimental stage. Although the total resource is comparable to that of tidal energy, there are no locations where wave energy is especially concentrated. Most of the wave-energy resource is located offshore in deep water, but the estimated cost of electricity from offshore devices is two to three times higher than for shoreline devices.[87] Capital costs are likely to be very high, as would be the cost of insuring against storm damage.

Thermal. An enormous amount of energy is stored in the oceans as low-temperature heat. The temperature difference between warm surface water and cold deep water, which in the tropics is as high as 20 °C, can be used to produce electricity. The total resource is on the order 10,000 EJ_p/yr; economics aside, the technical potential is less than 100 EJ_p/yr.[88]

Although the feasibility of ocean thermal energy conversion (OTEC) was demonstrated in the 1930s, the engineering difficulties of deploying the technology on a commercial scale are immense. The small temperature difference results in conversion efficiencies of only 2.5 percent, which in turn requires very large flows of water and huge pumping requirements. A 100-MW_e plant, for example, would have to pump nearly 30 cubic kilometers of seawater through its heat exchangers every year. Half this water would be drawn from the deep ocean through a pipe 1 kilometer long and 20 meters in diameter. Because OTEC is restricted to deep, tropical waters, electricity would either have to be transmitted via long undersea cables to tropical countries or used to produce electrolytic hydrogen. Preventing corrosion and storm damage to the plant also would be challenging.

Fusion Energy

Nuclear fusion—the joining of light nuclei to form more-stable heavy nuclei—is the energy source of the stars. For fusion to occur, nuclei must be brought very close together—close enough to overcome the strong repulsive force of the positively charged nuclei. In a star, the enormous gravitational field brings nuclei close together; in a thermonuclear weapon, the radiation from a nuclear fission explosive is used to squeeze the fusion fuels to high densities.

The energy potential of fusion is virtually unlimited. Using the fuels that are easiest to ignite, the current rate of global energy consumption could be sustained for 10 million years. Achieving the controlled release of this energy has proved extraordinarily difficult, however. The two main approaches are inertial and magnetic confinement. In the first scheme, pulsed lasers or particle beams are used to squeeze tiny pellets of fusion fuel, triggering a series of small nuclear explosions. In the second scheme, nuclei are held in a magnetic “bottle” long enough, and at sufficiently high temperatures, so that there is a significant probability that fusion will occur. After the expenditure of tens of billions of dollars over more than forty years, both approaches are on the threshold of demonstrating “break-even”: the release of more energy by fusion reactions than is consumed in squeezing or confining the fusion fuel.

Even if break-even and ignition are achieved in the next decade, several additional decades of research and development would be needed to yield a device suitable for commercial energy production. The most optimistic researchers agree that a demonstration reactor will not operate before 2025; others put the date at 2050 or later. Fusion may one day prove to be society’s ultimate energy source, but it is unlikely that it will be available in time to contribute to the stabilization of greenhouse-gas concentrations.

Possible Major Energy Sources

As noted above, five carbon-free energy sources could make a substantial contribution to world energy supply in 2050: biomass, fission, solar, wind, and decarbonized fossil fuels. Below I review the theoretical and practical potential of each of these sources, and explore the technical, economic, and other obstacles that would have to be overcome if they are to become major sources of energy.

Biomass Energy

Biomass—wood, crop wastes, and dung—is the main source of energy for a majority of the world's population. Because these fuels are not traded on world markets, total consumption is highly uncertain. Estimates range from 15 to 65 EJ_p/yr, or 4 to 15 percent of world energy consumption.[89]

The source of all biomass is photosynthesis, in which plants use solar energy to produce carbohydrates from carbon dioxide and water. The burning of biomass does not lead to a net emission of carbon dioxide so long as biomass is grown at the same rate as it is consumed. Unfortunately, this is not the case today. About 60 percent of biomass energy is supplied by fuelwood, much of which is harvested in an unsustainable manner, resulting in deforestation, loss of natural wildlife habitat, and a release of carbon dioxide into the atmosphere. Roughly 200 million hectares (Mha) would be required to supply this much fuelwood in a sustainable manner—twice as much as now exists in all forest plantations.[90] Moreover, biomass typically is burned inefficiently, resulting in high levels of indoor and outdoor air pollution. All things considered, biomass probably has been the most environmentally destructive energy source.

Biomass energy can, however, be used in a sustainable and environmentally responsible manner. In the United States, biomass supplied about 5 EJ of primary energy in 1995, including over 200 TWh of electricity (7 percent of U.S. consumption).[91] Most of this was supplied by wood waste, and, to a lesser extent, agricultural waste, solid waste, landfill gas, and ethanol produced from corn. Also in 1995, Brazil produced about 15 billion liters of ethanol and 7.4 TWh of electricity from sugar cane (0.45 EJ_p).[92]

Biomass has several advantages over other carbon-free energy sources. First, biomass can be used to produce solid, liquid, and gaseous fuels as well as electricity. Second, the technology for producing biofuels is mature and is available even in the poorest countries. Third, estimated costs of biofuels are reasonably close to the prices of fossil fuels. It is estimated that wood chips can be produced at delivered costs of $1.5 to 2.0/GJ. For comparison, the current price of coal is $1.0 to 1.6/GJ.[93] Alcohol made from corn or sugarcane currently is about twice as expensive as gasoline,[94] but alcohol made from wood using advanced processes could be competitive with gasoline.[95]

The energy potential of biomass is large. Plants store energy at a rate of about 3000 EJ/yr. Two-thirds of this productivity is on land, half of which is concentrated in the tropics. Humans already actively manage more than half of the useable land area for the production of food and fiber;[96] cropland, pasture, and managed forests store about 600 EJ/yr.[97] Some of this productivity is manifested as wastes that could be diverted for energy production, and some exists in the form of fallow or degraded cropland and pasture that could be converted to the production of energy crops. Below we examine the energy potential of both of these sources.

<u>Waste.</u> Wastes include crop residues, animal dung, wood waste, solid waste, and sewage. The energy value of all residues produced annually is about 130 EJ/yr. As indicated in Table 13, about one-quarter of this could be recovered for energy. The remainder is either uneconomical to collect, transport, or convert to energy, or is necessary to maintain soil quality, prevent erosion, and provide habitat for natural species. Production of recoverable residues should increase to roughly 80 EJ/yr in 2050, primarily due to increases in population and per-capita consumption.[98]

Table 13. Energy content of recoverable wastes (1990).

Waste	Production (EJ/yr)	Fraction recoverable	Recoverable (EJ/yr)
Crops	40	0.3	12
Wood	35	0.4	14
Dung	40	0.1	4
Solid waste and sewage	15	0.3	5
Total	130	0.27	35

Sources: David O. Hall, Frank Rosillo-Calle, Robert H. Williams, and Jeremy Woods, "Biomass for Energy: Supply Prospects," in Thomas B. Johansson, Henry Kelly, Amulya K.N. Reddy, and Robert H. Williams, eds., *Renewable Energy: Sources for Fuels and Electricity* (Washington, DC: Island Press, 1993), pp. 607–614.

Biomass plantations. Special energy crops could be grown on abandoned, degraded, or deforested land, or new land could be brought into production. A related option is to harvest wood from existing forests, but over time such forests would be transformed into managed forests that would not be very different from plantations.

The amount of energy that could be supplied by biomass plantations would depend on the amount of land dedicated to this purpose and the average yield of energy crops. Crops under consideration for temperate climates include woody plants, such as poplar and willow, as well as herbaceous plants, such as sorghum and switchgrass. Today, net yields are 150 to 250 gigajoules per hectare per year (GJ/ha°yr, averaged over relatively small experimental plots. In tropical and subtropical regions, the leading candidates are eucalyptus, with an average yield of 150 to 350 GJ/ha°yr, and sugarcane, with an average yield of 600 to 1000 GJ/ha°yr.[99] Although yields should increase as better varieties are identified and as management techniques improve, average yields would be lower if energy crops are grown on marginal lands. Here I will assume average net yields of 200 GJ/ha°yr in temperate regions and 300 GJ/ha°yr in tropical regions in 2050.

More difficult to estimate is the amount of land that could be devoted to energy crops. If we rule out the conversion of natural forests, energy crops would have to grown on a portion of the 5000 million hectares (Mha) of land that already has been domesticated: 1500 Mha of cropland (of which 1000 Mha is harvested in a given year), 3400 Mha of pasture, and 100 Mha of forest plantations. A significant fraction of this land is degraded or deforested. Although much of this would be suitable for reforestation, growing energy crops would make a larger contribution to stabilizing CO_2 concentrations.[100] To give one benchmark, about 200 Mha of natural tropical forest was converted to cropland, pasture, or plantation forest from

1980 to 1995.[101] If energy crops yielding 300 GJ/ha°yr could be grown on this land, a total of 60 EJ/yr could be supplied—more than is now supplied by all non-fossil commercial sources.

The long-term availability of land for energy crops will depend primarily on the balance between future growth in crop yields and in the demand for food. Past trends are encouraging: between 1961 and 1996, world production of cereals increased by 140 percent, while the area harvested increased by only 9 percent. Increased production more than compensated for population growth, as per-capita production increased 26 percent over this period. This increase in production was made possible by large increases in average cereal yield, from 1.35 tons per hectare (t/ha) in 1961 to 3.0 t/ha in 1997.[102]

It is unclear whether growth in yields will continue to keep pace with growth in consumption. Population is expected to increase 30 to 100 percent by 2050. In addition, per-capita consumption of cereals is expected to increase by 20 to 40 percent as diets improve and meat consumption rises.[103] These factors will increase cereal consumption by a factor of 1.6 to 3.2 by 2050—an average growth rate of 1.5 $\pm$ 0.6 percent per year. If crop yields increase by a similar or greater factor over this time period, the area harvested will remain about the same or shrink, and large areas will be available for energy crops. If, on the other hand, increases in yields do not keep pace with increases in demand, cropland may increase substantially. For example, if total consumption tripled but yields increased by only 50 percent, the total area harvested would double (assuming that post-harvest losses and end-use waste are not reduced).

How much yields will increase in the future is the subject of much debate.[104] Optimists point to the high yields that have been achieved in developed countries as evidence that the world average can increase substantially. Cereal yields in France and the United Kingdom are more than twice the world average, and China has attained yields 60 percent higher than the world average.[105] Biotechnology holds the promise of further increases. Pessimists note that most of the increase in yields was achieved before 1984. Between 1961 and 1984, world-average cereal yield grew by 2.7 percent per year; from 1984 to 1997, the average growth rate dropped to 1.3 percent per year, with no growth in the periods 1984–89 and 1990–95.[106] Much of the past growth in yields was due to increased use of fertilizer, pesticides, and irrigation, but further increases in these inputs are problematic because of diminishing returns, environmental impacts, and water shortages. Pessimists also point to the steady loss of productive cropland, at a rate of about 10 Mha/yr, due to erosion, salinization, desertification, and urbanization.[107] Climate change, and associated changes in temperature, soil moisture, the frequency of storms and drought, and the range of pests and plant disease, adds further uncertainty to projections of future crop yields.

In 1997, about 1500 Mha were classified as "arable" (i.e., cultivated in the last five years), of which about 1000 were harvested. If we make the somewhat pessimistic assumption that consumption will grow at a rate of 2 percent per year but yields increase only 1 percent per year, the area harvested in 2050 would be about 1700 Mha. Even allowing for increased cropping intensity, total cropland would expand by about 500 Mha.

Estimates of potentially arable land—land on which rain-fed crops could achieve reasonable yields, in addition to those currently under cultivation—range from 500 to 2500 Mha. Most of this land is in sub-Saharan Africa and Latin America. The wide range of values reflects incomplete knowledge of soil and climate conditions, differing evaluations of the potential of poor soils or steep terrain to support crop production, and differing views about the desirability and feasibility of converting natural forests and swamps (which constitute about half of the 2500 Mha estimate) into cropland.[108] Here I will assume that 500 to 1000 Mha of potentially arable land would be available for food or energy crop production.

Table 14 gives estimates of the global energy potential of biomass plantations in 2050 for three scenarios of cropland growth. If consumption increases 1 percent per year faster than average yields, the amount of land available for energy plantations, exclusive of natural forests, would be less than 300 Mha, and the energy production potential would be less than 80 EJ/yr.[109] If yield increases keep pace with increases in consumption, energy potential rises would be 160 to 300 EJ/yr. If yields increase 1 percent per year faster than consumption, energy production potential would be 300 to 430 EJ/yr.

Table 14. Global biomass plantation potential in 2050 for three scenarios of cropland growth.

	Cropland Growth Rate, 1995–2050 (%/yr) = (Consumption Growth – Yield Growth)		
Land area in 2050 (Mha)	–1	0	1
harvested for food	600	1000	1700
under cultivation	900	1400	2200
available for energy crops*	1100–1600	600–1100	0–300
Energy potential (EJ/yr)†	300–430	160–300	0–80

*Assumes 500–1000 Mha of potentially arable land for food or energy crops (80% tropical), in addition to 1500 Mha of current cropland (50% tropical).
†Assumes average net yield of 200 GJ/ha·yr for temperate, 300 GJ/ha·yr for tropical energy crops.

Summary. The energy potential of biomass depends primarily on the evolving balance between growth in food consumption and in the average yields of food crops. If, as is often assumed, increases in crop yields continue to keep pace with population- and affluence-driven increases in consumption, biomass could supply 250 to 400 EJ/yr in 2050 without a decrease in the area of natural forest. This would represent a substantial fraction of the carbon-free energy supply required for stabilization at an equivalent doubling. If crop yields grow faster than consumption, biomass might supply over 500 EJ/yr in 2050; if crop yields grow slower than consumption, biomass might supply as little as 80 EJ/yr.

Biomass is a flexible energy source from an end-use point of view. Although biofuels currently are more expensive than comparable fossil fuels, advances in production combined with modest increases in the price of fossil fuels could make biofuels economically competitive, even without carbon taxes. A major uncertainty is whether very large quantities of biomass can be grown and harvested in a sustainable and environmentally benign manner. There is no question that this could be done in principle, but whether it can be accomplished in practice depends on a wide variety of economic, social, and institutional factors. The history of agriculture, which has been characterized by widespread land abuse, is not encouraging.

Fission Energy

Of the non-carbon sources that could make a major contribution to future energy supply, fission is the only one that is deployed commercially on a significant scale today. In 1996, fission reactors supplied nearly 2300 TWh of electricity—19 percent of world electricity and over 6 percent of commercial primary energy.[110]

Near-term prospects for nuclear power are not very favorable. Forecasts range from a substantial decrease to a modest increase in installed capacity over the next twenty years, with fission's share of total world electricity production falling to less than 10 percent by 2020.[111] This is due to a combination of factors: the availability of cheaper alternatives, the retirement of older plants, and public opposition to nuclear power in many countries due to concerns about accident and waste-disposal risks and potential links to the spread of nuclear weapons.[112] The only region expected to experience significant growth in the near future is East Asia.

Cost. The main factor limiting the growth of fission is high capital cost. In the United States, the average cost of nuclear-generated electricity in the early 1990s was nearly twice that of gas- or coal-fired electricity, due mainly to high construction and non-fuel operation and maintenance costs.[113] Unlike most carbon-free sources, however, nuclear has a demonstrated potential to supply large amounts of electricity at prices that are competitive with fossil fuels. The best U.S. nuclear plants, for example, produce electricity at lower cost than the best coal-fired plants.[114] In countries with well-run nuclear plants and more expensive fossil fuels, such as Japan, nuclear is on average somewhat less expensive than fossil-generated electricity. Several recent studies predict that in many countries new nuclear plants would produce electricity at costs comparable to new coal- and gas-fired plants.[115]

Although nuclear power may have difficulty competing with coal and gas today, this may change if there is a serious effort to reduce the burning of fossil fuels. As shown in Table 10, a \$100-per-ton carbon tax would add \$0.013 to \$0.026/kWh to the price of gas- and coal-fired electricity, which could be sufficient to make nuclear attractive in many markets. It also would be important to make the costs of nuclear power more predictable, perhaps through the use of smaller, standardized reactors.

Uranium resources. Fission's energy-production potential is large, but just how large depends both on fuel-cycle technology and the size of exploitable uranium resources. It is estimated that 15 to 125 MtU million metric tons of uranium (MtU) could be extracted from terrestrial ores at a cost of less than \$260 per kilogram.[116] The type of reactor in widest use, the light-water reactor (LWR), requires about 200 tons of uranium per gigawatt-year if operated on a once-through fuel cycle, in which the spent fuel is treated as waste.[117] Thus, conventional uranium resources could supply 6,000 to 50,000 EJ_p in current reactors—the rough equivalent of oil and gas resources, and sufficient to sustain the current rate of nuclear energy production for 300 to 2500 years.[118]

Despite its recent stagnation, nuclear power could be expanded over the next fifty years to provide one-quarter to one-half of the world's electricity.[119] Conventional uranium resources could easily support high growth in nuclear electricity production for at least fifty years using LWRs operating on a once-through fuel cycle.[120] More efficient once-through fuel cycles could extend the conventional resource somewhat,[121] but a heavy reliance on nuclear energy over the longer term would require a transition to fuel cycles that recycle plutonium and uranium or that exploit unconventional uranium resources.

The traditional solution to the long-term resource problem is to separate and recycle the unburned plutonium and uranium in the spent fuel. Using breeder reactors, it is possible to decrease uranium requirements by a factor of 100, so that 25 MtU could provide over one million exajoules of primary energy. Recycling plutonium raises serious concerns about the possible diversion of this material for weapons, however (see below). Moreover, the higher cost of the breeder fuel cycle would be economically justified only if uranium becomes very expensive—at least $260/kgU.[122]

Less discussed is the possibility of using unconventional uranium resources. Of particular interest is the huge amount of uranium—4500 MtU—dissolved in the world's oceans at a concentration of about 3 ppm. Although initial investigations yielded costs as high as $800/kgU,[123] recent studies indicate that uranium could be extracted from seawater for as little as $100/kgU.[124] If the lower estimates prove accurate, plutonium recycling and breeder reactors could be postponed for many centuries even with a high growth in nuclear power production.

A large expansion of fission energy is unlikely to happen, however, unless public concerns about accidents, waste disposal, and the spread of nuclear weapons are resolved. Before discussing these issues in detail, it is worth noting that expert opinion is divided on this issue. Some believe that fission's public-acceptance problems have little or no basis in fact. In their view, current reactor designs are very safe, waste-disposal risks are infinitesimal, and links to the spread of nuclear weapons are purely hypothetical. Others believe that the liabilities of nuclear energy are so great and so intractable that no amount of research and development could solve them. In their view, fission is simply "beyond the pale" and should be phased out. But the need for carbon-free energy is so great, and the possible sources of this energy are so limited and problematic, that it would be irresponsible to rule out a much larger contribution by fission. Moreover, the possibilities for improving the acceptability of fission are at least as promising as those for the other major alternatives. It is to these possibilities that I now turn.

<u>Accidents.</u> Fission reactors produce radionuclides which, if released into the atmosphere, could kill thousands of people and contaminate for decades thousands of square kilometers of land. A release can occur if the fission chain reaction grows uncontrollably for a fraction of a second (a "criticality" accident), or if the heat generated by the decay of the radionuclides is not removed from the fuel for a few minutes or hours (a "loss-of-cooling" accident). In both cases, the danger is that volatile radionuclides would be released from the hot fuel. Nearly all commercial reactors have containment buildings that are designed to prevent the release of radioisotopes into the environment, but the containment might be breached by an explosion or earthquake. Accidents could be initiated by internal events, such as the failure of pipes or valves, or by external events, such as earthquake, fire, or flood.

The fifteen water-cooled, graphite-moderated reactors that operate in Russia, Ukraine, and Lithuania are susceptible to criticality accidents, and it was this type of event that triggered the destruction of the Chernobyl reactor in 1986. The Chernobyl accident led to the deaths of thirty-nine plant workers and firefighters and to the permanent evacuation of 135,000 people from an area of nearly 3,000 square kilometers.[125] It is estimated that thirty thousand people may die prematurely of cancer induced by radiation exposure from the release, although this is highly uncertain.[126] These reactors have fundamental design flaws, including the lack of a containment building, that have led experts to recommend that they be shut down permanently.

LWRs are virtually immune to criticality accidents, but they are vulnerable to loss-of-cooling accidents. The accident at the Three Mile Island (TMI) reactor in 1979 was a loss-of-cooling accident. The reactor core melted, but the amount of radioactivity released into the environment was too small to harm the surrounding population. This was the only accident at an LWR, in about five thousand reactor-years of operation worldwide, in which the reactor core was damaged.

The accident at TMI triggered numerous improvements in reactor safety. Detailed calculations indicate that the probability of core damage is less than 10^{-4} per reactor per year for current U.S. LWRs, and that the probability of a significant release of radioactivity is about ten times smaller.[127] Although these probabilities are low, they are not low enough. At this rate, accidents resulting in core damage and raising the prospect of a large release of radioactivity would occur once per decade in a world with one thousand nuclear reactors.

New LWRs should be considerably safer. Calculations indicate that General Electric's Advanced Boiling Water Reactor and Combustion Engineering's System 80+ pressurized water reactor would have core-damage probabilities lower than 10^{-6} per reactor-year for internally initiated accidents.[128] If rates this low could be achieved in practice, a very large expansion in nuclear capacity could occur over the next century with little chance of a serious accident.[129] The latest generation of LWRs could be perceived as safe enough to be broadly acceptable.

It will be difficult, however, to demonstrate that extremely low levels of risk have been achieved. Even these advanced LWRs depend on the proper operation of equipment, such as pumps and valves, to prevent accidents. Insurance against equipment failures is provided by having redundant and independent systems to perform a critical task. Although one might be able to show that a particular system has a very low failure rate under certain circumstances, it is far more difficult to demonstrate that its probability of failure is independent of the failure of other systems or to identify all possible accident sequences. Safety also depends on proper operation and maintenance of the reactor. Unfortunately, examples of poor management are not hard to find, and it is difficult to estimate the likelihood of operator errors that could trigger or exacerbate an accident. Finally, even if the risk of internally initiated accidents is made extremely low, it is harder to reduce risks from external events, such as earthquake, flood, or fire.

For these reasons, a substantial expansion of nuclear power may require the development of so-called "inherently safe" or "passively safe" reactors, which place less reliance on the proper functioning of equipment and human operators. For example, a cooling system that relies on natural circulation is safer—and its safety is easier to demonstrate—than a system that relies on pumps. Several design concepts have been put forward for passively safe LWRs, gas-cooled graphite-moderated reactors, and liquid-metal-cooled fast reactors.[130] It is technically feasible to build a reactor that can shut itself down and prevent core damage for several days or longer without operator intervention or off-site electricity. Small, modular reactors could improve quality control and safety by allowing standard units to be produced and tested in factories, much as aircraft are now produced. Although modular, passively safe reactors probably would be more expensive than conventional LWRs, shorter licensing and construction times, more reliable cost estimates, higher investor confidence, and reduced public opposition would provide offsetting advantages. Thus, it seems plausible that nuclear fission could supply a large fraction of future energy consumption in ways that would be safe—and would be perceived as safe.

Waste disposal. Nuclear reactors generate long-lived, highly radioactive wastes that must be isolated from the biosphere for many millennia. A number of solutions to this problem have been proposed over the years, ranging from disposal in deep sea beds to launching the waste into the sun. Most countries have adopted deep geological disposal in a mined repository, but no wastes have been disposed of so far. Although spent fuel and vitrified wastes can be stored safely in interim facilities for fifty to one hundred years or more, the continued accumulation of wastes in the absence of a proven, permanent repository is a barrier to the expansion of nuclear power in many countries.

Cost is not a major issue; geological disposal is expected to add only about $0.001/kWh to the price of nuclear-generated electricity in the United States. The main difficulty is selecting a site and certifying that, over many thousands of years and under almost any conceivable scenario, people would not be exposed to unacceptable risks. Even if scientists could demonstrate with high confidence that the risks associated with radioactive waste disposal at a particular site would be extremely small, it nevertheless may be difficult to overcome local opposition. In the United States, public acceptability considerations led Congress to choose the Yucca Mountain site in sparsely populated Nevada, even though it may not be the best site from a technical point of view.

The fact that the wastes contain radionuclides with extremely long half-lives have led some to conclude that it is virtually impossible to assure that fission-reactor wastes would not pose unacceptable risks to future generations. Although this is often construed as a unique feature of nuclear energy, other industrial activities routinely release toxic metals—which never decay—directly into the biosphere with little consideration of the long-term consequences. Indeed, when one considers the fraction that might plausibly enter the biosphere, the wastes generated by a nuclear reactor might be less hazardous than the toxic metals discharged from a coal-burning power plant.[131] Moreover, changes in climate resulting from the burning of fossil fuels may have very serious effects on future generations—far more serious than the risks associated with radioactive waste disposal.

There is, of course, considerable uncertainty about what might happen to nuclear wastes thousands of years after they are placed in a repository, and even more uncertainty about how humans might become exposed to the wastes. Calculations show that waste packages would remain intact for five hundred to one million years, depending on the design of the package, the thermal loading of the repository, the nature of the surrounding rock, and precipitation in the area.[132] After the packages leak, it would take one thousand to one million years for the most soluble radionuclides to reach the biosphere. The most hazardous radionuclides (plutonium and other transuranic elements), which are much less soluble, would take one hundred to one thousand times longer to reach the biosphere.[133] Natural analogues, such as natural reactors and uranium ore bodies, indicate that, at least in some geologies, the most hazardous radionuclides would be contained extremely well in the surrounding rock, and would decay to harmless levels long before they could come into contact with living things.[134]

How are we to regard small and speculative risks to unimaginably distant generations? The U.S. National Academy of Sciences and regulatory bodies in other countries have recommended that the radiation standards that are used today to protect the general population should apply to future individuals.[135] These standards are stringent. In the United States, the dose to an individual from all nuclear facilities must be less than 25 millirem per year (mrem/yr)—about one-tenth of the average dose rate from natural background radiation and about half the average dose rate from medical x-rays. Calculations for proposed repositories in Belgium, Canada, Finland, France, Japan, and Sweden indicate that the maximum dose to an individual would at all times be far below current limits.[136] Unfortunately, similar calculations show that considerably greater doses might be possible at times well in excess of one hundred thousand years at the Yucca Mountain site, or earlier in cases of human intrusion (such as drilling through a waste canister).[137]

Currently, every country is expected to dispose of its own nuclear wastes—even small countries such as Belgium, Netherlands, Switzerland, and Taiwan, whose combined areas are less than the area of Indiana. This practice is inefficient, uneconomical, and potentially risky. Countries should be encouraged to accept nuclear wastes from other countries, provided that their repositories meet international standards. One could require, for example, that the International Atomic Energy Agency certify that a particular site meets such standards before it would be allowed to accept wastes from other countries. A similar procedure could be developed for the interim storage of spent fuel and high-level waste.

Because it is likely that geologic disposal will continue to be problematic in some countries, research on other methods of disposal should be revived. The most promising alternative is sub-seabed disposal, in which waste canisters would be placed in the thick layer of fine, sticky mud that exists on the ocean floor.[138] Vast areas of the seabed have been undisturbed for tens of millions of years, and it is estimated that radionuclides would move through the mud at a rate of only about one meter per million years. If radioactivity somehow leaked into the water at the bottom of the ocean, there are no pathways by which humans could receive a measurable dose. Although sub-seabed disposal currently is prohibited by international treaty, this could be changed in 2019 if additional research shows that it is safe and if geologic disposal proves unworkable.[139]

It is sometimes claimed that reprocessing—separating and recycling the uranium and plutonium in spent reactor fuel—greatly reduces the cost and risk of waste disposal. Although reprocessing reduces the mass and the volume of high-level wastes by about a factor of five,[140] the capacity of a repository—and therefore the cost of disposal—is limited by the heat output of the wastes, not by their mass or volume. Because most of the heat is produced by fission products, reprocessing would not reduce the cost of waste disposal by more than a factor of two.[141] Likewise, the risks of waste disposal, even over the very long term, are dominated in most scenarios by long-lived fission products, such as technetium-99 and iodine-129, which are far more soluble in water than are plutonium and other transuranic elements.

It has also been suggested that separating radionuclides with long half-lives and transmuting them into short-lived or stable nuclides would greatly reduce waste-disposal risks. Transmutation would be accomplished in a reactor or accelerator. Although the amount of long-lived waste could be reduced, it would be extremely difficult to achieve separation and transmutation efficiencies so great that the need for high-level radioactive waste disposal would be eliminated. It is highly unlikely that the small reduction in waste-disposal risk in the very long term (which is already very small) would outweigh the high costs and increased accident and proliferation risks associated with separation and transmutation in the near term.[142]

Proliferation. All nuclear fuel cycles involve fuels that contain weapon-usable materials that can be obtained through a relatively straightforward chemical separation process.[143] Although fresh LWR fuel cannot be used for weapons purposes,[144] spent LWR fuel is 1 percent plutonium. This "reactor-grade" plutonium contains a higher percentage of undesirable isotopes than does the "weapon-grade" plutonium used in stockpiled nuclear weapons. These undesirable isotopes emit heat and radiation, complicating weapon design and leading some observers to argue incorrectly that reactor-grade plutonium is unsuited for weapons. In fact, any group that could make a nuclear explosive with weapon-grade plutonium would be able to make an effective device with reactor-grade plutonium.[145] Access to weapons-usable material—plutonium or high-enriched uranium (HEU)—is, moreover, the principal barrier to the acquisition of nuclear weapons by rogue nations or subnational groups. The plutonium discharged from civilian reactors should therefore receive the same degree of protection from theft or misuse as assembled nuclear weapons.

Under the Non-Proliferation Treaty, all but a handful of states[146] have promised not to acquire nuclear weapons and have agreed to accept safeguards on peaceful nuclear activities to verify that nuclear materials are not being diverted or misused. As long as the fuel remains intact, it is relatively easy to detect diversion of the plutonium-bearing spent fuel, because international inspectors can simply tag and count the number of fuel assemblies. Spent fuel also is very difficult to steal, both because of its unwieldy size and because it is highly radioactive. A spent fuel assembly from a typical LWR is 4 meters (13 feet) long, weighs 650 kilograms (1500 pounds), and would deliver a lethal dose of radiation to an unprotected person in a few minutes.[147] A single assembly contains enough plutonium for a nuclear weapon,[148] but because of the high radiation field the spent fuel is said to be "self-protecting."

The United States adopted the once-through fuel cycle in the 1970s primarily because the cycle maintains nuclear materials in forms that are relatively invulnerable to misuse. At current and foreseeable uranium prices it is also the least expensive fuel cycle. The main alternative to the once-through cycle involves the separation and recycling of the plutonium and uranium in the spent fuel. Not only is separation and recycle more expensive, it increases greatly the opportunities for theft and diversion of plutonium.

Recycle begins in reprocessing plants, where the highly radioactive spent fuel rods are chopped up and dissolved in nitric acid and the plutonium and uranium are chemically extracted from the solution. In contrast to spent fuel rods, which are easy to count and track, precise measurement of plutonium inventories in a reprocessing plant is notoriously difficult. The amount of plutonium in the spent fuel is uncertain and inventories are difficult to measure at various points in the process, leading to inevitable difference between the estimated amounts of plutonium entering and exiting the plants. In a large reprocessing plant, this "material unaccounted for" or "inventory difference" can amount to many bombs worth of plutonium per year.[149] Although material accounting can be improved, it does not appear that one could detect with high confidence and in a timely manner the diversion of a significant amount of plutonium from a large reprocessing facility.[150]

After reprocessing, the separated plutonium would be used to fabricate fresh mixed oxide (MOX) reactor fuel, generating additional opportunities for theft or diversion of plutonium. Plutonium could be stolen as it is transported from the reprocessing plant to the fuel-fabrication facility, or as the fresh MOX fuel is transported to the reactor. Plutonium also could be diverted inside the fuel-fabrication plant (which is subject to accounting uncertainties) and the fresh MOX fuel could be stolen or diverted from storage at the nuclear reactor.

Advocates of separation and recycle discount these dangers and offer four main advantages. First, it is sometimes claimed that recycle is cheaper than the once-through cycle, but this would be true only at very high uranium prices that are unlikely to be realized in the foreseeable future. Second, recycle extends the uranium resource, but there is no shortage of uranium and there may never be a shortage if uranium can be recovered from seawater at reasonable cost, as seems likely. Third, plutonium separation and recycle is said to reduce the costs and health risks of waste disposal. As noted above, any such advantages are likely to be very small. Fourth, separation and recycle would decrease the availability of plutonium to future generations, who might otherwise mine stores of spent fuel for plutonium.[151] But it is not clear that mining buried spent fuel would be simpler or less expensive than producing or diverting fresh plutonium or high-enriched uranium, and it is even less clear that the reduced availability of plutonium in the very long term would outweigh the increased near-term risks of theft and diversion associated with recycle.

It is possible that recycle will become more economical than the once-through cycle or that countries will continue to recycle despite the extra cost and risk of doing so. For this reason, we should investigate additional technical and institutional barriers designed to deter and detect theft or diversion. This could include novel reactor concepts, such as lifetime cores; new reprocessing techniques that do not involve the separation of pure plutonium;[152] and fuel cycles that minimize the production of high-quality plutonium, such as the thorium fuel cycle.[153]

The risks of diversion could be reduced more effectively by internationalizing certain parts of the nuclear fuel cycle. One of the most severe shortcomings of the current nonproliferation regime is that non-nuclear-weapon states are permitted to own and operate facilities capable of producing plutonium and HEU, and can produce, stockpile, and use these materials so long as they are under safeguards. But safeguards may be unable to detect the diversion of significant quantities of these materials in a timely manner from facilities that handle the materials in bulk form, such as reprocessing and MOX fuel-fabrication plants. It would be far easier to deter or detect diversions by states if such activities were managed directly by an international agency. Similar arrangements could be extended to the storage and use of fresh plutonium fuels, or even spent fuel. National reactors might be permitted to burn only low-enriched uranium fuels, with the spent fuel turned over to international reprocessing or storage centers; reactors burning plutonium fuels would be managed by an international authority.

Solar Energy

Sunlight is the ultimate source of many of the forms of energy discussed above: biomass and fossil fuels, hydro, wind, wave, and ocean thermal energy. Here "solar" refers only to the direct use of sunlight to produce heat or electricity.

The solar resource is huge. About 500,000 EJ of sunlight falls on the continents each year. The resource is spread more uniformly than are other carbon-free sources, at least on an annual basis. Sunny areas, such as the southwestern United States or southern Spain, receive up to 9 gigajoules of solar energy per square meter of land area per year (GJ/m^2yr), while cloudy, northern areas, such as the northwestern United States or the United Kingdom, receive as little as about 4 GJ/m^2yr.[154] The average rate of energy consumption in the industrialized countries is about 200 GJ/yr per person, which is equal to the sunlight falling on 20 to 50 square meters.

As with other diffuse sources, the challenge is to capture and deliver solar energy economically. In temperate climates, properly designed and oriented buildings can be partially heated and lighted with solar energy at costs that are competitive with current U.S. energy prices.[155] Today, however, less than 1 percent of new homes built in the United States incorporate significant "passive solar" features. The turnover of the building stock is very slow. Even if passive solar design became far more popular, it would not contribute more than one percent of total U.S. energy demand in 2050.[156]

Alternatively, roof-mounted collectors can be used to heat air or water for residential or commercial use in existing buildings. To produce solar heat at $5 per gigajoule (the current retail price of natural gas in the United States), installed costs must be less than $200 per square meter in sunny areas, and less than $100 per square meter in less-sunny areas such as

New York or London.[157] Although the collectors themselves currently are produced in the United States for about $150 per square meter, installed costs are several times higher.[158] The economics of solar heat are even less favorable for industrial users, who require higher temperatures and who pay lower prices for conventional fuels.[159] The potential for lowering the cost of solar heat is limited; the technology is mature and uses common materials. If energy prices double or quadruple, however, solar could provide a substantial fraction of the energy used for heat—perhaps 10 to 20 percent of total energy demand.[160]

The technical feasibility of generating electricity with solar heat has been demonstrated in multi-megawatt facilities, both with distributed parabolic-trough collectors and with central "power-tower" receivers illuminated by hundreds of sun-tracking mirrors. The cost of electricity from advanced devices located in very sunny areas is estimated at about 8 to 16 cents per kilowatt-hour.[161] With additional improvements in efficiency and cost, solar thermal electric plants could compete favorably with new nuclear plants in sunny locations.

The solar technology with the greatest potential is photovoltaics. Photovoltaic cells convert sunlight directly into electricity. They require no focusing or tracking mechanisms (although concentrating systems may use these),[162] boilers, turbines, or cooling water; they generate no waste products, heat, or noise. Photovoltaics are highly reliable, have long lifetimes, and require very little maintenance. Photovoltaic cells can be wired together to form units of any size, from a fraction of a watt to hundreds of megawatts. They can be integrated into the design of exterior building surfaces. Photovoltaics have two major liabilities, however: high cost and their inability to function when the sun doesn't shine.

The cost of photovoltaic modules has decreased tremendously, from $100 per peak watt in 1975 to as low as $4 per peak watt today for large purchases. The cost per peak watt of net AC output to the grid, including support structures, inverters, and so forth, is roughly double the cost of the photovoltaic modules (i.e., about $8 per installed peak watt).[163] At this price, photovoltaic electricity remains far too expensive for widespread use. At a price of $1 per installed peak watt, photovoltaic systems would produce electricity for 4 to 10 cents per kilowatt-hour, depending on the location, in which case they would compete favorably with other sources of electricity, particularly in areas where demand is correlated with sunshine.[164]

Although confident predictions of low prices in the near future abound, it may not be easy to reduce the price of photovoltaic systems by another factor of ten. One dollar per installed peak watt corresponds to a price of $50 to $100 per square meter for photovoltaic modules.[165] The cost of the raw materials alone is unlikely to be less than $30 per square meter.[166] As noted above, the simple flat-plate thermal collectors currently cost $150 per square meter. As another point of comparison, the installed price of common building materials, such as shingles or siding, is about $30 per square meter.[167]

Even if prices fall to levels that would be economically competitive with other sources, solar would be limited to 10–20 percent of total electricity production unless large-scale, inexpensive storage or intercontinental transmission of electrical energy could be achieved. For the storage technologies available today—pumped hydro, compressed-air storage, and batteries—storage would increase the cost of electricity by 40 to 200 percent.[168] The electrolytic production of hydrogen is often mentioned as a means of storing and distributing electrical energy, but solar electricity would have to be very inexpensive—less than 2 cents per kilowatt-hour—in order for electrolytic hydrogen to be cheaper than hydrogen produced from the gasification of biomass or fossil fuels.[169] In the longer term, storage rings or transmission lines using high-temperature superconductors may provide an efficient and affordable means to store solar electricity or transmit it from sunlit to nighttime or overcast areas.

Some have suggested that large arrays of solar cells could be placed in geosynchronous orbit around the earth, with the power transmitted in microwave form to fixed receiving antennae on earth. Because the array would receive sunlight at a constant rate, without interference from the atmosphere or clouds, a photovoltaic module in orbit would on average produce electricity at about five times the rate that it would at the sunniest locations on the earth's surface.[170] This constant and predictable supply would, moreover, eliminate the need for energy storage. Although conceptually appealing, these advantages are unlikely to compensate for the enormous costs of placing and maintaining equipment in orbit. At current prices, launch costs alone would amount to $100 to $500 per peak watt—equivalent to 80 to 400 cents per kilowatt-hour.[171] Putting aside questions about the overall technical feasibility of such a project, launch costs would have to drop by a factor of twenty or more for this concept to be economically competitive with ground-based generation.[172]

Wind Energy

Wind power has been harnessed by humans for millennia, but only in the last decade has wind generated significant amounts of electricity at costs comparable to conventional sources. In 1995, wind produced a total of 7.5 TWh of electricity, mostly in the United States, Germany, Denmark, and India.[173] From 1985 to 1995, installed wind-turbine capacity increased from 1.0 to 4.8 gigawatts—an average growth rate of 17 percent per year. If this high growth rate could be sustained for the next thirty years, wind would supply nearly 10 EJ_p/yr of primary energy by 2025.

The wind energy resource is best classified according to the average wind power density at a given height above the ground, in watts per square meter of vertical area (W/m^2). Today, electricity is produced at a cost of 5 to 8 cents per kilowatt-hour at sites with average wind power densities greater than 250 W/m^2 at a height of 10 meters.[174] As shown in Table 15, wind power densities of 250 W/m^2 or greater occur over 6.8 million square kilometers, or 5 percent of global land area. In theory, about 160,000 TWh/yr (1500 EJ_p/yr) could be generated with wind machines distributed over this area.

Table 15. Land area with wind power density greater than 250 W/m^2 at 10 meters, and theoretical and practical electrical production potential, for each continent.

Region	Area (10^6 km^2)	Electrical Potential (10^3 TWh/yr) Theoretical*	Practical†
North America	3.4	78	4.9
Europe (inc. FSU)	1.5	41	4.1
South America	1.0	22	2.2
Australia	0.6	13	0.4
Africa	0.2	4.7	0.5
Asia	0.2	4.7	0.5
Total	6.8	160	12

Source: Michael J. Grubb and Niels I. Meyer, "Wind Energy: Resources, Systems, and Regional Strategies," in Thomas B. Johansson, Henry Kelly, Amulya K.N. Reddy, and Robert H. Williams, eds., *Renewable Energy: Sources for Fuels and Electricity* (Washington, DC: Island Press, 1993), p. 197.

*Assumes an average production rate of 23 GWh/yr per square kilometer of land, or 1500 kWh/yr per m^2 of swept area (680 W/m^2 at 25 percent system efficiency and 100 percent availability) and 64 m^2 of land area per m^2 of swept area. For comparison, wind turbines in California averaged 800 kWh/m^{2}yr in the mid-1990s.

†Assumes that the practical limit for each continent is the smaller of one-tenth of the theoretical potential and one-quarter of the primary energy consumption in 2150 (about one-half of electricity consumption) given in Table 9 (i.e., no significant trading of wind-generated electricity among continents).

The amount of wind energy that could be generated in practice is considerably lower. Much of the wind resource is located very far from population centers (e.g., in northern Canada and Russia), where the costs of transmission and maintenance would be excessive. Environmental constraints, such as the presence of existing forests and protected areas, would further limit the siting of wind turbines, as would public-acceptance considerations. All things considered, only about one-tenth of high-wind areas—mostly cropland and pasture—may be suitable for electricity production. Moreover, because of the intermittent and unpredictable nature of wind power, production would be limited to less than half of regional electricity demand.[175] Thus, the practical potential of wind electricity is limited to about 12,000 TWh/yr (110 EJ_p/yr)—equal to total world electricity demand in 1995, or roughly one-third of projected world demand in 2050.

Advances in technology might make it possible to generate electricity economically at offshore sites or at sites with lower wind power densities. As shown in Table 16, the use of lower-power-density sites would expand the practical production potential to nearly 30,000 TWh/yr. Although wind is unlikely to become a dominant energy source, it has the potential to contribute a substantial fraction to total energy demand.

Table 16. Global land area and theoretical and practical production potential as a function of wind power density.

	Wind power density (W/m^2) at 10 m		
	>250	>200	>150
Area (10^6 km^2)	6.8	16	30
Theoretical Potential (10^3 TWh/yr)*	160	320	500
Practical Potential (10^3 TWh/yr)†	12	22	28
Primary Energy (EJ_p/yr)	110	200	260

Source: See Table 15.
*Assumes theoretical production potential of 1500 kWh/m^2yr for a power density of 250 W/m^2 or greater, 1000 kWh/m^2yr for a power density of 200–250 W/m^2, and 830 kWh/m^2yr for 150–200 W/m^2.
†Assumes that the practical limit for each continent is the smaller of one-tenth of the theoretical potential and one-quarter of the primary energy consumption (about one-half of electricity consumption) given in Table 9.

Decarbonized Fossil Fuels

There is no impending shortage of fossil fuels. As shown in Table 6, recoverable resources of conventional oil, gas, and coal are sufficient to meet world energy needs for at least another one hundred years.[176] Moreover, enormous quantities of unconventional fossil fuels—methane hydrates, oil shales, and tar sands—could be extracted at somewhat higher prices or with improved technology. The shortage is not of fuel, but of a capacity to cope with the products of combustion—in particular, carbon dioxide. If one could safely and inexpensively "decarbonize" or remove and sequester the carbon contained in fossil fuels, they could continue to serve as the basis for world energy supply. Unlike most other alternatives, this option has the advantage of relying on well-established industries and technologies, offering the potential of a smooth transition to carbon-free energy production.

About half of the carbon dioxide emitted into the atmosphere by human activities is sequestered naturally by the oceans and the biosphere on a timescale of a decade or so. Humans can increase biospheric storage in a cost-effective and environmentally beneficial way by slowing tropical deforestation and implementing reforestation programs.[177] The contribution of these processes and programs is included in the estimated limits on fossil-fuel carbon-dioxide emissions given in Table 5. Here we examine the more direct approach of capturing the carbon dioxide before it is released into the atmosphere and sequestering it deep underground or in the ocean.

Capture. There are two main approaches for removing the carbon from fuels. The first is to capture the carbon dioxide gas after combustion. This is practical only for large, centralized sources of carbon dioxide, primarily coal-fired power plants. The technology for capturing carbon dioxide from flue gases using chemical solvents is mature but expensive. It is estimated that carbon-dioxide capture would increase the price of electricity from a traditional coal-fired power plant by 40 to 120 percent ($0.02–0.06/kWh), equivalent to $100 to $260 per ton of carbon emission avoided.[178] The costs would be greater for a gas-fired power plant, due to the lower carbon content of the fuel.

The second approach is to chemically convert fossil fuels into hydrogen and carbon dioxide.[179] Hydrogen is produced from natural gas and gasified coal on a commercial scale today for the manufacture of ammonia and other chemicals; the cost per unit energy of the hydrogen product is about 70 percent greater than that of natural gas and five times greater than that of coal.[180] Even at these high prices, hydrogen could be an attractive fuel in the long term because it can be converted efficiently in fuel cells into electricity with virtually no pollution. Coal also can be converted into hydrogen-rich fuels, such as methane or methanol, that are easier to transport and store than is hydrogen. The cost of such chemical conversions is very high, however—equivalent to $150 to $500 per ton of carbon emissions avoided.[181]

Perhaps the most attractive decarbonization concept is based on the integrated coal-gasification combined-cycle (IGCC) power plant, in which the combustion of fuel gas derived from coal is used to drive a gas turbine, with the waste heat used to drive a steam turbine. In this case, the carbon dioxide would be separated from the fuel gas before combustion, generating a stream of almost pure hydrogen. Although the cost of electricity from an IGCC plant is estimated to be somewhat greater than that of a traditional coal-fired power plant, the incremental cost of capturing the carbon dioxide is smaller because of the high concentration of carbon dioxide in the fuel gas. Even so, carbon-dioxide recovery is estimated to add $0.013 to $0.026/kWh (25 to 50 percent) to the price of electricity, or $65 to $160 per ton of carbon emissions avoided.[182]

None of these techniques would eliminate carbon emissions completely. About 10 percent of the carbon contained in the fuel would be emitted into the atmosphere as carbon dioxide. This reduction would be sufficient, however, to allow stabilization at or below an equivalent doubling even if fossil fuels continued to be the dominant energy source throughout the next century.

Disposal. In order for decarbonization to contribute significantly to world energy supply over the next century, several hundred billion tons of carbon would have to be sequestered in ways that would prevent its release into the atmosphere for at least several hundred years.[183] Such huge quantities of carbon dioxide could be sequestered at reasonable cost only in natural geological formations or in the oceans. Other options, such the manufacture of solids or industrial chemicals or storage in engineered facilities or mined cavities, are too limited or too expensive to make a major contribution.[184] The characteristics of various disposal options are summarized in Table 17.

Table 17. Options for sequestering carbon dioxide.

<table>
<tr><th>Disposal option</th><th>Sequestration Potential (GtC)</th><th>Sequestration Period (yr)</th><th>Cost ($/tC)</th></tr>
<tr><td>Biomass (included in tables 3–5)</td><td>100</td><td>100+</td><td>0 – 80</td></tr>
<tr><td>Chemical manufacture</td><td>0.1/yr</td><td>100+</td><td>10 – 60</td></tr>
<tr><td>Underground disposal</td><td></td><td></td><td></td></tr>
<tr><td>Enhanced oil/gas recovery</td><td>20 – 70</td><td rowspan="2">>10^6</td><td>–40 – 60</td></tr>
<tr><td>Abandoned oil/gas wells</td><td>150 – 500</td><td rowspan="2">10 – 60</td></tr>
<tr><td>Saline aquifers</td><td>100 – 3000</td><td>$10^3 – 10^6$</td></tr>
<tr><td>Ocean disposal</td><td>>1000</td><td>100 – 1000</td><td>10 – 60</td></tr>
</table>

Sources: Howard Herzog, Elisabeth Drake, and Eric Adams, *CO_2 Capture, Reuse, and Storage Technologies for Mitigating Global Climate Change* (Cambridge, MA: Massachusetts Institute of Technology, January 1997), http://web.mit.edu/energylab/www/hjherzog/White_Paper.pdf; International Energy Agency, *Carbon Dioxide Disposal from Power Stations* (Stoke Orchard, UK: IEA Greenhouse Gas R&D Programme, 1995), p. 19, http://www.ieagreen.org.uk/sr3p.htm; International Energy Agency, *Carbon Dioxide Utilisation* (Stoke Orchard, UK: IEA Greenhouse Gas R&D Programme, 1995); http://www.ieagreen.org.uk/sr4p.htm.

Oil and gas wells are probably the least expensive and the most reliable option for the storage of carbon dioxide. Exploration and drilling costs would be low, and the prior existence of oil and gas deposits would ensure that carbon dioxide could be stored for millions of years if the original pressure of the reservoir is not exceeded. Total world capacity is estimated at 150 to 500 GtC, based on estimates of oil and gas resources. A small fraction of this storage potential—10 to 15 percent—could be used to enhance the recovery of oil and gas remaining in active wells, thereby lowering the costs of sequestration. Carbon dioxide was injected into oil wells in the United States on a small scale in the late 1970s to enhance oil recovery, when oil prices were much higher than at present. Natural gas often contains carbon dioxide, which today is separated and vented to the atmosphere; injecting this carbon dioxide is an obvious application of sequestration. In 1996, Statoil of Norway began injecting carbon dioxide from a gas field into an aquifer beneath the North Sea.

Storage in oil and gas wells alone would be not sufficient, however. A large fraction of fossil-fuel use occurs in areas such as Japan, western Europe, or the northeastern United States, where the cost to transport carbon dioxide to oil and gas wells would be very high. Disposal costs could be minimized by producing electricity or hydrogen close to oil and gas wells, but the savings would be more than offset by the high costs of transporting electricity and hydrogen over very long distances. Barring technical breakthroughs, such as inexpensive, long-distance superconducting electrical transmission systems, storage sites would be located closer to areas of energy consumption.

One option is store carbon dioxide underground in deep saline aquifers. In the United States, for example, 65 percent of power-plant carbon emissions occurs close to deep aquifers.[185] Storage sites would be located at depths greater than 800 meters, in order to maintain the carbon dioxide in a dense supercritical phase and under an impermeable layer to prevent the escape of carbon dioxide or mixing with shallow aquifers used for drinking water or irrigation. The injected carbon dioxide would displace and partially dissolve in existing water, and would react chemically with certain types of rock, particularly those rich in calcium and magnesium, to form solid compounds.

The potential storage capacity of underground aquifers is highly uncertain; estimates range from less than 100 GtC to more than nearly 3000 GtC.[186] The wide range is partly due to a lack of basic geological data, such as the volume, porosity, and permeability of aquifers, and partly due to assumptions about how much carbon dioxide could be stored by unit volume and about what types of aquifer structures would provide long-term storage. The transport and storage of carbon dioxide on land raises concerns about public safety and environment impact from pipeline or well failures, but these should not be more difficult to address than those associated with, say, the handling of natural gas.

Another option is to inject carbon dioxide into the deep ocean. Since most of the carbon dioxide emitted into the atmosphere would dissolve in the ocean eventually, one could think of this as simply accelerating a natural processes that would result from the burning of fossil fuels. The carbon sequestration potential of the oceans is huge—at least 1000 GtC. In contrast to underground aquifers, which can sequester carbon for millions of years, a significant fraction of the carbon dioxide injected into the deep ocean would return to the atmosphere over period of several hundred years.

The rate of return of carbon dioxide to the atmosphere would be determined primarily by depth of injection. At depths greater than 3700 meters, the density of the carbon dioxide is greater than that of seawater and the carbon dioxide would sink to the bottom of the ocean, creating a CO_2 "lake" on the ocean floor. In this case, about 15 percent of the injected carbon dioxide would return to the atmosphere over a period of roughly one thousand years. Pipelines have not been laid at depths greater than 1000 meters, but there may be other ways of achieving much greater depths. For example, long vertical pipes might be suspended from a tanker or offshore platform, or a dense plume might be created that would fall naturally to the ocean floor or become entrained in downwelling ocean currents.[187] The fraction and rate of return can be significantly greater for carbon dioxide dispersed at depths of less than 2000 meters, depending on ocean currents and topography near the point of injection, leading to higher atmospheric concentrations after one to two hundred years. Careful site-specific studies would have to be completed to ensure that the environmental benefits of reduced carbon dioxide concentrations would outweigh the costs and risks of ocean disposal.

The environmental impact and legal status of ocean disposal are uncertain. Sequestration will increase the acidity of seawater; depending on the dispersal mechanism, the decrease in pH could be biologically significant over large volumes of water. For example, the injection of 10 MtC/yr (corresponding to the carbon from half a dozen large coal-fired power plants) in a dense plume would reduce the pH below 7 (the level at which mortality is observed in some marine organisms) over about 500 km^3; the corresponding volume for disposal via a towed pipe or a deep seabed lake is only 1–5 km^3.[188] Environmental effects should be minimal as long as carbon dioxide is injected at depths greater than 1000 meters, since nearly all marine life is found above this level. In any case, dumping of wastes in the oceans is regulated by international law, and issuance of the required permits would take into account possible effects on deep-sea marine life and the availability of land-based disposal alternatives.[189]

The cost of disposal itself—that is, the cost of injecting carbon dioxide deep underground or into the ocean—is small compared with the costs of capture; estimates range from $1 to $30 per ton of carbon.[190] More significant may be the cost of transportation to the disposal site. The most straightforward option is to transport the carbon dioxide via pipeline at high pressure as a liquid or supercritical fluid. For a large pipeline carrying 5 to 30 MtC/yr (equivalent to the carbon dioxide emitted by three to twenty large coal-fired power plants), transport costs would be a few cents per ton of carbon per kilometer ($0.01–0.04/tC-km) for either underground or ocean disposal.[191] Transport and disposal by tanker is possible for ocean disposal, and may be cheaper at longer distances.[192] Depending on transport distance, total disposal costs would range from about $10 to $60 per ton of carbon.

Thus, the capture, transport, and disposal of hundreds of billions of tons of carbon is unlikely to cost much less than $100 per ton. As shown in Table 10, this would represent a substantial increase in the price of coal or coal-fired electricity. Even so, decarbonized coal could be economically competitive with other carbon-free energy sources, such as biomass, fission, and solar.

Summary

Table 18 summarizes the advantages and disadvantages of the five sources that could provide a large fraction of the carbon-free energy supply required by 2050 in order to stabilize greenhouse-gas concentrations at an equivalent doubling. Each of these sources has great promise, but each must overcome considerable technical, economic, or environmental barriers before it could realize its potential. These barriers are unlikely to dissolve spontaneously—a focused and enhanced program of research and development will be necessary.

Table 18. Pros and cons of the major carbon-free energy supply options.

	Pros	Cons
Biomass	portable fuels (H_2, ethanol) low technology low capital cost	high fuel cost high land requirements, limited resource base high environmental impact?
Fission	already deployed on large scale economically competitive today in some countries	high capital cost electric only public acceptance (accidents, waste disposal, proliferation)
Solar	huge, uniformly distributed resource low environmental impact	very high capital cost electric only intermittent; storage required
Wind	economically competitive today in high-wind areas low land use, environmental impact	limited low-cost resource electric only intermittent
Decarbonized fossil fuels	portable fuels (H_2, methanol) existing industrial base well-developed technology	very high cost uncertainties about stability, environmental impact of disposal

Conclusions and Recommendations

The goal of the Framework Convention on Climate Change is to stabilize greenhouse-gas concentrations at a level that would prevent dangerous interference with the climate system. Based on what we know today about climate change and its impacts, we should aim to stabilize concentrations at no more than an equivalent doubling of carbon dioxide. At this level, global average temperature would rise by 1.5 to 4.5 °C. This can be compared with temperature changes of only about 1 °C in average temperature over the last ten thousand years, and changes on the order of 5 °C over the last two million years. At the upper end of these estimates, the expected increases in temperature and associated changes in precipitation and evaporation would significantly alter climate over a substantial fraction of the earth's area, triggering changes in ecosystems and agriculture that would accurately be described as "catastrophic." In addition to large changes in long-term averages, there also is concern that climate might become more extreme or that climate might change very suddenly.

Our knowledge of how the climate system will respond to increasing greenhouse-gas concentrations is incomplete and highly uncertain. Any stabilization target should therefore be considered tentative and subject to change based on improved models and information. It could turn out that the changes associated with an equivalent doubling would be relatively mild and tolerable, in which case the target could be revised upward. By the same token, we might conclude find that even a doubling would not be intolerable. Nevertheless, it is worthwhile to explore in detail the implications of the best judgments we can make today. Only by constructing such scenarios can we formulate long-term goals and chart a realistic strategy for achieving them. This vision can also inform decisions about the best way to achieve short-term goals, such as compliance with the Kyoto Protocol.

To achieve stabilization at an equivalent doubling, fossil-fuel carbon emissions must be roughly 5 GtC/yr in 2050, compared with 6.3 GtC/yr in 1996. The estimate for emissions in 2050 is uncertain by 50 percent, due to uncertainties about future concentrations of greenhouse gases other than carbon dioxide, the flow of carbon within the atmosphere-ocean-biosphere system, the rate at which stabilization is achieved, and releases of carbon dioxide from other sources than fossil fuels, such as deforestation. The pathway to stabilization may be uncertain, but one thing is absolutely clear: stabilization at an equivalent doubling can be achieved only if carbon emissions peak in the first quarter of the next century and decline steadily thereafter.

The limit on fossil-fuel carbon emissions is equivalent to a limit on the consumption of fossil fuels in ways that release carbon dioxide into the atmosphere. By 2050, traditional fossil fuels can supply only about 270 EJ_p/yr (a figure that is also uncertain by 50 percent), compared with 330 EJ_p in 1996. At the same time that carbon emissions must decline, increases in population and per-capita income will cause global energy consumption to rise from about 400 EJ_p in 1996 to 600 to 1200 EJ_p in 2050. There must be a major transformation in world energy supply, similar to past transitions from wood to coal and from coal to oil and gas, in which traditional fossil fuels are replaced by carbon-free sources. This transformation must be well under way within the next ten to twenty years, and must be largely complete by 2050.

For stabilization at an equivalent doubling, carbon-free energy supply must increase by an order of magnitude, from 54 EJ_p in 1996 to 600 ± 300 EJ_p/yr in 2050. Only five sources are capable of supplying a substantial fraction of this non-carbon supply: solar, fission, decarbonized fossil fuels, and, to a lesser extent, biomass and wind. Other potential sources are either too limited, too expensive, or too unproven to make a substantial contribution by 2050. Each of the major alternatives currently has significant economic, technical, or environmental handicaps. Solar is environmentally benign but very expensive, and a major contribution from solar would require massive energy storage. Nuclear fission can produce electricity at prices competitive with coal, but it suffers from public-acceptance problems related to the risks of accidents, waste disposal, and the spread of nuclear weapons. Coal is abundant and can be converted into either electricity or portable fuels, but the cost of capturing, transporting, and disposing of the carbon dioxide is high. Biomass has the potential to supply large quantities of affordable portable fuels, but this would require vast areas of land, in competition both with agriculture and the preservation of natural ecosystems. Wind is economically competitive at windy sites close to cities or existing transmission lines, but attractive sites are limited.

The Need for Research and Development

The most pressing need—more urgent than near-term reductions in emissions—is a program of research and development aimed at reducing the liabilities of the major carbon-free alternatives listed above. A sensible strategy to stabilize greenhouse-gas concentrations at a reasonable level requires substantial increases in supplies of carbon-free energy, beginning no later than twenty years from now. Research and development is needed to produce carbon-free options that are less expensive and more desirable, but it can take decades for R&D to yield commercial results. Energy-supply systems have long lifetimes and slow rates of replacement; previous transformations of the energy supply system have taken roughly fifty years to complete. We must do the necessary R&D today if solutions are to be available when we need them.

Unfortunately, the trends generally are in the opposite direction. Public and private spending on energy research and development has declined steadily over the last two decades in the United States. As shown in Figure 8, total spending on energy research and development dropped from over $12 billion in 1980 to about 4.5 billion in 1996 (in constant 1997 dollars). Downward trends are also observed in other industrialized countries; worldwide, public-sector support for energy R&D fell from $13 billion in 1985 to $9 billion in 1995.[193] The decline in R&D spending is primarily the result of a return to low oil and gas prices, together with increasing deregulation of electricity markets, increased trade and international competition, constraints on government spending, and the elimination of unsuccessful projects, such as the breeder fission reactor.[194]

The breakdown of U.S. government expenditures on energy-technology R&D from 1978 onward is shown in Figure 9. Total spending dropped by nearly a factor of five over this twenty-year period. Spending declined in every program, by factors of 36, 6, 5, 3, and 1.4 for fission, renewables, fossil, fusion, and conservation, respectively. Research and development on carbon-free energy supply fell by a factor of 11, from $3.3 billion in 1978 to $0.3 billion in 1997.[195]

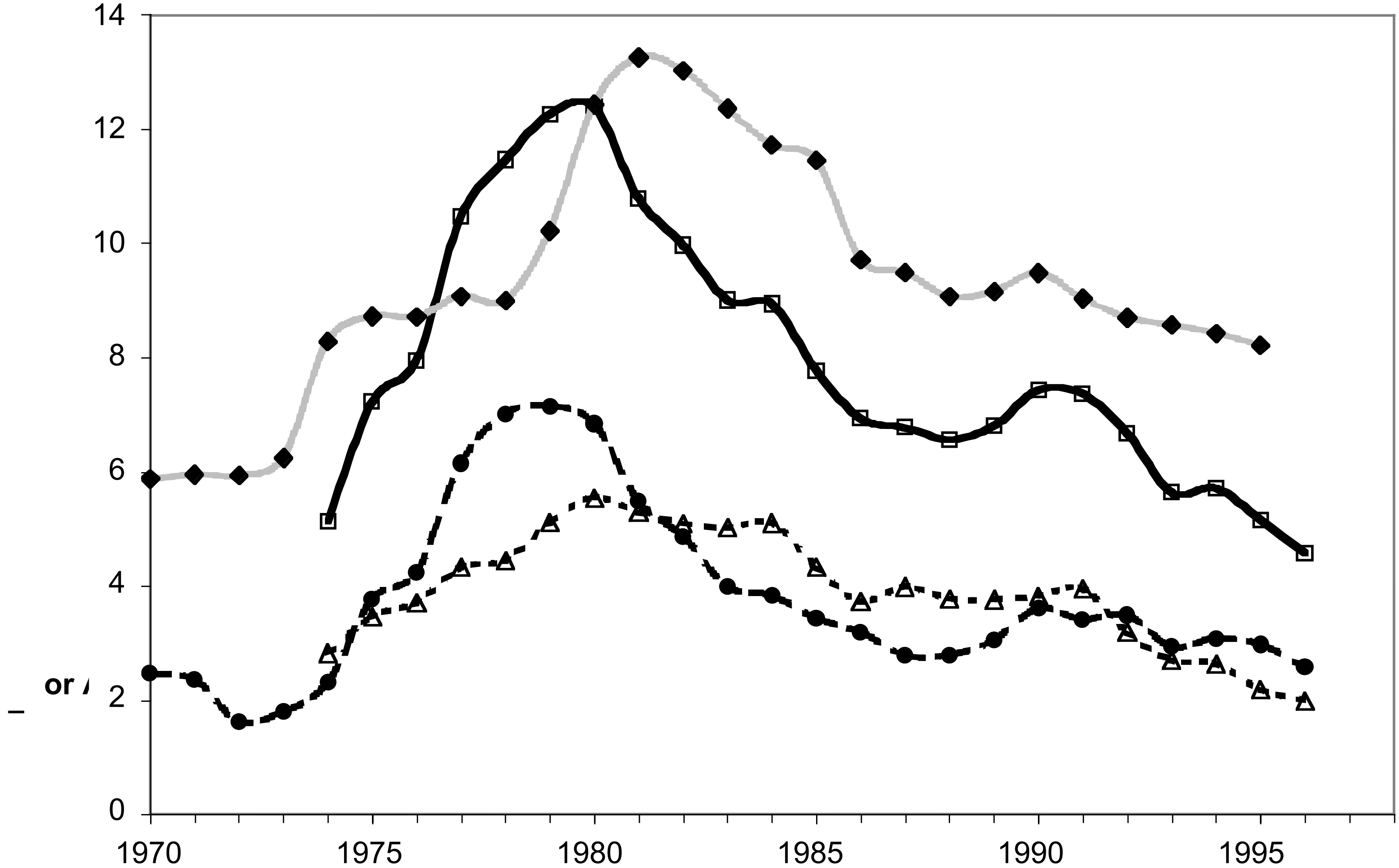
Spending on energy R&D was high in the late 1970s and early 1980s because of the "energy crisis" triggered by the rapid increase in oil prices. Those price increases were caused by monopoly effects, not by a shortage of oil. Indeed, high prices stimulated exploration and production, effectively breaking the OPEC monopoly and resulting in a steady decline in oil prices. Oil prices dropped to nearly $12 per barrel by late 1998, compared with over $60 per barrel in 1981 (in 1997 dollars).[196] As the energy crises faded, so did funding for energy research and development.

Today we face a new energy challenge: switching from traditional fossil fuels to carbon-free energy sources. This challenge is not as acute or as visible as the energy crisis of the late 1970s, but it is more important. In a recent report on U.S. energy research and development, the President's Committee of Advisors on Science and Technology (PCAST) argued that current R&D programs "are not commensurate in scope and scale with the energy challenges and opportunities the twenty-first century will present. The inadequacy of current energy R&D is especially acute in relation to the challenge of responding prudently and cost-effectively to the risk of global climatic change from society's greenhouse-gas emissions, of which the most important is carbon dioxide from combustion of fossil fuels."[197]

The PCAST report recommended increasing federal energy R&D from $1.3 billion in 1997 to $2.4 billion in 2003, with R&D on carbon-free supply rising from $0.3 to $0.8 billion.[198] Although I believe these increases are far too modest, the Clinton administration and the Congress cut the proposed increases in half.[199]

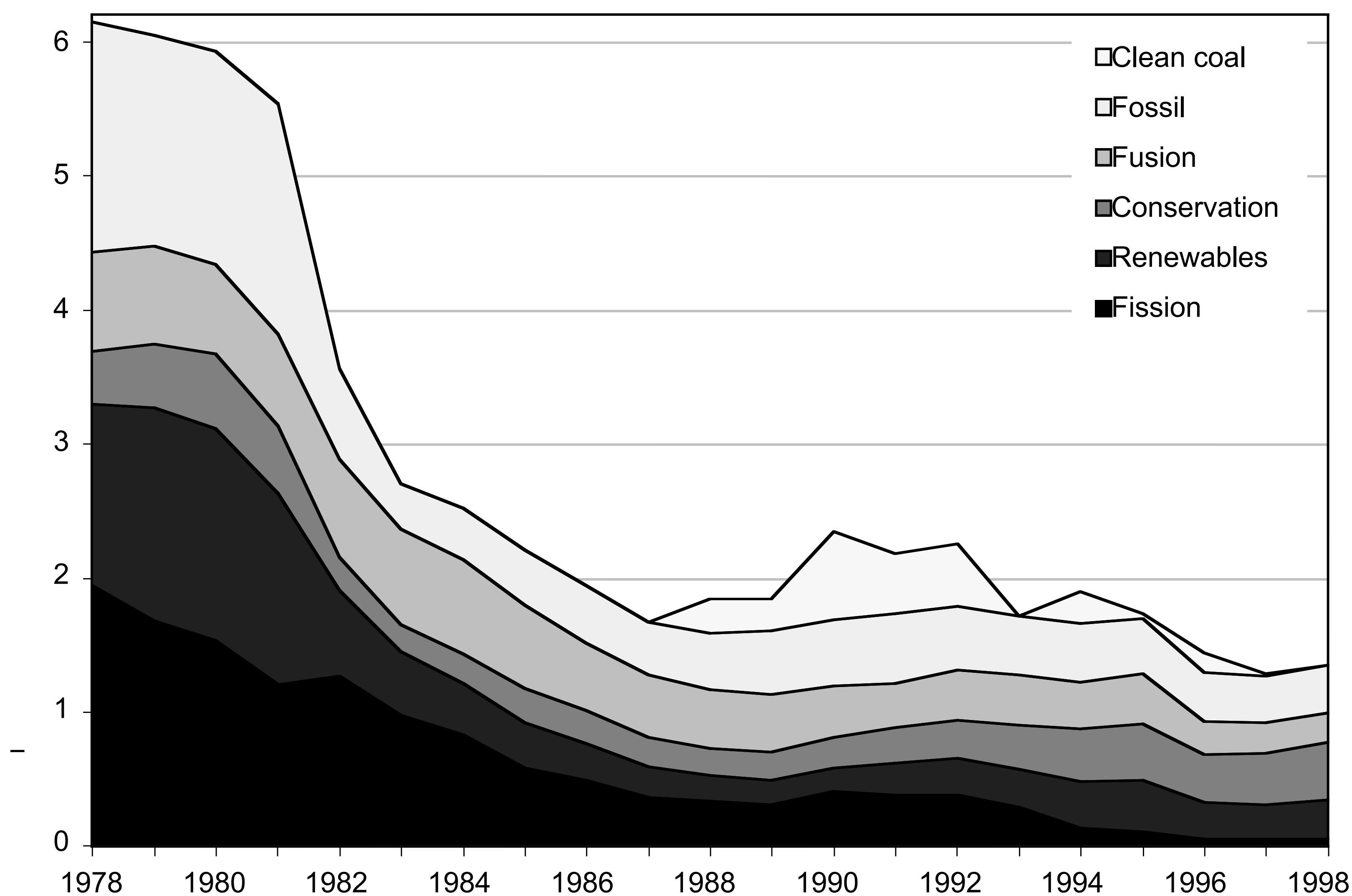
How much should we spend on energy research and development? One point of comparison is the amount spent on energy. In the mid 1990s, U.S. energy expenditures totaled about $500 billion per year.[200] Public and private energy R&D spending (about $4.5 billion in 1996) is less than 1 percent of energy expenditures—far below the average of 3.6 percent for all U.S. industries.[201] Global energy capital expenditures—new electrical generation plants,

Figure 8. Average energy price and energy research and development expenditures in the United States.



Sources: Energy Information Administration, *State Energy Price and Expenditure Report 1995* (Washington, DC: EIA, 1998), http://www.eia.doe.gov/emeu/sep/states.html; J.J. Dooley, *U.S. National Investment in Energy R&D: 1974–1996* (Washington, DC: Pacific Northwest Laboratory, December 1997), http://www.pnl.gov/bsap/energydata.html#publications.

Figure 9. U.S. federal energy-technology research and development expenditures.



oil and gas pipelines, and the like—were about $250 billion per year in the mid-1990s. This market is expected to double in size during the next two or three decades as developing countries install new generation and transmission capacity.[202] If the United States is to capture a significant fraction of this growing market, it must invest a proportionate amount in research and development today.

Current energy R&D spending also is insufficient when compared with past programs to develop new technologies. For example, the U.S. government spent about $6 billion, in addition to the billions spent by industry, to develop the light-water reactor.[203] A serious effort to reinvent fission energy probably would require government support at a rate of several hundred million dollars per year for ten to twenty years. For comparison, the fiscal year 1998 federal budget contains only $20 million for fission technology R&D.

Another issue is energy security. Today, the United States imports half the oil it consumes—a greater fraction than at any previous time.[204] In 1995, payments for net oil imports amounted to $60 billion per year—a significant fraction of the U.S. trade deficit. Within the next decade, oil imports from OPEC countries will reach pre-oil-embargo levels. It is estimated that roughly one-sixth of the U.S. defense budget—$50 billion per year—goes toward protecting supplies of Mideast oil,[205] and that the cost to the U.S. economy of a single, major disruption in Mideast oil would be over $400 billion.[206]

More to the point, energy research and development can be justified in terms of its potential to avoid costly changes in climate. As noted above, it is estimated that the economic costs associated with an equivalent doubling would be on the order of 2 percent of gross world product. Even if these costs do not materialize for another hundred years, the present value, discounted at a rate of 5 percent per year, would be $30 to $40 billion per year.[207] Economic models of the costs and benefits of climate change suggest that it would be worth spending $5 to $12 per ton of carbon today to reduce emissions, which would be equivalent to $40 to $80 billion per year.[208] One analysis concluded that the "insurance value" of energy R&D to mitigate climate change was $10 to $30 billion per year.[209] When the costs of air pollution and oil shocks are included, the authors found that energy R&D expenditures of at least $6 billion per year by the United States alone would be justified as an insurance premium.

If additional energy R&D is justified, why doesn't private industry do it? One reason is that private firms do not receive all of the benefits of the R&D they perform. Many firms profit from a single firm's R&D, and the total benefits to society can greatly exceed the benefits to all firms. For example, the security advantages of a proliferation-resistant nuclear fuel cycle or the environmental advantages of carbon-free energy accrue to society as a whole, not to firms. Another reason is that the time horizon of private firms is too short to support R&D with a long-term payoff. Private industry requires rates of return of 10 to 15 percent per year; at this rate, expected benefits thirty years hence have essentially no value. For investments in social welfare, such as avoiding dangerous changes in climate, a discount rate of 3 to 6 percent per year is more appropriate.[210] In addition, some research is too risky or too expensive for industry to support, even though the expected gains to society would be positive. Thus, public R&D can spread risks and benefits among firms, capture social benefits that do not accrue to firms, and support R&D with potentially huge payoffs but high risks or long time horizons.

As a modest step to correcting the deficiency of energy R&D, I would propose instituting a tax of $1 per ton of carbon, with the proceeds directed to a fund for carbon-free energy R&D. A tax of $1 per ton would raise fossil-fuel prices by only about 1 percent, but it would be sufficient, in the United States and on a global basis, to double public-sector energy R&D.

As noted above, a tax of $1 per ton is 100 to 500 times smaller than the tax that would be required by 2050 to stabilize at an equivalent doubling in the absence of breakthroughs in carbon-free energy supply. If energy R&D produces carbon-free energy technologies that can produce energy at the same price as fossil fuels—and there is a good chance that it can—then R&D spending would truly be "pennies on the dollar."

In the past, it has taken about twenty years to realize significant commercial benefits from energy research and development. To prepare for—and profit from—the transformation in energy supply that must begin in earnest in the next decade or so, we must do the R&D today. Our options are limited. We are not smart enough to pick sure winners, and the stakes are too high to rule out any major alternative. We need a balanced R&D program that includes substantial investments in all the sources that could provide a substantial fraction of global energy supply in 2050: biomass, fission, wind, solar, and decarbonized fossil fuels.

Notes

[1] "The Parties included in Annex I [the industrialized countries] shall, individually or jointly, ensure that their aggregate anthropogenic carbon dioxide equivalent emissions of the greenhouse gases listed in Annex A do not exceed their assigned amounts…with a view to reducing their overall emissions of such gases by at least 5 per cent below 1990 levels in the commitment period 2008 to 2012." Kyoto Protocol to the United Nations Framework Convention on Climate Change, FCCC/CP/1997/L.7/Add.1 (10 December 1997), Article 3.1. Available at http://www.unfccc.de/fccc/docs/cop3/protocol.html.

[2] The equilibrium temperature of a perfect emitter (a "blackbody") is given by T = [P/s]ˇ, where P is the rate of energy absorption or emission per unit area and s is the Stefan-Boltzmann constant (5.67∞10^{-7} W/m^2K^4). In the case of Earth, P = ˇ(1–a)W, where a is the albedo (the fraction of sunlight reflected back to space, about 0.31) and W is the solar constant (about 1368 W/m^2); P = ˇ(1–0.31)(1368) = 235 W/m^2. Thus, T = [(235 W/m^2)/(5.67∞10^{-7} W/m^2K^4)]ˇ = 254 K = –19 °C.

[3] Although human activities have increased evaporation, the increment is very small compared with natural flows and the average concentration of water vapor in the atmosphere remains constant at about 4000 parts per million by volume (i.e., there are 4000 water molecules for every million molecules in the atmosphere). The warming caused by increased concentrations of other greenhouse gases can, however, cause a significant increase in evaporation and in the concentration of water vapor—about 3 percent per degree centigrade increase in average surface temperature—which would lead to additional warming. This is referred to as the "water-vapor feedback."

[4] "Technical Summary," in J.T. Houghton, L.G. Meira Filho, B.A. Callander, N. Harris, A. Kattenberg and K. Maskell, eds., *Climate Change 1995: The Science of Climate Change* (Cambridge: Cambridge University Press, 1996), p. 34.

[5] A. Kattenberg, F. Giorgi, H. Grassl, G.A. Meehl, J.F.B. Mitchell, R.J. Stouffer, T. Tokioka, A.J. Weaver, T.L. Wigely, "Climate Models—Projections of Future Climate," in Houghton, et al., eds., *The Science of Climate Change*, pp. 291–357; Edward Bryant, *Climate Process and Change* (Cambridge: Cambridge University Press, 1997), p. 134.

[6] United Nations Framework Convention on Climate Change, May 1992, http://www.unfccc.de.

[7] J.T. Houghton, L.G. Meira Filho, B.A. Callander, N. Harris, A. Kattenberg and K. Maskell, eds., *Climate Change 1995: The Science of Climate Change*; Robert T. Watson, Marufu C. Zinyowera, and Richard H. Moss, eds., *Climate Change 1995: Impacts, Adaptations and Mitigation of Climate Change: Scientific-Technical Analyses*; and James P. Bruce, Hoesung Lee, and Erik F. Haites, eds., *Climate Change 1995: Economic and Social Dimensions of Climate Change* (Cambridge: Cambridge University Press, 1996).

[8] The observed increase in global-average surface temperature from the mid-nineteenth century to 1990 is 0.45 ± 0.15 °C. [N. Nicholls, G.V. Gruza, J. Jouzel, T.R. Karl, L.A. Ogallo, and D.E. Parker, "Observed Climate Variability and Change," in Houghton, et al., eds., *The Science of Climate Change*, p. 143]. The predicted increase from 1765 to 1990 is 0.3 to 0.6 °C. [Results of the model described in M. Hulme, S.C.B. Raper, and T.M.L. Wigely, "An Integrated Framework to Address Climate Change (ESCAPE) and Further Developments of the Global and Regional Climate Models (MAGICC)," *Energy Policy*, Vol. 23 (1995), pp. 347–355, assuming a total radiative forcing in 1990 of 1.32 W/m^2 and a climate sensitivity of 1.5 to 4.5 °C.]

[9] Nicholls, et al., "Observed Climate Variability and Change," p. 149, 156, 163; R.A. Warrick, C. Le Provost, M.F. Meier, J. Oerlemans, and P.L. Woodworth, "Changes in Sea Level," in Houghton, et al., eds., *The Science of Climate Change*, p. 366.

[10] Michael E. Mann, Raymond S. Bradley, and Malcolm K. Hughes, "Global-scale Temperature Patterns and Climate Forcing over the Past Six Centuries," *Nature*, Vol. 392 (23 April 1998), pp. 779–787; http://www.ngdc.noaa.gov/paleo/pubs/mann1998/frames.htm.

[11] Bryant, *Climate Process and Change*, p. 90, 192.

[12] Bryant, *Climate Process and Change*, p. 90–91, 157.

[13] The three variations in Earth's orbit are: (1) the variation in the eccentricity or roundness of the orbit, with a period of about 100,000 years; (2) the variation in the tilt of Earth's axis, with a period of about 41,000 years; and (3) the variation in the time of perihelion (the time of the year when Earth is closest to the sun), with a period of about 23,000 years.

[14] Bryant, *Climate Process and Change*, p. 89; Jeffrey P. Severinghaus, Todd Sowers, Edward J. Brook, Richard B. Alley, and Michael L. Bender, "Timing of Abrupt Climate Change at the End of the Younger Dryas Interval from Thermally Fractionated Gases in Polar Ice," *Nature*, Vol. 391 (8 January 1998), pp. 141–146; Scott Lehman, "Sudden End of an Interglacial," *Nature*, Vol. 390 (13 November 1997), pp. 117–119; William K. Stevens, "If the Climate Changes, It May Do So Fast, New Data Show," *New York Times*, 27 January 1998.

[15] A model developed by Manabe and Stouffer showed that the thermohaline circulation collapses when CO_2 concentrations reach two to four times the preindustrial level. [S. Manabe and R.J. Stouffer, "Century-scale Effects of Increased Atmospheric CO_2 on the Ocean-atmosphere System," *Nature*, Vol. 364 (1993), pp. 215–218.] A model developed by Stocker and Schmittner showed that, for a 1 percent per year increase in CO_2 concentration and a climate sensitivity of DT_{2X} = 3.7 °C, the thermohaline circulation would collapse at CO_2 concentrations above 670 ppmv. Extrapolating their results to a climate sensitivity of 4.5 °C (the upper end of the IPCC range), the threshold concentration would be about 560 ppmv. [Thomas S. Stocker and Andreas Schmittner, "Influence of CO_2 Emission Rates on the Stability of the Thermohaline Circulation," *Nature*, Vol. 388 (28 August 1997), pp. 862–865.] In a poll of

climate scientists, the median probability that a doubling of CO_2 would cause of "state change" in climate (the most common example of which is a collapse of the thermohaline circulation) was on the order of a few percent. [M. Granger Morgan and David W. Keith, "Subjective Judgments by Climate Experts," *Environmental Science and Technology*, Vol. 29, No. 10 (1995), p. 472.]

[16] William H. Calvin, "The Great Climate Flip-flop," *The Atlantic Monthly*, Vol. 281, No. 1 (January 1998), pp. 47–64.

[17] Miko U.F. Kirschbaum and Andreas Fischlin, "Climate Change Impacts on Forests," in Watson, et al., eds., *Impacts, Adaptations and Mitigation of Climate Change*, p. 111.

[18] See, for example, Andrew J. Davis, Linda S. Jenkison, John H. Lawton, Bryan Shorrocks, and Simon Wood, "Making Mistakes When Predicting Shifts in Species Range in Response to Global Warming," *Nature*, Vol. 391 (19 February 1998), pp. 783–786.

[19] Thomas M. Smith, Rik Leemans, and Herman H. Shugart, "Sensitivity of Terrestrial Carbon Storage to CO_2-induced Climate Change: Comparison of Four Scenarios Based on General Circulation Models," *Climate Change*, Vol. 21 (August 1992), pp. 367–384; Robert A. Monserud, Nadja M. Tchebakova, and Rik Leemans, "Global Vegetation Change Predicted by the Modified Budyko Model," *Climate Change*, Vol. 25 (September 1993), pp. 59–83.

[20] Cynthia Rosenzweig and Martin L. Parry, "Potential Impact of Climate Change on World Food Supply," *Nature*, Vol. 367, pp. 133–138.

[21] Carryover grain stocks have been about 300 million metric tons (Mt) or less in the 1990s. For comparison, global grain consumption is over 2000 Mt/yr. Thus, stocks would be wiped out in a single season if grain harvests fell by 15 percent, assuming no changes in consumption. Price increases would stretch stocks (by decreasing meat consumption and post-harvest waste), but this simple calculation indicates how vulnerable humanity is to a major climate-induced crop failure.

[22] Death, illness, and discomfort result not only from the direct effects of climate change (e.g., heat stroke), but, probably more importantly, from resulting changes in the geographic range of diseases and disease vectors. See, for example, Pim Martens, *Health and Climate Change: Modelling the Impacts of Global Warming and Ozone Depletion* (London: Earthscan, 1998).

[23] D.W. Pearce, W.R. Cline, A.N. Achanta, S. Fankhauser, R.K. Pachauri, R.S.J. Tol, and P. Vellinga, "The Social Costs of Climate Change: Greenhouse Damage and the Benefits of Control," in Bruce, et al., eds., *Economic and Social Dimensions of Climate Change*, pp. 203–205.

[24] William D. Nordhaus, "Expert Opinion on Climate Change," *American Scientist*, Vol. 82 (Jan/Feb 1994), pp. 45–51.

[25] Kattenberg, et al., "Climate Models—Projections of Future Climate," p. 297.

[26] See the discussion in M. Munasinghe, P. Meier, M. Hoel, S.W. Hong, and A. Aaheim, "Applicability of Techniques of Cost-Benefit Analysis to Climate Change," in Bruce, et al., eds., *Economic and Social Dimensions of Climate Change*, pp. 150–177.

[27] One might think that cost-benefit analysis would achieve the objective of the FCCC if the proper values were assigned to non-market costs and benefits. It is entirely possible, however, that a large fraction of ecosystems would not be able to adapt naturally, or that food production in certain regions would be threatened, at the point where marginal costs and benefits are equal. It is also possible, if ecosystem impacts are valued properly, that economic devel-

opment might not be able to proceed in a sustainable manner when marginal costs equal marginal benefits.

[28] "…there was a proposal by some delegations that levels of atmospheric CO_2 concentrations lower than 550 ppmv should guide limitation and reduction efforts." Ad-hoc Group on the Berlin Mandate, *Report of the Ad Hoc Group on the Berlin Mandate on the Work of Its Third Session*, FCCC/AGBM/1996/5, 23 April 1996, par. 41; http://www.unfccc.de/fccc/docs/1996/agbm/05.htm. It is not clear whether the delegates intended to express support for stabilization at less than a doubling of CO_2 concentration (550 ppmv), or less than an *equivalent* doubling (460 ± 30 ppmv after subtracting the contributions of other greenhouse gases).

[29] Assumes 1997 concentrations and radiative forcings of 363 ppmv and 1.64 W/m^2 for carbon dioxide, 1.76 ppmv and 0.49 W/m^2 for methane, 0.315 ppmv and 0.16 W/m^2 for nitrous oxide, and a forcing of 0.28 W/m^2 for various halocarbons. Thus, $\Delta F = 1.64 + 0.49 + 0.16 + 0.28 = 2.57$ W/m^2, and $C_{eq} = 280\ e^{(2.57/6.3)} = 421$ ppmv.

[30] The long-term contribution of tropospheric ozone and aerosols can be ignored for several reasons. First, the influence of tropospheric ozone and aerosols on climate is highly uncertain. Second, because the residence times of these substances in atmosphere are on the order of days, any effect on climate is regional, not global. Third, ozone and aerosols are generated by the burning of fossil fuels; reductions in fossil-fuel burning will result in proportional decreases in ozone and aerosol concentrations. Fourth, ongoing efforts to control air pollution and acid deposition will lead to long-term reductions in ozone and aerosol concentrations, independent of efforts to limit fossil-fuel burning.

[31] D. Schimel, et al., "Radiative Forcing of Climate Change," in Houghton, et al., eds., *The Science of Climate Change*, p. 94.

[32] Ruminant animals and animal wastes emit 80 ± 15 Mt/yr and 14 ± 4 Mt/yr of methane, respectively. Changes in feeding and waste management could reduce these emissions by 29 ± 16 Mt/yr and 5 ± 3 Mt/yr, for a total reduction of 35 ± 18 percent. Vernon Cole, "Agricultural Options for Mitigation of Greenhouse Gas Emissions," in Watson, et al., eds., *Impacts, Adaptations and Mitigation of Climate Change*, p. 764.

[33] Kathleen Hogan, *Current and Future Methane Emissions from Natural Sources* (Washington, DC: U.S. Environmental Protection Agency, EPA 430-R-93-011, 1993).

[34] L.D.D. Harvey and Z. Huang, "Evaluation of the Potential Impact of Methane Clathrate Destabilization on Future Global Warming," *Journal of Geophysical Research*, Vol. 100, pp. 2905–2926.

[35] Schimel, "Radiative Forcing of Climate," p. 95. Forcing includes indirect effects of stratospheric water vapor production. More recent estimates suggest stabilization at 1.8 ppmv for constant emissions at the 1996 level. E.J. Dlugokencky, K.A. Masarie, P.M. Lang, and P.P. Tans, "Continuing Decline in the Growth Rate of the Atmospheric Methane Burden," *Nature*, Vol. 393 (4 June 1998), pp. 447–450.

[36] Schimel, "Radiative Forcing of Climate," p. 97.

[37] This estimate takes into account uncertainties in the contribution of various sources to total methane emissions [M. Prather, R. Derwent, D. Ehhalt, P. Fraser, E. Sanhueza, and X. Zhou, "Other Trace Gases and Atmospheric Chemistry," in Houghton, et al., eds., *Radiative Forcing of Climate*, p. 86]; uncertainties in the reduction in emission per unit activity for each source [Cole, "Agricultural Options for Mitigation of Greenhouse Gas Emissions," and Mark D. Levine, "Mitigation Options for Human Settlements," in Watson, et al., eds., *Impacts,*

Adaptations and Mitigation of Climate Change, p. 731, 757–764]; and author's estimates of the long-term change in activity for each methane source.

[38] The application of nitrogen fertilizer is expected to more than double by 2025. [*Long-term Scenarios of Livestock-Cropland Use Interactions in Developing Countries* (Rome: Food and Agriculture Organization of the United Nations, Land and Water Bulletin No. 6, 1997).] Thus, emissions of nitrous oxide would remain approximately constant even if production per kilogram of fertilizer applied were cut in half.

[39] Prather, et al., "Other Trace Gases and Atmospheric Chemistry," in Houghton, et al., eds., *Radiative Forcing of Climate*, p. 118.

[40] Schimel, "Radiative Forcing of Climate," p. 98.

[41] See footnote 37.

[42] Schimel, "Radiative Forcing of Climate," p. 92, 93. Does not include the indirect effect of stratospheric ozone depletion.

[43] Schimel, "Radiative Forcing of Climate," p. 92, 93, 100, 102.

[44] Estimates were produced using the model described in T.M.L. Wigley, "Balancing the Carbon Budget: Implications for Projections of Future Carbon Dioxide Concentration Changes," *Tellus*, Vol. 45B, pp. 405–425, which was made available to the author. Because the Wigley model produces emissions that are higher than most other models for a given stabilization target, the results were adjusted downward to reflect the median of ten models compared in I.G. Enting, T.M.L. Wigley, and M. Heimann, *Future Emissions and Concentrations of Carbon Dioxide: Key Ocean/Atmosphere/Land Analyses* (Aspendale, Australia: CSIRO Division of Atmospheric Research, Technical Paper No. 31, 1993), p. 99. These models assume that ocean circulation and biology do not change. There is evidence to suggest that changes in ocean circulation would significantly decrease ocean uptake (and, therefore, carbon emissions for stabilization at a given level), but this may be compensated for by increased biospheric sequestration. [Jorge L. Sarmiento, Tertia M.C. Hughes, Ronald J. Stouffer, and Syukuro Manabe, "Simulated Response of the Ocean Carbon Cycle to Anthropogenic Climate Warming," *Nature*, Vol. 393 (21 May 1998), pp. 245–252. Similarly, models of biospheric uptake generally do not account for limitations imposed by the availability of other nutrients, such as nitrogen and phosphorus, possibly resulting in overestimation of carbon emissions. [David S. Schimel, "The Carbon Equation," *Nature*, Vol. 393 (21 May 1998), pp. 208–209.]

[45] The uncertainty in emission rates due to uncertainties in stabilization target (460 ± 30 ppmv), fertilization factor (Dn(80s) = 1.1 ± 0.7 GtC/yr), ocean flux (2.0 ± 0.8 GtC/yr), and stabilization profile (S450 or WRE450) were evaluated using the Wigley model. Modeling uncertainties were estimated using results for ten different models for stabilization at 450 ppmv given in Enting, Wigley, and Heimann, *Future Emissions and Concentrations of Carbon Dioxide*, p. 99.

[46] The baseline assumption is that the carbon-dioxide concentration stabilizes in 2150. A more rapid approach achieves stabilization in 2100; a more gradual approach, in 2200.

[47] This is in contrast to the statement in the IPCC reports that cumulative emissions are not sensitive to the emissions pathway taken to achieve stabilization at a given level. (See, for example, Schimel, et al., "Radiative Forcing of Climate Change," p. 84.)

[48] There are many opportunities to reduce near-term emissions at low or no cost, and we should take full advantage of them. But after measures with very high rates of return have been implemented, additional expenditures would more wisely be invested in energy research and development, since this would have a much greater effect on reducing emissions fifty years hence. A possible exception is if climate change is highly sensitive to the rate of increase of greenhouse gases, as well as the ultimate stabilization level. In that case, it would make sense to pay more for near-term reductions to ensure a more gradual approach to stabilization.

[49] In this paper, "tons" refers to metric tons. One metric ton is equal to 1000 kilograms (about 2200 pounds). One metric ton is equal to about one U.S. long ton and 1.1 U.S. short tons.

[50] D. Schimel, et al., "Radiative Forcing of Climate," pp. 78–79.

[51] Note, however, that the corresponding estimates of baseline (1990) emissions range from 0.7 to 2.5 GtC/yr. Normalizing these to a baseline of 1.1 GtC/yr gives a range of emissions in 2050 of 0.1 to 2.5 GtC/yr, with a median of about 1 GtC/yr. J. Alcamo, A. Bowman, J. Edmonds, A. Grubler, T. Morita, and A. Sugandhy, "An Evaluation of the IPCC IS92 Emission Scenarios," in J.T. Houghton, L.G. Meira Filho, J. Bruce, Hoesung Lee, B.A. Callander, E. Haites, N. Harris, and K. Maskell, eds., *Climate Change 1994: Radiative Forcing of Climate Change and an Evaluation of the IPCC IS92 Emission Scenarios* (Cambridge: Cambridge University Press, 1995), pp. 284–286.

[52] Alcamo, et al., "An Evaluation of the IPCC IS92 Emission Scenarios," p. 286; Sandra Brown, "Management of Forests for Mitigation of Greenhouse Gas Emissions," in Watson, et al., eds., *Impacts, Adaptations and Mitigation of Climate Change*, p. 775.

[53] Results of COMICC carbon-cycle model, for $D_n(80s) = 1.1 \pm 0.7$ GtC/yr. [Wigely, "Balancing the Carbon Budget."]. Simulations with another model produce a net uptake by the terrestrial biosphere of 180 ± 60 GtC from 1990 to 2100 for anthropogenic emissions of 1560 ± 270 GtC over this period, compared to the limit of 580 ± 230 used here for stabilization at an equivalent doubling. [Xiangming Xiao, Jerry M. Melillo, David W. Kicklighter, A. David McGuire, Ronald G. Prinn, Chien Wang, Peter H. Stone, and Andrei P. Sokolov, *Transient Climate Change and Net Ecosystem Production of the Terrestrial Biosphere* (Cambridge, MA: MIT, Joint Program on the Science and Policy of Global Change, report #28, November 1997), p. 8; http://web.mit.edu/globalchange/www/rpt28.htm.] Some models predict even greater carbon storage by the biosphere, but they generally do not take into account the limitations on plant growth imposed by the availability of other nutrients—in particular, nitrogen and phosphorus—and therefore may substantially overestimate carbon storage. [David S. Schimel, "The Carbon Equation," *Nature*, Vol. 393 (21 May 1998), pp. 208–209.]

[54] Kirschbaum and Fischlin, "Climate Change Impacts on Forests," p. 104.

[55] See citations in Melillo, et al., "Terrestrial Biotic Responses," p. 466.

[56] J.M. Melillo, D.W. Kicklighter, A.D. McGuire, B. Moore III, C.J. Vörösmarty, and A.L. Schloss, "The Effect of CO_2 Fertilization on the Storage of Carbon in Terrestrial Ecosystems: A Global Modeling Study," cited in Melillo, et al., "Terrestrial Biotic Responses," p. 466. In another model, carbon storage increases by 490 GtC from 1860 to 2070 for a CO_2 increase to 640 ppmv, but by only 310 GtC if expected climate change is included—a reduction of 180 GtC (of which about 110 GtC occurs after 2000). Sarmiento, et al., "Simulated Response of the Ocean Carbon Cycle," pp. 245–252.

[57] Gregg Marland, Tom Boden, and Bob Andres, *Revised Global CO_2 Emissions from Fossil-fuel Burning, Cement Manufacture, and Gas Flaring: 1751–1995,* NDP-030/R8 (Oak Ridge, TN: Oak Ridge National Laboratory, 9 January 1998), http://cdiac.esd.ornl.gov/ftp/ndp030/global95.ems.

[58] An exajoule (EJ) is 10^{18} joules or a billion gigajoules. It is approximately equal to the amount of energy released in burning 34 million metric tons of coal or 160 million barrels of oil. In 1995, the world consumed about 1 EJ of commercial energy per day; Iowa, Arizona, Austria, Switzerland, and Malaysia each consumed about 1 EJ per year. Carbon emission factors are for lower heating values. See Neboj√a Nakicenovic, "Energy Primer," in Watson, et al., eds., *Impacts, Adaptations and Mitigation of Climate Change,* p. 80; and Heath E. Mash, Robert J. Andres, Gregg Marland, and Tom Boden, "Emissions of Carbon Dioxide from the Combustion of Fossil Fuels," presented at Air and Waste Management Association, 11–13 October 1995.

[59] Subtracting total oil and gas resources (350 GtC) from total carbon emissions allowed by 2100 (660 GtC) gives allowed coal emissions of about 300 GtC, with an uncertainty of roughly ±350 GtC.

[60] "Fossil-fuel burning" or "traditional uses of fossil fuels" refers to energy technologies that release carbon dioxide into the atmosphere, as is the case for virtually all fossil-fuel energy production today. Below, I discuss the possibility of capture and disposal of carbon dioxide from fossil fuels.

[61] "Primary" energy is the chemical energy embodied in the fuel (coal, oil, gas, or biofuels). In this paper, the primary energy content of electricity produced from non-chemical-fuel sources (hydro, nuclear, geothermal, wind, and solar) is equal to the thermal energy that would be required to produce the same amount of electricity in the average thermal power plant. Thus, 1 kilowatt-hour (kWh) of hydropower electricity receives the same weight as 1 kWh of coal-fired electricity. Today, 3 joules of thermal energy are required to produce 1 joule of electrical energy (i.e., the average efficiency is 33 percent). I assume that this will fall to 2.5 J_{th}/J_e (i.e., 40 percent efficiency) by 2025.

"Commercial" energy refers to fuels that are traded on national or international markets: coal, oil, gas, some modern biofuels, and electricity generated by a variety of sources. Traditional or noncommercial fuels, such as fuelwood and dung, today supply 10 to 15 percent of total primary energy consumption. Fossil fuels account for about 75 percent of total (commercial plus noncommercial) consumption.

[62] See, for example, Lee Schipper and Stephen Meyers, with Rich Howarth and Ruth Steiner, *Energy Efficiency and Human Activity: Past Trends, Future Prospects* (Cambridge: Cambridge University Press, 1992).

[63] This relationship is exact only when the growth rates are expressed as continuous rates. When expressed as annual rates, the equation is approximately correct if the rates are less than 5 percent per year.

[64] J. Leggett, W.J. Pepper, and R.J. Stewart, "Emission Scenarios for the IPCC: An Update," in J.T. Houghton, B.A. Callander, and S.K. Varney, eds., *Climate Change 1992* (Cambridge: Cambridge University Press, 1992); Neboj√a Nakicenovic, Arnulf Grübler, and Alan McDonald, eds., *Global Energy Perspectives* (Cambridge: Cambridge University Press, 1998); and Shell International Ltd., *The Evolution of the World's Energy Systems* (London: Shell International, 1996).

[65] Global-average per-capita income rose from $2,140 in 1950 to $5,200 in 1990 (1990 dollars, adjusted for purchasing-power parity), for an average growth rate of 2.2 percent per year over this forty-year period. In contrast, per-capita income grew at an average rate of 1.1 percent per year from 1870 to 1950, and at only 0.6 percent per year from 1820 to 1870. Angus Maddison, *Monitoring the World Economy: 1820 to 1992* (Paris: Organization for Economic Cooperation and Development, 1995), p. 228.

[66] Maddison, *Monitoring the World Economy.*

[67] Alan Manne, Robert Mendelsohn, and Richard Richels, “MERGE: A Model for Evaluating Regional and Global Effects of GHG Reduction Policies,” in N. Nakicenovic, W.D. Nordhaus, R. Richels, and F.L. Toth, eds., *Integrative Assessment of Mitigation, Impacts, and Adaptation to Climate Change* (Vienna: International Institute for Applied Systems Analysis, 1994).

[68] Ruth A. Judson, Richard Schmalensee, and Thomas M. Stoker, *Economic Development and the Structure of the Demand for Commercial Energy* (Cambridge, MA: MIT, Joint Program on the Science and Policy of Global Change, report #33, April 1998); http://web.mit.edu/globalchange/www/rpt33.htm. Income is adjusted from 1985 to 1998 dollars.

[69] These rates are based on estimates of total per-capita energy consumption (commercial plus traditional) and per-capita GDP in constant dollars, adjusted for purchasing-power parity.

[70] In one model, uncertainties in the future price of electricity from carbon-free sources accounts for 50 or more percent of the uncertainty in carbon emissions in the 2020–2050 time frame, and is much more important than uncertainties in the rate improvement in energy intensity or labor productivity. [Mort D. Webster, *Uncertainty in Future Carbon Emissions* (Cambridge, MA: MIT Joint Program on the Science and Policy of Global Change, report #30, November 1997); http://web.mit.edu/globalchange/www/rpt30.htm, p. 18.]

[71] See, for example, Evan Mills, Deborah Wilson, and Thomas Johansson, “Beginning to Reduce Greenhouse Gas Emissions Need Not Be Expensive: Examples from the Energy Sector,” in J. Jäger and H.L. Ferguson, eds., *Climate Change: Science, Impacts, and Policy* (Cambridge: Cambridge University Press, 1991), pp. 311–328; Interlaboratory Working Group, *Scenarios of U.S. Carbon Reductions: Potential Impacts of Energy Technologies by 2010 and Beyond* (Berkeley, CA: Lawrence Berkeley National Laboratory, 1997); J.C. Hourcade, “A Review of Mitigation Cost Studies,” in Bruce, et al., eds., *Economic and Social Dimensions of Climate Change*, pp. 309–312.

[72] A gigajoule (GJ) is approximately equal to the energy released in burning 34 kilograms of coal or 6.4 US gallons of gasoline. In 1995, the average American consumed about 1 GJ of primary commercial energy per day.

[73] This equation can be derived by assuming a linear relationship between the growth rate of per-capita energy consumption and the logarithm of per-capita consumption:

$$r_{gdppc} = \frac{1}{E}\frac{dE}{dt} = \frac{d}{dt}\log E = -\alpha \cdot \log E + \beta$$

where α and β are constants that vary from region to region. Equation 7 is solution to this differential equation, with $\tau = 1/\alpha$ and $E\times = e^{\angle\beta/\alpha.}$

[74] These parameters are not "best fits" in the strict statistical sense, although they come reasonably close to meeting this criteria if conditions of war or economic collapse are omitted. Based on a combination of curve fits and educated guesses, I selected a value of $E_\times$ for each region and then determined the corresponding best-fit value of τ.

[75] Eduard Bos, My T. Vu, Ernest Massiah, Rodolfo A. Bulatao, *World Population Projections* (Baltimore: The Johns Hopkins University Press, 1994).

[76] Robert Repetto and Duncan Austin, *The Costs of Climate Protection: A Guide for the Perplexed* (Washington, DC: World Resources Institute, 1997).

[77] The WEC C scenario, which is designed to reduce fossil-fuel carbon emissions to a level consistent with stabilization at an equivalent doubling (2 GtC/yr in 2100), assumes "a carbon tax that gradually increases to US$400 per tC in 2100." [WEC and IIASA, *Global Energy Perspectives to 2050 and Beyond*, p. 7.] The carbon tax is $145/tC in 2050, in addition to energy taxes amounting to 100 percent in developing countries and 300 percent in developed countries. [Leo Schrattenholzer, IIASA, private communication, 15 July 1998.] Calculations by Edmonds, Dooley, and Kim indicate that a tax of about $100/tC in 2020, escalating to $325–450/tC in 2050 and $750–1200/tC in 2100, would be needed to stabilize CO_2 concentrations at 450 ppmv (depending on the prices of various energy-supply alternatives); stabilization at 550 ppmv would require taxes of $50/tC, $75–110/tC, and $300–650/tC in 2020, 2050, and 2100, respectively. [Jae Edmonds, Jim Dooley, and Sonny Kim, *Long-term Energy Technology: Needs and Opportunities for Stabilizing Atmospheric CO_2 Concentrations* (Washington: American Council for Capital Formation, Center for Policy Research Special Report, October 1998), p. 10; http://www.accf.org/edmondsdooleykim1098.htm.] Thus, stabilization at an equivalent doubling (460 ± 30 ppmv of CO_2) would require a tax of $200–550/tC in 2050.

According to Table 5, global fossil-fuel carbon emissions must be reduced 16 ± 44 percent below the 1990 level by 2050 to stabilize greenhouse-gas concentrations at an equivalent doubling. Top-down models indicate that a tax of $50 to $400/tC would be needed in 2050 to reduce developed-country carbon emissions 0 to 50 percent below the 1990 level, and $20 to 220/tC to reduce emissions of Eastern Europe and the former Soviet Union to the 1990 level. Other studies have estimated marginal costs of reducing long-term emissions in developing countries of $10 to $600/tC. (The required tax is approximately equal to the marginal cost if tax revenue is not recycled; with efficient recycling, the tax would be higher). Studies of global abatement costs estimate annual costs equal to 0.3 to 3.7 percent of 2050 GWP to reduce carbon emissions from 41 below to 18 percent above 1990 levels by 2050, equivalent to a tax of at least $40 to $400/tC (in all but one case, greater than $230/tC). Another study indicated that, with emission trading, the tax required to reduce emissions 2 percent below the 1990 level ranges from $200 to $500/tC. See Hourcade, "A Review of Mitigation Cost Studies," in Bruce, et al., eds., *Economic and Social Dimensions of Climate Change*, pp. 303–339.

[78] Total primary energy demand is 600 EJ/yr in the "WEC C" scenario in 2050, compared to 840 to 1050 EJ/yr in the reference scenarios. Of this, 260 to 290 EJ/yr is supplied by non-fossil sources. If fossil supply was limited to the 310 to 340 EJ/yr level of the WEC C scenario, non-fossil sources would have to supply 500 to 740 EJ/yr in the reference scenarios. WEC and IIASA, *Global Energy Perspectives to 2050 and Beyond*, p. 49.

[79] Richard Baron, *Economic/Fiscal Instruments: Taxation* (Paris: OECD, "Policies and Measures for Common Action" working paper, July 1996), p. 20.

[80] In a 1998 University of Maryland poll, 76, 63, 36, 19, and 11 percent of respondents said that they would be willing to accept increased energy costs of $10, $25, $50, $75, and $100 per household per month, which at current rates of consumption is equal to $8, $21, $42, $63, and $84 per ton of carbon, respectively. In a 1998 Mellman Group poll, 75 and 64 percent said they would be willing to pay an extra $10 and $20 per month, respectively, to have utilities produce electricity from carbon-free sources. In a 1997 Ohio State University poll, 51 percent said they be willing to pay $10 or more per month for energy to reduce pollution. In a 1997 Pew poll, 73 and 60 percent said they would be willing to pay 5 and 25 cents more per gallon of gasoline to significantly reduce global warming (equivalent to $20/tC and $100/tC, respectively), but in a 1997 Mellman poll only 48 percent favored a 10 cent-per-gallon tax ($40/tC) for this purpose. Steven Kull, *Americans on Global Warming: A Study of U.S. Public Attitudes* (College Park, MD: Program on International Policy Attitudes, December 1998); http://www.pipa.org/buenos_aires.htm.

[81] Energy Information Administration, *International Energy Annual 1996* (Washington, DC: U.S. Department of Energy, 1998); available at ftp://ftp.eia.doe.gov/pub/pdf.

A terawatt-hour (TWh) is a billion kilowatt-hours or 10^{12} watt-hours, and is equal to 0.0036 EJ. As discussed above, the primary energy content of electricity from non-thermal sources, such as hydro, is counted as the energy needed to produce the same amount of electricity in a thermal plant. At today's average efficiency (33 percent), 1 TWh = 0.011 EJ_p; at 40 percent efficiency assumed for 2025 and thereafter, 1 TWh = 0.009 EJ_p.

[82] In 1989, 5900 MW_e of installed capacity produced 35 TWh of electricity, for an average capacity factor of 68 percent, and direct uses of geothermal heat totaled 36 TWh. Installed capacity rose to 6800 MWe in 1995; assuming the capacity factor and ratio of heat to electricity remained about the same, total production would be 40 TWh of electricity and 42 TWh of direct-use heat (0.43 and 0.15 EJ_p, respectively). Civis G. Palmerini, "Geothermal Energy," in Jose Roberto Moreira and Alan Douglas Poole, "Hydropower and Its Constraints," in Thomas B. Johansson, Henry Kelly, Amulya K.N. Reddy, and Robert H. Williams, eds., *Renewable Energy: Sources for Fuels and Electricity* (Washington, DC: Island Press, 1993), pp. 583–585; Energy Information Administration, *Renewable Energy Annual 1996* (Washington, DC: U.S. Department of Energy, 1997), p. 127; available at ftp://ftp.eia.doe.gov/pub/pdf/renewables/060396.pdf.

[83] The accessible high-temperature (>150 °C) hydrothermal resource in the United States is estimated at 4000 to 6000 EJ. [Patrick L.J. Muffler, ed., *Assessment of Geothermal Resources of the United States* (Washington, DC: United States Geological Survey, Circular 790, 1979).] Since the United States covers one-fourteenth of the ice-free surface area of the earth but contains a larger share of hydrothermal resources, the global resource probably is roughly 40,000 EJ. If we assume that one-fourth of the accessible resource could be extracted, and that most of the heat would be used to produce electricity at half the average efficiency for thermal power plants, the long-term contribution to world primary energy would be roughly 5,000 EJ. If consumed over a period of fifty to two hundred years, this would be an average of 25 to 100 EJ/yr. The amount that could be extracted economically would be smaller.

[84] Palmerini, "Geothermal Energy," pp. 570–572; Geoff Brown, "Geothermal Energy," in Godfrey Boyle, ed., *Renewable Energy: Power for a Sustainable Future* (Oxford: Oxford University Press, 1996), pp. 378–380.

[85] A fourth source of energy is differences in salinity. The difference in salinity between the Earth's river flow and the oceans is equal to 200 EJ_p/yr. Available technologies to convert this energy into electricity are extremely expensive, however.

[86] James E. Cavanagh, John H. Clarke, and Roger Price, "Ocean Energy Systems," in Johansson, et al., eds., *Renewable Energy*, p. 522.

[87] Les Druckers, "Wave Energy," in Boyle, ed., *Renewable Energy*, p. 316.

[88] The oceans absorb sunlight at a rate of about $2\infty10^6$ EJ/yr. If we assume that roughly ten percent of this is absorbed in areas with temperature differences of 20 °C, that the heat is converted to electricity with an efficiency of 2.5 percent, and that 1 EJ_e = 2.5 EJ_p, then the total resource is roughly 10^4 EJ_p/yr.

[89] Tillman estimated average biomass consumption from 1985 to 1990 at 13 EJ/yr. [D.A. Tillman, *The Combustion of Solid Fuels and Wastes* (New York, NY: Academic Press, 1991), p. 66.] The Food and Agriculture Organization (FAO) of the United Nations estimated 1993 consumption of fuelwood, charcoal, bagasse, and animal and vegetable wastes at 20 EJ_p/yr. [FAO, *FAOSTAT-PC* (Rome: FAO, April 1995).] Hall estimated 1985 consumption at 55 EJ/yr. [David O. Hall, "Biomass Energy," *Energy Policy*, Vol. 19, No.8 (October 1991), p. 711–737.] Assuming that per-capita consumption has remained constant, Tillman's and Hall's estimates would be equivalent to 15 and 65 EJ_p/yr in 1995, respectively.

[90] Assuming current fuelwood supply of 40 EJ/yr, an average net yield of 10 dry ton of wood per hectare per year, and an energy content of 20 gigajoules per dry ton.

[91] EIA, *International Energy Annual 1996*, p. 91; EIA, *Renewable Energy Annual 1996*, pp. 17–36.

[92] EIA, *International Energy Annual 1996*, p. 91; EIA, *Renewable Energy Annual 1996*, pp. 128–131; José Goldemberg, Lourival C. Monaco, and Isaias C. Macedo, "The Brazilian Fuel-Alcohol Program," in Johansson, et al., eds., *Renewable Energy*, p. 844.

[93] British Petroleum, *BP Statistical Review of World Energy 1998*, available at http://www.bp.com/bpstats. Average 1997 prices were $29, $39, and $46 per tonne in the United States, Europe, and Japan, respectively. Price per gigajoule assumes an average energy content of 28 GJ/t.

[94] The average cost of Brazilian ethanol was about $7.9/GJ in the mid-1980s. [Goldemberg, et al., "The Brazilian Fuel-Alcohol Program," p. 848.] In the United States, ethanol can be produced from corn at about $10/GJ. [Charles E. Wyman, Richard L. Bain, Norman D. Hinman, and Don J. Stevens, "Ethanol and Methanol from Cellulosic Biomass," in Johansson, et al., eds., *Renewable Energy*, p. 897.] For comparison, the average 1997 U.S. wholesale price of gasoline was $4.3/GJ ($0.673/gal at 0.156 GJ/gal). [Energy Information Administration, "U.S. Refiner Motor Gasoline Prices by Grade and Sales Type," available at ftp://ftp.eia.doe.gov/pub/petroleum/data/monthly/pmm/tables06.txt.]

[95] Wyman, et al., "Ethanol and Methanol from Cellulosic Biomass," pp. 897–907.

[96] The land area of the earth is 14.92 billion hectares (Gha), of which 5.25 Gha is ice, rock, tundra, desert, or lakes. Of the remaining 9.67 Gha, 1.45 Gha is cropland, 3.36 Gha is permanent pasture, 0.50 Gha is managed forest (0.07 tropical, 0.21 temperature, and 0.22 boreal), and 0.15 Gha is urban.

[97] Assumes average net primary productivities of 120 EJ/Gha for cropland, 90 EJ/Gha for pasture, and 330, 220, and 140 EJ/Gha for managed tropical, temperate, and boreal forests.

[98] Thomas B. Johansson, Henry Kelly, Amulya K.N. Reddy, and Robert H. Williams, "A Renewables-Intensive Global Energy Scenario," in Johansson, et al., eds., *Renewable Energy*, pp. 1077–1094.

[99] David O. Hall, Frank Rosillo-Calle, Robert H. Williams, and Jeremy Woods, "Biomass for Energy: Supply Prospects," in Johansson, et al., eds., *Renewable Energy*, pp. 616–626.

[100] For a given level of productivity, forests and energy crops would have about the same net effect on carbon emissions, while the forests are growing. After forests mature, however, there will be no net sequestration of carbon, while energy plantations can displace fossil-fuel emissions indefinitely. Moreover, the productivity of energy plantations generally will be much greater than forests. Of course, there are other considerations, such as the preservation of natural habitat and biodiversity, which favor the reforestation or regeneration of natural forests.

[101] United Nations, Food and Agriculture Organization, *State of the World's Forests 1997*, available at http://www.fao.org/waicent/faoinfo/forestry/SOFOTOC.htm.

[102] United Nations, Food and Agriculture Organization, *FAOSTAT*, available at http://apps.fao.org/lim500/agri_db.pl.

[103] Per-capita grain utilization has increased with income since 1960, particularly for per-capita GDP less than $10,000/yr. A regression analysis shows that, if per-capita GDP doubles, per-capita grain utilization increases by about 90 kg/yr. If per-capita GDP is expected to grow at a rate of 1 to 2 percent per year, or by a factor of 1.7 to 3.0 from 1995 to 2050. Per-capita grain utilization would therefore be expected to increase by 70 to 140 kg/yr, or by a factor of 1.2 to 1.4. Grain utilization data from U.S. Department of Agriculture, "World Agriculture: Trends and Indicators," available at http://jan.mannlib.cornell.edu/data-sets/international/89024.

[104] See the review in "Food and Agriculture," *World Resources 1996–97*, pp. 228–236;

[105] FAO, *FAOSTAT*.

[106] FAO, *FAOSTAT*.

[107] Margaret Evans, "Agriculture and Environment: A Review, 1972–1992," *Ambio*, Vol. 23, No. 3 (May 1994), p. 194; Henry W. Kendall and David Pimentel, "Constraints on the Expansion of the Global Food Supply," *Ambio*, Vol. 23, No. 3 (May 1994), p. 200.

[108] As another point of reference, Nilsson and Schopfhauser estimate that, of the 2500 Mha suitable for plantations and agroforestry, only about 350 Mha would be available for reforestation for the purpose of sequestering carbon. (Sten Nilsson and Wolfgang Schopfhauser, "The Carbon-Sequestration Potential of a Global Afforestation Program," *Climatic Change*, Vol. 30 (1995), pp. 267–293.) Since energy crops would yield economic returns, the amount available for this purpose should be substantially greater. (Note that the 2500 Mha suitable for reforestation and the 2500 Mha judged as potentially arable overlap but are not identical, since the latter includes over 1000 Mha of natural forest.)

[109] The use of average growth rates here is a mathematical convenience, and does not imply that that consumption or yields grow exponentially with time. In fact, both probably will follow a more S-shaped growth curve, as population growth declines and per-capita consumption saturates, and as natural limits to yield growth come into play.

[110] Energy Information Administration, *Nuclear Power Generation and Fuel Cycle Report, 1997* (Washington, DC: U.S. Department of Energy, September 1997); available at http://www.eia.doe.gov/cneaf/nuclear/n_pwr_fc/npgfcr97.pdf.

[111] The OECD projects total capacity to grow from 353 GW_e in 1996 to 400–500 GW_e by 2015, for an average growth rate of 0.6 to 1.9 percent per year. [NEA and IAEA, *Uranium 1997*, p. 60.] EIA projections range from 170 to 420 GW_e in 2020, compared to 351 GW_e in 1996. In the EIA reference case, nuclear generates 2020 of 23,150 TWh in 2020 (8.7 percent). In the low economic growth scenario, nuclear generates 1750 of 18,360 TWh (9.5 percent); in the high economic growth scenario, nuclear generates 2360 of 27,190 TWh (8.7 percent). [Energy Information Administration, *International Energy Outlook 1998* (Washington, DC: Department of Energy), p. 89.]

[112] For a review of the situation in the United States, see Mark Gielecki and James G. Hewlett, "Commercial Nuclear Electric Power in the United States: Problems and Prospects," *Monthly Energy Review* (Washington, DC: Energy Information Administration, August 1994).

[113] David Bodansky, *Nuclear Energy: Principles, Practices, and Prospects* (Woodbury, NY: American Institute of Physics Press, 1996), p. 302–317; Energy Information Administration, *Electric Plant Cost and Power Production Expenses, 1988* (Washington, DC: U.S. Department of Energy, August 1990); Energy Information Administration, Analysis of Nuclear Plant Operating Costs: A 1995 Update (Washington, DC: U.S. Department of Energy, April 1995); available at ftp://ftp.eia.doe.gov/pub/pdf/coal.nuclear/oiaf9501.pdf.

[114] EIA, *Electric Plant Cost and Power Production Expenses*.

[115] See studies cited in Bodansky, *Nuclear Energy*, pp. 312–317.

[116] According to the OECD, about 16 MtU is recoverable at costs less than $260/kgU, including 12 MtU of "speculative resources." [Organisation for Economic Cooperation and Development, *Uranium 1997: Resources, Production and Demand* (Paris: OECD, 1998).] Exploration for uranium has virtually ceased in the last twenty years, however, due to low uranium prices. If the price of uranium rose, exploration would be stimulated and the estimated resource would grow. Indeed, Holdren estimates that 50 to 125 MtU are recoverable at costs of less than $130/kgU. [J.P. Holdren and R.K. Pachauri, "Energy," in International Council of Scientific Unions, *An Agenda of Science for Environment and Development into the 21st Century* (Cambridge: Cambridge University Press, 1992), p. 106.] For comparison, $260/kgU is about ten times the current price of uranium, and roughly equal to the historical high price. Even at this relatively high price, uranium ore would contribute only about $0.006/kWh to the cost of nuclear-generated electricity.

[117] Light-water reactors use low-enriched uranium fuel and ordinary water as a coolant and moderator. There are two variants of the LWR: boiling-water reactors (BWRs), in which the coolant/moderator boils, and pressurized-water reactors (PWRs), in which it does not. Of the 351 GW_e of operable net capacity as of 1 January 1997, 303 GW_e (86.3 percent) were LWRs, 18.6 GW_e (5.3 percent) were pressurized heavy-water reactors (PHWRs), 15.2 GW_e (4.3 percent) were light-water cooled, graphite-moderated reactors (LGRs), 11.9 GWe were gas-cooled graphite-moderated reactors (GCRs), and 3.1 GWe were fast breeder reactors (FBRs). [EIA, *Nuclear Power Generation and Fuel Cycle Report, 1997*, Appendix D.] LWR uranium requirements currently range from 170 tU/GW_ey in Sweden to 230 tU/GW_ey in Japan. [Nuclear Energy Agency and International Atomic Energy Agency, *Uranium 1997:*

Resources, Production, and Demand (Paris, Organisation for Economic Co-operation and Development, 1998), p. 391.]

[118] Assuming an average of 200 tU/GW_ey and 2.5 EJ_p/EJ_e. As shown in Table 7, oil and gas resources are estimated at 15,000 to 43,000 EJ_p.

[119] In scenarios developed by the IAEA and the WEC, nuclear contributes up to 1900 GW_e or 150 EJ_p/yr of primary energy by 2050, and 6000 GW_e or 450 EJ_p/yr by 2100. See International Atomic Energy Agency, *Nuclear Power: An Overview in the Context of Alleviating Greenhouse Gas Emissions*, IAEA-TECDOC-793 (Vienna: IAEA, 1995); WEC and IIASA, *Global Energy Perspectives to 2050 and Beyond*. In recent scenarios published by the Nuclear Energy Agency, nuclear capacity rises to 1120 GW_e in 2050. Nuclear Energy Agency, "Nuclear Power and Climate Change," available at http://www.nea.fr/html/ndd/climate/climate.pdf.

[120] For example, in the high-growth scenarios of the IAEA and WEC cited above, installed capacity grows to 1500 to 1900 GWe in 2050, at which point cumulative uranium consumption would be 6 to 9 MtU. Including the lifetime fuel requirements of all reactors then in existence would raise this to 11 to 16 MtU. [Author's estimate.] In the NEA scenario cited above, cumulative uranium requirements would be 5.6 MtU in 2050.

[121] Modest improvements in the efficiency of uranium use can be achieved with a once-through cycle. LWR uranium requirements can be reduced to 150 tU/GW_ey by decreasing the tails assay to 0.1 percent (the economic optimum for a uranium price of $260/kg and an enrichment price of $70/SWU) and increasing the fuel burn-up to 53 GW_td/tU (assuming a U-235 enrichment of 4.4 percent and a thermal efficiency of 33 percent). Pressurized heavy-water reactors fueled with natural uranium use about 160 tU/GW_ey (assuming a burn-up of 7.5 GW_td/tU and a thermal efficiency of 30 percent). The use of thorium as a fertile fuel would further decrease the uranium requirements of either reactor on a once-through fuel cycle, to perhaps 130 tU/GW_ey.

[122] Matthew Bunn, Steve Fetter, and John P. Holdren, "The Economics of Plutonium Recycle" (to be published).

[123] M.J. Driscoll, "Recent Work at MIT on Uranium Recovery from Seawater," (unpublished paper, 1983), quotes costs of $260–390/kgU, which is equivalent to $400–600/kgU in 1998 dollars. Studies conducted in Japan in the late 1980s indicated near-term costs (in today's dollars) of over $800/kgU, with longer-term costs as low as $300/kgU. ["Recovery of Uranium from Seawater to End with Production of 15 kg U_3O_8," *Atoms in Japan* (March 1989), pp. 12–13; K.F. Hansen, et al., *Nuclear Power in Japan* (Baltimore: Japanese Technology Evaluation Center, October 1990), p. 22; Masayoshi Kanno, President, Nagaoka University of Technology (personal communication, 15 August 1991).]

[124] Toru Hiraoka ["Nuclear Electricity Generation by Seawater Uranium," *Journal of the Atomic Energy Society of Japan*, Vol. 36, No. 7 (1994), pp. 644–645] assumes a cost of ¥21,000/kgU, equal to about $200/kgU in 1998 dollars. Tadao Seguchi, director of material development at the Japan Atomic Energy Research Institute, estimate that uranium could be recovered from seawater at a cost of about $100/kgU (personal communication, 23 May 1998). Jacques Foos, director of the Laboratory of Nuclear Sciences, National Academy of Arts and Trade (Paris), estimates extraction costs at $80 to $260/kgU (personal communication, 11 March 1997).

[125] Bodansky, *Nuclear Energy*, p. 224–227.

[126] The collective dose over fifty years to the global population is estimated at about 600,000 person-Sievert (60 million person-rem). [International Atomic Energy Agency, "Long-term Committed Doses from Man-made Sources," http://www.iaea.or.at/worldatom/inforesource/bulletin/bull381/dose.htm.] Most of this dose will be received by individuals far from the reactor, at dose rates well below the natural background, where the health effects of radiation are uncertain. The estimate given here assumes that individual risk is proportional to dose, no matter how low the dose, with one additional premature cancer death per 20 person-Sieverts. Uncertainties in the population dose and in the risk factor make this estimate of thirty thousand cancer deaths uncertain by a factor of at three. It is possible that very low doses of radiation have no health effects, in which case the expected number of cancer deaths could be far lower.

[127] A detailed study of five U.S. LWRs gave mean probabilities of core damage ranging from $4\infty 10^{-6}$ to $60\infty 10^{-6}$ per reactor per year for internally initiated accidents. For two of these reactors, the same study gave mean probabilities of core damage ranging from $3\infty 10^{-6}$ to $120\infty 10^{-6}$ for earthquakes and $11\infty 10^{-6}$ to $20\infty 10^{-6}$ for fires. [U.S. Nuclear Regulatory Commission, *Severe Accident Risks: An Assessment for Five Nuclear Power Plants*, NUREG-1150 (Washington, DC: 1990). The upper-limit probabilities for earthquake damage have since been revised downward, so that the total probability of core melt is probably less than 10^{-4} per reactor-year.

[128] Bodansky, *Nuclear Energy*, p. 237.

[129] The high-growth IAEA and WEC scenarios cited above involve 160,000 to 240,000 cumulative reactor-years during the twenty-first century. If the core-damage probability is 10^{-6} per reactor year, the probability of no core-damage accidents during this period would be 80 to 85 percent. The probability of no significant release of radiation during this period would be at least 98 percent.

[130] These include advanced LWRs by Westinghouse, General Electric, and ABB-Combustion Engineering (AP600, SBWR, SIR, and PIUS), General Atomic's modular high-temperature gas-cooled reactor (MHTGR), and the PRISM sodium-cooled fast reactor.

[131] This comparison is based on the "water dilution volume" (WDV), or the volume of pure water that would be required to dilute a hazardous substance to current U.S. national primary drinking water standards. For the toxic metals contained in coal, the WDV is about 4 cubic kilometers per gigawatt-year of electrical output (4 km^3/GW_ey). The WDV of fission waste decreases with time; after 1,000, 10,000, 100,000 and 1,00,000 years it is about 4000, 1000, and 70, and 20 km^3/GW_ey, respectively. Nearly all the metals released during coal burning are discharged into the biosphere. Releases of fission waste into the biosphere, as measured by the fraction of the WDV, should be extremely small at times less than 10,000 years, and less than one percent after 100,000 years. Thus, the toxicity of wastes generated by coal could pose a greater hazard than those generated by fission. Of course, there are many differences in the nature of risk posed by dispersed toxic metals and concentrated radioactive wastes (e.g., exposure pathways, the type of health effects, the existence of a threshold for such effects, etc.); the point is simply that fission is not unique in generating very-long-lived hazardous waste.

The WDV for coal assumes coal consumption of 3.4 Tg/GWy, concentrations of 0.1 part-per-million by weight (ppmw) for cadmium and mercury, 1 ppmw for uranium and selenium, and 10 ppmw for arsenic, copper, chromium, and lead [National Academy of Sciences, *Atmosphere-biosphere Interactions: Toward a Better Understanding of the Ecological Conse-*

quences of Fossil Fuel Combustion (Washington, DC: National Academy Press, 1981)]; national primary drinking water standards of 5 micrograms per liter (mg/L) for cadmium, 2 mg/L for mercury, 30 mg/L for uranium, 50 mg/L for selenium and arsenic, 1300 mg/L for copper, 100 mg/L for chromium, and 15 mg/L for lead [U.S. Environmental Protection Agency, Office of Ground Water and Drinking Water, "Current Drinking Water Standards," available at http://www.epa.gov/OGWDW/wot/appa.htm]. The WDV for fission assumes a national primary drinking water standard of 15 picocuries of gross alpha-particle activity per liter (pCi/L) and a gross alpha-activity of 60, 15, and 1.0, and 0.3 kCi/GW_ey at 10^3, 10^4, 10^5, and 10^6 years after discharge, assuming spent LWR fuel with a burn-up of 33 GW_td/t and a thermal efficiency of 31.8 percent [U.S. Department of Energy, *Characteristics of Potential Repository Wastes* (Oak Ridge, TN: Oak Ridge National Laboratory, 1992)].

[132] Bodansky, *Nuclear Energy*, p. 158.

[133] Bodansky, *Nuclear Energy*, p. 146.

[134] This evidence is based on the behavior of natural deposits of uranium and thorium and natural nuclear reactors. For example, at the natural reactors in Oklo, Gabon, plutonium and most metallic fission products have moved very little over more than a billion years. At Morro do Ferro, Brazil, the migration of thorium and rare earth elements, which are chemically similar to plutonium and many fission products, at has been negligible, as has the migration of uranium and its decay products from the Koongarra ore body in Australia. See, for example, J.L. Knight, "Use of Natural Analogues in Waste Disposal," *Interdisciplinary Science Reviews*, Vol. 23, No. 3 (September 1998), pp. 233–241.

[135] Although this is intuitively appealing, it assumes that future generations would not be able to detect, avoid, or remove radioactive contaminants, or be able to prevent or cure cancers resulting from exposure to them. In other words, such a standard implicitly assumes that 100,000 or 1,000,000 years from now human civilization will be at roughly the same level of technological development as it is today. It seems far more likely that human civilization would be far more technologically advanced (in which case radioactive wastes would pose no risk) or far less advanced (in which case the risk associated with exposure to wastes would tiny compared to the risk of other accidents and disease). There is, moreover, the possibility that human civilization will cease to exist on Earth 100,000 or 1,000,000 years hence.

Although the standard is unlikely to be revised upward, it is unclear why should we be concerned about a hypothetical dose of 25 mrem/yr to the most exposed person a million years from now when today we are indifferent to variations in natural background radiation ten times larger. According to Bodansky, "we want strong evidence that the waste repository cannot cause severe harm," not proof that the repository would cause virtually no harm to anyone under any circumstances. It might be more reasonable to demonstrate that the expected dose rate to the surrounding population would be less than 25 mrem/yr at all times, and that the probability that the dose to the most exposed individual would exceed 25 rem would be very low (e.g., less than 10^{-6}).

[136] Charles McCombie, "Nuclear Waste Management Worldwide," *Physics Today*, Vol. 50, No. 6 (July 1997), p. 61; Trevor Sumerling and Paul Smith, "Disposal of Nuclear Fuel Waste," *Interdisciplinary Science Reviews*, Vol. 23, No. 3 (September 1998), pp. 228–230; Jean-Paul Schapira, director of research, Centre National de la Rechereche Scientifique (personal communication, 5 December 1998).

[137] Bodansky, *Nuclear Energy*, p. 164–165.

[138] Charles D. Hollister and Steven Nadis, "Burial of Radioactive Waste under the Seabed," *Scientific American*, Vol. 276 (January 1998), pp. 60–65; Steven Nadis, "The Sub-Seabed Solution," *Atlantic Monthly*, Vol. 278, No. 4 (October 1996), pp. 28–39.

[139] The 1972 London Convention is ambiguous about whether its prohibition on the dumping of wastes in the oceans covers the placement of wastes in the seabed. In Article 1.4 of the 1996 Protocol to the London Convention, however, the definition of dumping includes "seabed storage of wastes." Annex I of the Protocol specifies that materials containing radioactivity levels greater than de minimis concentrations, as defined by the IAEA, "shall not be considered eligible for dumping; provided further that within 25 years of 20 February 1994, and at each 25 year interval thereafter, Contracting Parties shall complete a scientific study relating to all radioactive wastes and other radioactive matter other than high level wastes or matter, taking into account such other factors as Contracting Parties consider appropriate and shall review the prohibition on dumping of such substances in accordance with the procedures set forth in article 22." According to Article 22, a two-thirds majority vote is required to so amend Annex I. See James Waczewski, "Legal, Political, and Scientific Response to Ocean Dumping and Sub-seabed Disposal of Nuclear Waste," *Journal of Transnational Law & Policy*, Vol. 7, No. 1 (1997); http://www.law.fsu.edu/journals/transnational/issues/7-1/wacz.html.

[140] The spent fuel discharged from an LWR is about 95 percent uranium, 1 percent plutonium and other transuranic elements, and 4 percent fission products. Vitrified reprocessing wastes would have a mass of about 10 tonnes and a volume of about 3.4 cubic meters per gigawatt-year of electrical output; the spent fuel from which these wastes are derived would have a mass of 48 t/GWy and a volume of 14 m^3/GWy. Bodansky, *Nuclear Energy*, p. 127–128.

[141] The heat-output ratio of HLW to spent fuel depends on the time elapsed since discharge and the time elapsed between discharge and plutonium separation. At 10 years after discharge, the ratio is 0.9 to 1.0; 100 years after discharge, the ratio is 0.4 to 0.6, if the plutonium is separated 1 to 10 years after discharge. Although the ratio continues to decrease with time, it seems unlikely that wastes would be stored more than 100 years before emplacement in a repository. Because the cost of waste disposal is dominated by the cost of building and licensing the repository, and because the capacity of the repository is limited by total heat loading, the cost of HLW disposal 100 years after discharge would be no less than half that of spent fuel.

[142] The population dose for the once-through LWR fuel cycle, including waste disposal, results in about 0.3 latent cancer fatalities/GW_ey. It is estimated that separation and transmutation would reduce this by 20 percent. National Academy of Sciences, *Nuclear Waste: Technologies for Separations and Transmutation* (Washington, DC: National Academy Press, 1996), p. 3.

[143] Weapon-usable materials contain a high percentage (typically greater than 90 percent) of "fissile" isotopes, or isotopes that can sustain a fast-fission chain reaction. Fissile isotopes include uranium-235 (the only fissile isotope that exists in nature), uranium-233, and several isotopes of plutonium (239, 240, 241). Nearly all commercial reactors use natural or low-enriched uranium, which contain a small percentage of uranium-235 and cannot be used in a bomb. However, any fuel containing large concentrations of uranium-238 will produce weapon-usable plutonium, which can be chemically separated. Uranium-233 is produced from natural thorium, but unless the uranium-233 is diluted with uranium-238 (which would lead to the production of plutonium), the fresh fuel would contain weapon-usable high-

enriched uranium. See "Report to the American Physical Society by the Study Group on Nuclear Fuel Cycles and Waste Management," *Reviews of Modern Physics*, Vol. 50, No. 1, Part II (January 1978), p. S29, S95.

[144] By definition, low-enriched uranium (LEU) has a uranium-235 concentration of less than 20 percent; the LEU used in LWRs has a uranium-235 concentration of about 4 percent. Weapons-usable high-enriched uranium (HEU) has a uranium-235 concentration greater than 80 percent. LEU cannot be used directly in weapons, but it could be used as source material for the production of nuclear weapons. Enrichment is considered a more difficult technology to master than the chemical separation of plutonium from spent fuel, but this could change in the future. The diversion and use of LEU as source material would be attractive, since 70 percent of the separative work required to produce weapon-grade (90 percent uranium-235) HEU would already have been done in producing the LEU (4 percent uranium-235).

[145] National Academy of Sciences, Committee on International Security and Arms Control, *Management and Disposition of Excess Weapons Plutonium* (Washington, DC: National Academy Press, 1994), p. 37; J. Carson Mark, "Explosive Properties of Reactor-grade Plutonium," *Science & Global Security*, Vol. 4, No. 1 (1993), pp. 111–128.

[146] As of 3 December 1998, a total of 185 states were members of NPT; of these, all but the five nuclear-weapon states (China, France, Russia, the United Kingdom, and the United States) have renounced nuclear weapons. Only four countries remain outside the NPT: India, Israel, and Pakistan (which are assumed to possess nuclear weapons), and Cuba. Arms Control and Disarmament Agency, "Signatories and Parties to the Treaty on the Non-Proliferation of Nuclear Weapons," http://www.acda.gov/treaties/npt3.htm.

[147] The length and mass are typical of a PWR fuel assembly; a BWR assembly would be somewhat longer but have about one-third the mass. The dose rate at a distance of 1 meter from a spent PWR fuel assembly (40 GW_td/t) is about 200 Sv/hr 1 year after discharge, 20 Sv/hr after 15 years, and 3 Sv/hr after 100 years. For comparison, 4 Sv is a lethal dose. National Academy of Sciences, Committee on International Security and Arms Control, *Management and Disposition of Excess Weapons Plutonium* (Washington, DC: National Academy Press, 1994), p. 151.

[148] A typical PWR fuel assembly contains about 5 kilograms of reactor-grade plutonium—enough for an efficient nuclear weapon. For comparison, the critical masses of weapons-grade and reactor-grade plutonium with a thick uranium tamper are 4.7 and 6.7 kilograms, respectively. See "Report to the American Physical Society," p. S29.

[149] Marvin M. Miller, "Are IAEA Safeguards on Plutonium Bulk-handling Facilities Effective?" (Washington, DC: Nuclear Control Institute, August 1990), http://www.nci.org/mmsgrds.htm.

[150] The IAEA defines "high confidence" as a 90 percent probability of detecting the diversion of a significant quantity of nuclear material. A "significant quantity" is defined as 8 kilograms of plutonium or 25 kilograms of uranium-235 in the form of HEU, which represents the amount thought to be needed for a state to make its first nuclear explosive, taking into account processing losses. "Timely warning" is based on the estimated time it would take for a state to convert the diverted material into a finished weapon component; for unirradiated plutonium or HEU, the IAEA goal is to detect diversions within one month. [Office of Technology Assessment, *Nuclear Safeguards and the International Atomic Energy Agency*, OTA-ISS-615 (Washington, DC: U.S. Government Printing Office, June 1995), p. 45, 57; http://

www.wws.princeton.edu:80/~ota/disk1/1995/9530_n.html.] These goals have been criticized as being too lax, because an efficient nuclear weapon can be manufactured with much less than 8 kilograms of plutonium, because diverted plutonium oxide can be converted into a plutonium weapon component in as little as one week, and because diversion should be detected soon enough to prevent the plutonium from being incorporated into a weapon. A more sensible goal would be to detect with high confidence diversions of 2 kilograms of plutonium in less than one week, but it does not appear that such a goal can be met at a large reprocessing plant. See Miller, "Are IAEA Safeguards Effective?"

[151] See Per Peterson, *Science and Global Security*, Vol. X, No. Y.

[152] Schemes that have been suggested include mixing or precipitating plutonium with intense gamma-ray- or neutron-emitting radionuclides. The IAEA considers materials emitting more than 100 rads per hour at a distance of one meter to be sufficiently self-protecting so as to require a lower level of safeguarding. The comparable dose rate from typical spent fuel assembly is 20,000 rads/hr after one year, of which about 2500 rads/hr is from cesium-137. Thus, plutonium fuels might be considered self-protecting if they contained cesium-137 at concentrations 25 times lower than spent fuel. This would be a significant barrier for subnational groups, but not for most nations that host nuclear industries. Increasing the radioactivity of fresh fuel would, moreover, could add significantly to the costs and hazards of fabricating and handling reactor fuel.

[153] See Alex Galperin, Paul Reichert, and Alvin Radkowsky, "Thorium Fuel for Light Water Reactors—Reducing the Proliferation Potential of Nuclear Power Fuel Cycle," *Science and Global Security*, Vol. 6, No. 3 (1997), pp. 265–290, and Paul R. Kasten, "Review of the Radkowsky Thorium Reactor Concept," *Science and Global Security*, Vol. 7, No. 3 (1998), pp. 237–269.

[154] One must bear in mind, however, that near the equator sunshine is fairly constant throughout the year, while closer to the poles most of the energy is delivered during summer. Eldon C. Boes and Antonio Luque, "Photovoltaic Concentrator Technology," in Johansson, et al., eds., *Renewable Energy*, p. 374, and Bob Everett, "Solar Thermal Energy," in Boyle, ed., *Renewable Energy*, pp. 46–47.

[155] For large tracts of standardized designs, the cost of energy saved is estimated to be roughly \$5/GJ, which is comparable to the current retail price of natural gas in the United States. Michael Brower, *Cool Energy: Renewable Solutions to Environmental Problems* (Cambridge, MA: MIT Press, 1992), p. 45.

[156] If the fraction of new homes incorporating passive solar features increased from 1 percent today to 50 percent in 2050, such homes would represent less than 10 percent of the total U.S. housing stock in 2050. If the energy demand of passive solar houses was half that of their conventional counterparts, total energy demand (of which residential demand is now about 20 percent) would be reduced by roughly 1 percent.

[157] The sunniest areas of the United States receive about 8 GJ/m^2yr of solar energy. This energy can be captured and delivered as hot water by flat-panel collectors with an average efficiency of about 50 percent. If the installed cost is amortized over 30 years at a discount rate of 10 percent per year, solar heat at \$5/GJ would imply an installed cost of $(\$5/GJ)(8\ GJ/m^2yr)(0.5)(yr/0.1) = \$200/m^2$.

[158] The average cost of medium-temperature collectors was \$156 per square meter in 1996. [Energy Information Administration, *Renewable Energy Annual 1997, Vol. I* (Washington,

DC: U.S. Department of Energy, 1998), p. 23.] Based on a small sample of companies advertising on the World Wide Web, the retail price for complete but uninstalled medium-temperate systems is \$500 to \$1000 per square meter in the United States. Installed costs are \$900 to \$2700 per square meter in the United Kingdom and \$400 to \$1000 per square meter in Greece. [Bob Everett, "Solar Thermal Energy," in Boyle, ed., *Renewable Energy*, p. 83, converted from 1990 U.K. pounds into 1998 U.S. dollars.] Boyle reports installed costs of only \$200 to \$500 per square meter in Israel. Although Boyle attributes the lower costs in Greece and Israel to economies of scale, they are more likely due to factors that are less generalizable, such as lower labor costs, temperatures rarely below freezing, flat-roofed residences, and the use of simple but visually intrusive systems involving a large roof-mounted tank.

[159] The sunniest areas in the United States receive 8 GJ/m^2yr of direct sunlight on a surface that tracks the sun. Parabolic-trough collectors, which focus the sunlight on a centrally mounted pipe and are capable of delivering temperatures up to 400 °C, can capture this energy with perhaps 80 percent efficiency. The current price of natural gas to industrial users in the United States is about \$3/GJ. If the installed cost is amortized over 10 years at a discount rate of 15 percent per year, solar heat at \$3/GJ would imply an installed cost of (\$3/GJ)(8 GJ/m^2yr)(0.8)(yr/0.2) = \$100/m^2 for such collectors. For comparison, the current uninstalled price of high-temperature collectors in the United States is about \$200/m^2 [EIA, *Renewable Energy Annual 1997 Vol. I*, p. 23.]

[160] Industrial heat and residential and commercial space and water heating are responsible for about 40 percent of total energy consumption in the United States and the United Kingdom. Solar probably could provide one-quarter to one-half of this heat without additional thermal storage.

[161] Pascal de Laquil III, David Kearney, Michael Geyer, and Richard Diver, "Solar-thermal Electric Technology," in Johansson, et al., eds., *Renewable Energy*, p. 280. Estimated capital costs for large, advanced plants are in the range of \$2000 to \$3000/kWe. Assuming an average capacity factor of 25 to 35 percent, a fixed charge rate of 10 percent per year (including taxes and insurance), and operation and maintenance charges of 1 to 2 cents per kilowatt-hour, solar-thermal electricity would cost 8 to 16 cents per kilowatt-hour.

[162] At today's high prices for high-efficiency photovoltaic cells, concentrator systems may have an advantage over flat-plate systems. If cell prices fall to \$50 to \$100 per square meter, however, it is unlikely that concentrating systems would be less expensive than flat-plate systems.

[163] Godfrey Boyle, "Solar Photovoltaics," in Boyle, ed., *Renewable Energy*, p. 128; Henry Kelly, "Introduction to Photovoltaic Technology," in Johansson, et al., eds., *Renewable Energy*, p. 300.

[164] Assuming a total system cost of \$1 per peak watt of net AC output, a fixed charge rate of 10 percent per year (including taxes, insurance, and maintenance) and 2500 kWh/m^2yr of solar energy, the cost of electricity would be (\$1/W_p)∞(0.1/yr)∞(1000 W/m^2)∞(m^2yr/2500 kWh) = 0.04/kWh. In location receiving only 1000 kWh/m^2yr, the cost of electricity would be \$0.1/kWh.

[165] Today, photovoltaic modules have average efficiencies ranging from 5 percent for amorphous silicon to 15 percent for monocrystalline silicon. In the future, average efficiencies should reach 10 to 20 percent. Assuming, optimistically, that balance-of-plant costs would be reduced in proportion to module costs, an installed cost of \$1/W_p would correspond to a

module cost of about $\$0.5/W_p$. If the average efficiency of the modules is 20 percent, the cost per square meter would be $(\$0.5/W_p)\infty(0.2\ W_p/W_s)\infty(1000\ Ws/m^2) = \$100/m^2$; if the average efficiency is only 10 percent, the module cost would be $\$50/m^2$.

[166] Kelly, "Introduction to Photovoltaic Technology," pp. 304–311.

[167] "Shingles and Siding," *Consumer Reports*, Vol. 62, No. 8 (August 1997), pp. 27–33.

[168] The cost of electricity storage has two main components: the cost of building and operating the storage facility, and the cost of electricity lost in the storage process. The latter cost is equal to $c(\varepsilon^{-1} - 1)$, where c is the cost of the electricity being stored ($/kWh) and ε is the efficiency (electricity in divided by electricity out). Efficiencies for pumped hydro, compressed air, and batteries are typically 80 percent or less, so the cost of lost electricity per delivered kilowatt is roughly c/4. The former cost is approximately equal to $Cf/(n^{\circ}365)$, where C is the capital cost of the facility ($/kW), f is the fixed charge rate (including taxes, insurance, operations, and maintenance), and n is the average number of hours of storage per day; if we assume that $f \cup 0.1$ and $n \cup 10$, the cost per kilowatt-hour is C/35,000. Capital costs for these technologies ranges from $500 to $2000 per kilowatt, which contributes $0.015 to $0.06 per kilowatt-hour to the cost of stored electricity. Thus, if PV electricity costs $0.04 per kilowatt-hour to produce, stored PV electricity would cost $0.065 to $0.11 per kilowatt-hour (an increase of 60 to 175 percent). If PV electricity costs $0.1 per kilowatt-hour, stored electricity would cost $0.14 to $0.185 per kilowatt-hour (an increase of 40 to 85 percent).

[169] See, for example, Joan M. Ogden and Joachim Nitsch, "Solar Hydrogen," in Johansson, et al., eds., *Renewable Energy*, pp. 925–1009. In the case of fossil fuels, the carbon dioxide would be sequestered.

[170] The sunniest areas on earth receive about 2500 kilowatt-hours of solar energy per square meter per year on a south-facing, inclined surface, or an average rate of about 280 watts per square meter. Above the earth's atmosphere, the rate is 1365 watts per square meter.

[171] Photovoltaic cells weighing only 5 grams per peak watt (0.12 millimeters thick) have been produced for use on a solar-power aircraft. [R. Piellisch, "Solar Powered Flight," *Sunworld*, March–April 1991, pp. 17–20.] Launch costs currently range from $20 to $100 per gram for geosynchronous orbit. [Data for launch vehicles given at http://www.ksc.nasa.gov/facts/faq13.txt, adjusted for inflation.] Thus, launch costs would amount to $100 to $500 per peak watt, or about $75 to $370 per average watt in orbit. Assuming that launch costs are amortized over 30 years at a discount rate of 10 percent per year, launch costs would add $0.8 to $4 per kilowatt-hour to the price of electricity.

[172] Let x be the cost of cells per peak watt and y be the cost of placing cells in geosynchronous orbit per peak watt. If we ignore the costs and losses involved in converting, transmitting, receiving, and storing the energy, space-based power would be cost-effective only if $1.365x \approx 0.3(x + y)$, where 0.3 and 1.365 are the number of average watts per peak watt at a very sunny ground-based site and in space, respectively. Thus, $y \leq 3.8x$. Assuming $x = \$1$ per peak watt, $y \leq \$4$ per peak watt, or roughly $1 per gram—20 to 100 times less than current launch costs.

[173] Paul Gipe, "1996 Overview of Wind Generation Worldwide," 26 August 1996; available at http://rotor.fb12.tu-berlin.de/overview96.html.

[174] An average wind power density of 250 W/m^2 or greater at a height of 10 meters is equal to a U.S. wind class of five or greater. Because wind velocity generally increases with height, this corresponds to a power density of 500 W/m^2 or greater at a height of 50 meters.

Nearly all existing wind-power development as occurred at sites with class 5 or greater winds. In the United States, which has the largest and most mature installed wind capacity, average generation costs are 5 to 7 cents per kilowatt-hour. [Energy Information Administration, *Renewable Energy Annual 1996* (Washington, DC: U.S. Department of Energy, 1997), pp. 42–47.] In Germany, Denmark, and the Netherlands, where growth in installed capacity has been greatest in recent years, utilities are required to buy wind-generated electricity for 9 to 10 cents per kilowatt-hour; generation costs probably are less than 8 cents per kilowatt-hour. [Gipe, "Overview of Wind Generation," p. 5.]

[175] Of course, cheap energy storage or intercontinental electricity transmission could make possible the production of a larger fraction of total energy supply, but the limit suggested here already assumes substantial progress in this direction.

[176] According to Table 9, total world energy consumption from 1995 to 2100 will be about 100,000 EJ, with a range from 65,000 to 140,000. For comparison, recoverable oil, gas, and coal resources total 120,000 EJ, with a range from 70,000 to 290,000. Price effects should ensure that the low consumption scenario corresponds to the low resource scenario, and the high consumption scenario with the high resource scenario.

[177] The total amount of carbon that could be sequestered through reforestation programs is likely to be considerably less than the amount of carbon released through deforestation (about 150 GtC to date), given that much of the deforested land is (and will remain) cultivated. Enhanced storage of biomass in existing forests due to carbon-dioxide fertilization was included in the carbon cycle models used to estimate the emissions pathways that would result in stabilization at an equivalent doubling of carbon-dioxide concentrations.

[178] Various studies cited in Howard J. Herzog, "The Economics of CO_2 Capture," presented at the Fourth International Conference on Greenhouse Gas Control Technologies, Interlaken, Switzerland (September 1998), http://web.mit.edu/energylab/www/hjherzog/economics.PDF; International Energy Agency, *Carbon Dioxide Capture from Power Stations* (Stoke Orchard, UK: IEA Greenhouse Gas R&D Programme, 1994), http://www.ieagreen.org.uk/sr2p.htm; Howard Herzog, Elisabeth Drake, and Eric Adams, *CO_2 Capture, Reuse, and Storage Technologies for Mitigating Global Climate Change* (Cambridge, MA: Massachusetts Institute of Technology, January 1997); http://web.mit.edu/energylab/www/hjherzog/White_Paper.pdf.

[179] In theory fossil fuels could also be converted into hydrogen and pure carbon, but much of the energy content of the original fuel would remain in the carbon, rendering such processes far more expensive.

[180] The cost of hydrogen produced from natural gas at $3/GJ via large-scale steam reforming is $5.1/GJ, exclusive of transportation. [K. Blok, R.H. Williams, R.E. Katofsky, and C.A. Hendriks, "Hydrogen Production from Natural Gas, Sequestration of Recovered CO_2 in Depleted Gas Wells and Enhanced Natural Gas Recovery," *Energy*, Vol. 22, No. 2/3 (1997), p. 166.] The cost of hydrogen produced from coal at $1.2/GJ is greater than $6/GJ.

[181] For example, the conversion of $3/GJ natural gas containing 14 kgC/GJ to $5.1/GJ hydrogen is equivalent to $150/tC. The conversion of $1.5/GJ coal containing 24 kgC/GJ to $7/GJ hydrogen is equivalent to $230/tC. The conversion of $1.5/GJ coal to $5.5/GJ methanol containing 16 kgC/GJ is equivalent to $500/tC.

[182] Various studies cited in Herzog, "The Economics of CO_2 Capture."

[183] Table 9 gives carbon-free energy requirements for stabilization at an equivalent doubling. If decarbonized coal supplied half of these requirements, cumulative carbon disposal would

equal 130 ± 50 GtC in 2050 and 400 ± 200 GtC in 2100, assuming that 20 kgC was sequestered per gigajoule of primary energy supply.

184 International Energy Agency, *Carbon Dioxide Utilisation* (Stoke Orchard, UK: IEA Greenhouse Gas R&D Programme, 1995); http://www.ieagreen.org.uk/sr4p.htm.

185 P.D. Bergman and E.M. Winter, "Disposal of Carbon Dioxide in Deep Saline Aquifers in the U.S.," US/Japan Joint Technical Workshop, October 1996, State College, PA.

186 International Energy Agency, *Carbon Dioxide Disposal from Power Stations* (Stoke Orchard, UK: IEA Greenhouse Gas R&D Programme, 1995), p. 19; http://www.ieagreen.org.uk/sr3p.htm.

187 Large blocks of dry ice could be dropped into the ocean, but this would be far more expensive.

188 Jennifer A. Caulfield, David I. Auerbach, E. Eric Adams, and Howard J. Herzog, "Near-field Impacts of Reduced pH from Ocean CO_2 Disposal," *Energy Conversion and Management*, Vol. 38 (1997), pp. S343–S348.

189 According to IV of the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (the 1972 London Convention), "the dumping of all other wastes or matter [other than those specified in Annexes I and II] requires a prior general permit. Any permit shall be issued only after careful consideration of all the factors set forth in Annex III, including prior studies of the characteristics of the dumping site, as set forth in Sections B and C of that Annex." Annex III, in turn, mentions as factors "possible effects on marine life," and "the practical availability of alternative land-based methods of…disposal…to render the matter less harmful…"

190 IEA, *Carbon Dioxide Disposal*, p. 20; Herzog, Drake, and Adams, "CO_2 Capture, Reuse, and Storage," p. 25.

191 Skovholt gives costs of $0.015/tC-km for 1.6-meter-diameter onshore pipeline with a capacity of 30 MtC/yr, $0.03/tC-km for a 1-m pipeline with a capacity of 5.5 MtC/yr, and $0.10/tC-km for a 0.4-m pipeline with a capacity of 0.8 MtC/yr. The capacity of offshore pipelines was estimated to be nearly doubled that of onshore pipelines of equal diameter while the cost was about the same, nearly halving the cost per ton of carbon by kilometer. [Otto Skovholt, "CO_2 Transportation System," *Energy Conversion and Management*, Vol. 34, No. 9–11 (1993), pp. 1095–1103.] Summerfield et al. estimate a transport cost of $0.08/tC-km for a 0.55-m onshore pipeline and $0.01/tC for a 0.4-m offshore pipeline with a capacity of 1.1 MtC/yr. The cost drops to about $0.04/tC-km for a 0.9-m offshore pipeline with a capacity of 6.5 MtC, which Summerfield et al. consider the practical limit in deep water; transport costs should be lower for larger diameter onshore pipelines. [I.R. Summerfield, S.H. Goldthorpe, N. Williams, and A. Sheikh, "Costs of CO_2 Disposal Options," *Energy Conversion and Management*, Vol. 34, No. 9–11 (1993), p. 1105–1112.] Hendriks calculates similar costs. [C.A. Hendriks, *Carbon Dioxide Removal from Coal-fired Power Plants* (Dordrecht, Netherlands: Kluwer Academic Press, 1994).]

192 Dan Golumb, "Transport Systems for Ocean Disposal of CO_2 and Their Environmental Effects," *Energy Conversion and Management*, Vol. XX, No. YY (1997); Yuichi Fujioka, Masahiko Ozaki, Kazuhisa Takeuchi, Yuji Shindo, and Howard J. Herzog, "Cost Comparison in Various CO_2 Ocean Disposal Options" (unpublished manuscript, 1997).

[193] Jae Edmonds, Jim Dooley, and Sonny Kim, *Long-term Energy Technology: Needs and Opportunities for Stabilizing Atmospheric CO_2 Concentrations* (Washington, DC: American Council for Capital Formation, Center for Policy Research, October 1998).

[194] John P. Holdren, "Federal Energy Research and Development for the Challenges of the 21st Century," in Lewis M. Branscomb and James H. Keller, eds., *Investing in Innovation: Creating a Research and Innovation Policy That Works* (Cambridge, MA: MIT Press, 1998).

[195] This includes fission and renewables only. As argued above, fusion is highly unlikely to supply a significant fraction of total energy supply in the next fifty years. Up to FY97, only a tiny portion of the fossil budget—less than $10 million—was spent on decarbonization.

[196] Composite refiner acquisition cost of crude oil from Energy Information Administration, *Petroleum Marketing Monthly* (Washington, DC: EIA, January 1998); ftp://ftp.eia.doe.gov/pub/oil gas/petroleum/data publications/petroleum marketing monthly/current/txt/tables01.txt.

[197] President's Committee of Advisors on Science and Technology, Panel on Energy Research and Development, *Report to the President on Federal Energy Research and Development for the Challenges of the Twenty-first Century* (Washington, DC: Office of Science and Technology Policy, November 1997), p. ES-1; http://www.whitehouse.gov/WH/EOP/OSTP/Energy.

[198] Includes renewables, fission, and carbon sequestration and hydrogen manufacture from fossil fuels; excludes fusion and conservation.

[199] "$6bn Package to Cut US Carbon Emissions Comes Under Attack," *Nature*, Vol. 391 (12 February 1998), p. 619.

[200] *Statistical Abstract of the United States 1998*, table 954; http://www.census.gov/prod/3/98pubs/98statab/cc98stab.htm.

[201] *Statistical Abstract of the United States 1998*, table 998.

[202] Nakicenovic, Grübler, and McDonald, eds., *Global Energy Perspectives*, p. 102.

[203] PCAST, *Report to the President*, pp. 5–6. Prior to 1979, the federal government spent about $1.4 billion on light-water-reactor R&D, which is at least $5 billion in 1997 dollars. About $0.8 billion was spent from 1979 and 1997.

[204] Energy Information Administration, *Annual Energy Review 1997* (Washington, DC, July 1998), table 5.1; http://www.eia.doe.gov/emeu/25opec/sld002.htm.

[205] Earl C. Ravenal, "Disengagement from Europe: The Framing of an Argument," in Ted Galen Carpenter, ed., *NATO at 40: Confronting a Changing World* (Lexington, MA: Lexington Books, 1990), p. 235.

[206] David L. Greene, Donald W. Jones, and Paul N. Leiby, "The Outlook for U.S. Oil Dependence," *Energy Policy*, Vol. 26, pp. 55–69.

[207] Assumes a GWP of $200 to 310 trillion in 2100. See Nakicenovic, Grübler, and McDonald, eds., *Global Energy Perspectives*.

[208] Pearce, et al., "The Social Costs of Climate Change," in Bruce, et al., eds., *Economic and Social Dimensions of Climate Change*; and Charles D. Kolstad, "Integrated Assessment Modeling of Climate Change," in William D. Nordhaus, ed., *Economics and Policy Issues in Climate Change* (Washington, DC: Resources for the Future, 1998), p. 267. If we assume that a $12/tC tax would reduce emissions by roughly 10 percent below a baseline of 8 GtC/

yr, the tax would generate $90 billion per year in revenue, a portion of which could be recycled into energy R&D.

[209] Robert N. Schock, William Fulkerson, Merwin L. Brown, Robert L. San Martin, David L. Greene, and Jae Edmonds, "How Much is Energy R&D Worth As Insurance?" in *Annual Reviews of Energy and the Environment*, Vol. 24 (1999); assumes U.S. expenditures are one-quarter of global expenditures.

[210] See William R. Cline, *The Economics of Global Warming* (Washington, DC: Institute for International Economics, 1992), pp. 233–266.

Selected Reports, Working Papers, and Reprints of the Center for International Security and Cooperation, Stanford University

To order, call (650) 725-6488 or fax (650) 723-0089. Selected publications and a complete publications list are also available on the center's website at http://www.stanford.edu/group/CISAC/.

Herbert L. Abrams. *Can the Nation Afford a Senior Citizen As President? The Age Factor in the 1996 Election and Beyond*. 1997 (28 pages).

David Alderson, David Elliott, Gregory Grove, Timothy Halliday, Stephen Lukasik, and Seymour Goodman. *Workshop on Protecting and Assuring Critical National Infrastructure: Next Steps*. 1998.

Andrei Baev, Matthew J. Von Bencke, David Bernstein, Jeffrey Lehrer, and Elaine Naugle. *American Ventures in Russia. Report of a Workshop on March 20-21, 1995, at Stanford University*. 1995.

Michael Barletta, *The Military Nuclear Program in Brazil*. 1997.

David Bernstein. *Software Projects in Russia: A Workshop Report*. 1996.

David Bernstein, editor. *Defense Industry Restructuring in Russia: Case Studies and Analysis*. 1994.

David Bernstein, editor. *Cooperative Business Ventures between U.S. Companies and Russian Defense Enterprises*. 1997.

George Bunn and David Holloway. *Arms Control Without Treaties? Rethinking U.S.-Russian Strategic Negotiations in Light of the Duma-Senate Slowdown in Treaty Approval*. 1998.

Irina Bystrova. *The Formation of the Soviet Military-Industrial Complex*. 1996.

Jor-Shan Choi, *A Regional Compact Approach for the Peaceful Use of Nuclear Energy—Case Study: East Asia*. 1997.

Cross-Industry Working Team (XIWT) and Consortium for Research on Information Security and Policy (CRISP), *Critical Infrastructure: The Path Ahead*. Proceedings of XIWT Symposium on Cross-Industry Activities for Information Infrastructure Robustness, held 3–4 November, 1998. 1999.

David Darchiashvili and Nerses Mkrttchian. *Caucasus Working Papers*. 1997.

John S. Earle and Saul Estrin. *Employee Ownership in Transition*. 1995.

John S. Earle and Ivan Komarov. *Measuring Defense Conversion in Russian Industry*. 1996.

Lynn Eden and Daniel Pollack. *Ethnopolitics and Conflict Resolution*. 1995.

David Elliot, Lawrence Greenberg, and Kevin Soo Hoo. *Strategic Information Warfare—A New Arena for Arms Control?* 1997.

Geoffrey E. Forden. *The Airborne Laser: Shooting Down What's Going Up*. 1997.

James E. Goodby. *Can Strategic Partners Be Nuclear Rivals?* (First in a series of lectures on "The U.S.–Russian Strategic Partnership: Premature or Overdue?") 1997.

James E. Goodby. *Loose Nukes: Security Issues on the U.S.–Russian Agenda* (Second in a series of lectures on "The U.S.–Russian Strategic Partnership: Premature or Overdue?") 1997.

James E. Goodby. *NATO Enlargement and an Undivided Europe* (Third in a series of lectures on "The U.S.–Russian Strategic Partnership: Premature or Overdue?") 1997.

James E. Goodby and Harold Feiveson (with a foreword by George Shultz and William Perry). *Ending the Threat of Nuclear Attack*. 1997.

Seymour Goodman. *The Information Technologies and Defense: A Demand-Pull Assessment*. 1996.

Seymour Goodman, Peter Wolcott, and Patrick Homer. *High-Performance Computing, National Security Applications, and Export Control Policy at the Close of the 20th Century*. 1998.

Lawrence T. Greenberg, Seymour E. Goodman, and Kevin J. Soo Hoo. *Old Law for a New World? The Applicability of International Law to Information Warfare*. 1997.

Yunpeng Hao. *China's Telecommunications: Present and Future*. 1997.

John R. Harvey, Cameron Binkley, Adam Block, and Rick Burke. *A Common-Sense Approach to High-Technology Export Controls*. 1995.

Hua Di. *China's Security Dilemma to the Year 2010*. 1997.

Leonid Kistersky. *New Dimensions of the International Security System after the Cold War.* 1996.

Amos Kovacs. *The Uses and Nonuses of Intelligence*. 1996.

Allan S. Krass. *The Costs, Risks, and Benefits of Arms Control*. 1996.

Gail Lapidus and Renée de Nevers, eds. *Nationalism, Ethnic Identity, and Conflict Management in Russia Today*. 1995.

Kenneth B. Malpass et al. *Workshop on Protecting and Assuring Critical National Infrastructure*. 1997.

Michael May. *Rivalries Between Nuclear Power Projectors: Why the Lines Will Be Drawn Again*. 1996.

Robert L. Rinne. *An Alternative Framework for the Control of Nuclear Materials.* 1999.

Capt. Alexander Skaridov, Cmdr. Daniel Thompson, and Lieut. Cmdr. Yang Zhiqun. *Asian-Pacific Maritime Security: New Possibilities for Naval Cooperation?* 1994.

Roger D. Speed. *The International Control of Nuclear Weapons*. 1994.

Xiangli Sun. *Implications of a Comprehensive Test Ban for China's Security Policy*. 1997.

Terence Taylor. *Escaping the Prison of the Past: Rethinking Arms Control and Non-Proliferation Measures*. 1996.

Terence Taylor and L. Celeste Johnson. *The Biotechnology Industry of the United States. A Census of Facilities.* 1995.

Dean A. Wilkening. *The Evolution of Russia's Strategic Nuclear Forces.* 1998.

Dean A. Wilkening. *How Much Ballistic Missile Defense Is Enough?* 1998.

Dean A. Wilkening. *How Much Ballistic Missile Defense Is Too Much?* 1998.

Dean A. Wilkening. *A Simple Model for Calculating Ballistic Missile Defense Effectiveness*. 1998.

Zou Yunhua. *China and the CTBT Negotiations*. 1998.

Zou Yunhua. *Chinese Perspectives on the South Asian Nuclear Tests.*

MacArthur Consortium Working Papers in Peace and Cooperation

Pamela Ballinger. *Slaughter ujhyyof the Innocents: Understanding Political Killing, Including Limited Terror but Especially Large-Scale Killing and Genocide*. 1998.

Pamela Ballinger. *Claim-Making and Large-Scale Historical Processes in the Late Twentieth Century*. 1997.

Tarak Barkawi. *Democracy, Foreign Forces, and War: The United States and the Cold War in the Third World*. 1996.

Byron Bland. *Marching and Rising: The Rituals of Small Differences and Great Violence in Northern Ireland.* 1996.

David Dessler. *Talking across Disciplines in the Study of Peace and Security: Epistemology and Pragmatics As Sources of Division in the Social Sciences.* 1996.

Lynn Eden and Daniel Pollak. *Ethnopolitics and Conflict Resolution.* 1995.

Daniel T. Froats, *The Emergence and Selective Enforcement of International Minority-Rights Protections in Europe after the Cold War.* 1996.

Robert Hamerton-Kelly. *An Ethical Approach to the Question of Ethnic Minorities in Central Europe: The Hungarian Case.* 1997.

Bruce A. Magnusson. *Domestic Insecurity in New Democratic Regimes: Sources, Locations, and Institutional Solutions in Benin.* 1996.