Climate Change and the Future of Nuclear Energy

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Introduction

In December, world attention turned to Kyoto, Japan, where parties to the Framework Convention on Climate Change negotiated a protocol to reduce the greenhouse-gas emissions of the industrialized countries by five percent over the next ten to fifteen years. The agreement was attacked from both sides, with environmental groups claiming that deeper reductions are urgently needed, and opponents claiming that reductions are unnecessary and would curtail economic growth.

The current focus on near-term reductions is misguided. Deep reductions in the emissions of the industrialized countries over the next ten or twenty years would be costly, but would not go very far toward achieving the ultimate objective of the Climate Convention. The modest reductions called for by the Kyoto agreement are a prudent first step, but only if they are part of a larger, long-term strategy. The centerpiece of any strategy to achieve the objective of Climate Convention is a transformation in world energy supply, beginning no later than 10 or 20 years from now, in which traditional fossil fuels are replaced by energy sources that do not emit carbon dioxide.

Of the energy sources that are technically feasible today, only fission, solar, and decarbonized fossil fuels, and, to a lesser extent, biomass and wind, are capable of supplying a substantial fraction of future world energy demand without significant carbon dioxide emissions. All of these sources now have serious economic or environmental shortcomings. Nuclear fission, which is the only one that is deployed commercially on a large scale today, suffers from concerns about high cost, accident and waste disposal risks, and potential links to the spread of nuclear weapons. The most urgent need, therefore, is a broad-based program of energy research and development to attempt to ameliorate these concerns, and thereby ensure that inexpensive and acceptable substitutes will be available worldwide when they are needed.

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The Objective of Emission Controls

The objective of the Climate 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.”[2] The level that would prevent “dangerous interference” is undefined, but the Convention states that stabilization “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.”

Most studies of climate change focus on the effects of a doubling of the carbon dioxide concentration from the preindustrial level of about 280 parts per million (ppm). According to the Intergovernmental Panel on Climate Change (IPCC), a doubling would, over the long term, increase the global-average surface air temperature by 1.5 to 4.5 °C, with a best estimate of 2.5 °C.[3] The wide range is due largely to uncertainties about how clouds would change as the atmosphere warmed. More important than changes in average global temperature, but even more difficult to predict, are regional changes in seasonal temperature, precipitation, and soil moisture, and in the frequency of extreme events such as storms and drought. In general, average temperature increases in northern continental regions are expected to be twice the global average. Average precipitation is predicted to increase by 5 to 15 percent, but some regions, such as the northern mid-latitudes, are expected to become drier in the summer because of even greater increases in evaporation.[4]

Would these changes constitute “dangerous interference” with the climate system? One way to gain insight is to examine past changes in climate. Figure 1 shows, in a schematic way, how the average temperature of the Earth has varied over the last million years. Also shown are estimates of future changes expected in a “business-as-usual” scenario, in which greenhouse gas concentrations reach an equivalent doubling by 2070 and continue to rise thereafter. Several features of this temperature history deserve special attention.

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

[3] “Technical Summary,” in J.T. Houghton, L.G. Meira Rilho, 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.

[4] 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 J.T. Houghton, et al., eds., ***Climate Change 1995: The Science of Climate Change,*** pp. 291–357; Edward Bryant, ***Climate Process and Change*** (Cambridge: Cambridge University Press, 1997), p. 134.

First, global-average temperature has increased by about 0.5 °C over the last 100 years, consistent with estimates based on the increase in greenhouse gases during this period. The last decade is the warmest period since at least the 14th century, and one of the warmest in the last 10,000 years.

Second, average temperature has been relatively stable for the last 10,000 years, with variations up or down of only about 1 °C. This period of stable climate coincides with the development of agriculture and human civilization. However, even these small variations in global-average temperature were associated with significant changes in regional climate that had important consequences for ecosystems and human societies. For example, 4000 to 6000 years ago, when global-average temperature was about 1 °C higher than at present, the tropics were wetter and experienced catastrophic floods four to ten times greater than those witnessed today, and temperate latitudes were significantly drier.[5] Between 1100 and 1300 AD, when temperatures in Europe were about 1 °C higher than at present, the Vikings colonized Greenland; the subsequent cool period, 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.[6]

Third, over the last two million years the climate has oscillated between long ice ages and shorter interglacial periods, with a period of about 100,000 years. During the last ice age, average temperatures and sea levels were about 5 °C and 120 meters lower than at present; during the last interglacial period, temperatures and sea levels were about 2 °C and 5 meters higher than present. These changes in temperature, which were accompanied by dramatic shifts in the distribution of vegetation, are comparable to that which would accompany a doubling of the carbon dioxide concentration.

Glacial periods are correlated with known variations in the Earth's orbit, which change the amount of summer sunshine received by the poles. These variations in sunshine are too small, by themselves, to account for the observed changes in climate. There must exist strong feedback mechanisms in the climate system—for example, changes in the biosphere or ocean currents—which serve to amplify the warming caused by increased sunshine. The sensitivity of the climate system to past variations in sunshine should make us wary about its sensitivity to changes in the radiation balance caused by increased greenhouse gas concentrations.

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[5] Bryant, ***Climate Process and Change***, p. 90, 192.
[6] Bryant, ***Climate Process and Change***, p. 90-91, 157.

Fourth, past shifts in climate sometimes have been very rapid. For example, there were about two dozen instances during the last ice age when temperatures rose or fell by up to 5 °C over periods of less than a few decades. As the Earth emerged from the last ice age 13,000 years ago, the climate suddenly returned to ice-age conditions; 1300 years later, a warming in the Arctic of about 7 °C occurred over about 50 years, after which the current warm climate has prevailed.[7] These rapid shifts in climate might have been caused by a switching on and off of the North Atlantic thermohaline circulation, which today transports huge quantities of heat northward, keeping Europe much warmer than other regions of the same latitude. These episodes alert us to the possibility that rapid, large-scale changes in climate might be triggered if temperatures increase beyond some threshold. Although the threshold, if one exists, is unknown, it might be no greater than the upper range of the temperature increase predicted for a doubling of carbon dioxide.[8]

Another way to gain insight into how much change would be dangerous is to model the effects of climate change on ecosystems, agriculture, and economies. In general, an increase in carbon-dioxide concentrations, and the associated increase in global average 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 by climate models for a doubling of carbon dioxide concentrations, models indicate that present-day vegetation patterns would remain stable for an average of only 60 percent of the world's surface area. Current vegetation boundaries would shift by 300 to 1,000 kilometers, greatly outstripping the ability of most species to migrate naturally.[9] Rising sea levels will also cause wetlands to be lost at a faster rate than new wetlands would be created.

The capacity of human societies to modify agricultural practices in response to changes in climate is much greater than during previous periods of change, particularly in developed countries. A detailed study concluded that, for climate conditions predicted in 2060 under a "business-as-usual" scenario (an average temperature increase of about 2 °C), total world grain production would decline by

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[7] Bryant, ***Climate Process and Change***, p. 89.

[8] Thomas F. Stocker and Andreas Schmittner, "Influence of CO2 Emission Rates on the Stability of the Thermohaline Circulation," ***Nature***, Vol. 388 (28 August 1997), pp. 862–865.

[9] T.M. Smith, R. Leemans, and H.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, pp. 367–384; and R.A. Monserud, N.M. Tchebakova, and R. Leemans, "Global Vegetation Change Predicted by the Modified Budyko Model," ***Climate Change***, Vol. 25, pp. 59–83, cited in Bryant, ***Climate Process and Change***, p. 193–194.

up to 5 percent, compared to what it would have been without climate change.[10] With a greater degree of adaptation (e.g., changes in crops and additional irrigation), the study concluded that global harvests could be maintained at no-climate-change levels. Climate changes are, however, projected to have a greater negative effect on production in developing countries, which could lead to shortages in countries that cannot afford to buy grain on world markets. In addition, the study did not consider the possible effects of increases in climate variability or rapid changes in climate.

Much attention has been given to the economic costs of climate change and of mitigating greenhouse gas emissions. Most studies include the costs associated with sea-level rise, forest and fishery losses, and changes in agriculture, energy demand, hurricane damage, and water supply, but ignore or underestimate impacts that are difficult to monetize, such as the value of ecosystem and species loss, air and water pollution, and human death, illness, discomfort, and aesthetics. As with studies of ecosystem and agricultural impacts, 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.[11] For some countries, such as low-lying islands, losses could be a much greater percentage of GDP. For comparison, 2 percent of current gross world product (GWP) is over $500 billion per year.

There is, of course, great uncertainty in these estimates. In a poll of 19 experts, best guesses of the cost of a 3° warming by 2090 centered around 2 percent of GWP, but ranged from 0 to 21 percent.[12] Half believed that there is at least a 10 percent chance that the cost would be greater than 6 percent of GWP. The average respondent believed that costs would triple if the average temperature increase were 6 °C instead of 3 °C, and that there would be a 5 percent chance of a 25 percent drop in GWP—the rough equivalent of the Great Depression.

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[10] Cynthia Rosenzweig and MartinL. Parry, "Potential Impact of Climate Change on World Food Supply," ***Nature***, Vol. 367 (13 January 1994), pp. 133–138.

[11] 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 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), pp. 203–205.

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

Selecting a Stabilization Target

One way to develop a strategy is to construct reasonable scenarios and to ask what we should be doing today if these scenarios were to become reality. We do not know very accurately how climate will change in response to increased greenhouse-gas concentrations, or how natural systems and human societies will be affected by changes in climate. But it is worthwhile to set tentative limits on greenhouse gas concentrations based on the current state of knowledge, trace the implications of such limits for the future of world energy supply, and to ask what we should be doing today to prepare for these changes.

Based on what we know today, it would be difficult to justify a stabilization target greater than an equivalent doubling of carbon dioxide, to 560 ppm. Stabilization at this level would result in an increase in average temperature of 1 to 2.5 °C over the next century, and a total increase of 1.5 to 4.5 °C. At the upper end of this range, substantial and costly changes in climate would be certain, and the risk of catastrophic changes would be substantial. Even the “best estimate” change in temperature—2.5 °C total and 1.5°C over the next century—would entail significant risk of costly changes in climate, particularly in the northern regions.

The stabilization target can be expressed as an “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. The relationship between radiative forcing, ΔF, and carbon dioxide concentration, C, is given by

$$\Delta F = 6.3 \log_e(C/C_0) \ \ \mathrm{W/m^2} \tag{1}$$

where C_0, the preindustrial concentration of carbon dioxide, is about 280 ppm. A doubling of carbon dioxide produces a radiative forcing of 4.4 $\mathrm{W/m^2}$.

Over the last 150 years, deforestation and the burning of fossil fuels have increased the concentration of carbon dioxide from about 280 ppm to 363 ppm. The total radiative forcing, including contributions from other long-lived greenhouse gases, is 2.6 $\mathrm{W/m^2}$, which is equivalent to a carbon-dioxide concentration of about 420 ppm.[13] Thus, we already are halfway toward an equivalent doubling of carbon dioxide.

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[13] Assumes 1997 concentrations and radiative forcings of 1.76 ppm and 0.49 $\mathrm{W/m^2}$ for methane, 0.315 ppm and 0.16 $\mathrm{W/m^2}$ for nitrous oxide, and a forcing of 0.28 $\mathrm{W/m^2}$ for various halocarbons. The equivalent carbon dioxide

Limits on Fossil-fuel Emissions

To translate a stabilization target into a limit on global emissions of carbon dioxide from the burning of fossil fuels, we must subtract the long-term radiative forcing of greenhouse gases other than carbon dioxide, use carbon-cycle models to determine rates of emission that lead to stabilization at the desired level, and account for carbon dioxide emissions from other sources, such as land-use changes and cement manufacture.

Other greenhouse gases. Carbon dioxide is the most important greenhouse gas, and it is more amenable to monitoring and control than other gases. We must, however, take into account emissions of methane, nitrous oxide, and halocarbons, which also exert a long-term influence on climate. Increased concentrations of these gases currently are responsible for a radiative forcing of 0.9 W/m^2, equivalent to an additional 60 ppm of carbon dioxide. The long-term contribution of ozone and various aerosols, which today may have a significant influence on climate, can be ignored.[14]

Anthropogenic emissions of methane and nitrous oxide are due primarily to agricultural and waste disposal activities. Strategies exist for reducing methane and nitrous oxide emissions from most identified sources, but the practical potential for reductions is limited. For example, the largest source of methane emissions—domestic livestock—could be reduced by 20 to 40 percent through improvements in feeding and manure management,[15] but such reductions will be more than offset by an increase in the number of animals. Similar arguments can be made for most other anthropogenic sources of methane and nitrous oxide, and it is also possible that natural emissions of these gases may increase as a result of climate change. Thus, even if aggressive efforts are made to limit emissions of methane and nitrous oxide, significant reductions in long-term, global emissions are not likely. If rates

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concentration, C_{eq}, is the CO_2 concentration that would produce a radiative forcing equal to that from all greenhouse gases (in this case, 1.64 + 0.49 + 0.16 + 0.28 = 2.57 W/m^2); $C_{eq} = C_0\, e^{\Delta F/6.3} = (280)e^{(2.57/6.3)} = 421$ ppm.

[14] First, the influence of ozone and aerosols on climate is highly uncertain. Second, because their residence times in atmosphere are on the order of days, any effect on climate will be regional, not global. Third, ozone and aerosols are generated by the burning of fossil fuels. Stabilizing equivalent carbon-dioxide concentrations at 560 ppm or below will require that fossil-fuel burning be reduced by at least a factor of two below current levels over the long term, resulting in proportional decreases in the concentrations of ozone and aerosols. Fourth, 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, particularly as pollution-control technologies advance and diffuse to developing countries.

[15] Vernon Cole, “Agricultural Options for Mitigation of Greenhouse Gas Emissions,” in Robert T. Watson, Marufu C. Zinyowera, and Richard H. Moss, eds., ***Climate Change 1995: Impacts, Adaptations and Mitigation of Climate Change: Scientific-Technical Analyses*** (Cambridge: Cambridge University Press, 1996), p. 764.

of emission remain constant at today's levels, the combined radiative forcing of these two gases would increase from 0.65 W/m^2 to about 1.0 W/m^2.[16]

Halocarbons also contribute to greenhouse warming. Although the Montreal Protocol and its Amendments will lead to a phase-out of substances containing chlorine and bromine, their residence times are so large 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 forcing from halocarbons and other trace gases is about 0.28 W/m^2; long-term values might be somewhat lower or higher.

For stabilization at an equivalent doubling of carbon dioxide, gases other than carbon dioxide are likely to contribute a radiative forcing of about 1.3 W/m^2. Carbon dioxide would then be limited to a forcing of 3.1 W/m^2 and a concentration of about 460 ppm. It is possible, but highly unlikely, that other greenhouse gases could be limited to a long-term forcing of 0.8 W/m^2, in which case carbon dioxide concentration could be as high as 490 ppm under an equivalent doubling.

Carbon emissions. Carbon dioxide emitted into the atmosphere is gradually absorbed by the oceans and by plants. Carbon-cycle models, which simulate these processes, can be used to estimate the rates of emission that would result in stabilization of the carbon dioxide concentration at a given level. Figure 2 shows the rate of emission over the next 150 years for stabilization at 450 to 500 ppm (the dark red and blue lines, respectively). The uncertainty in the emission pathway, which is mostly due to uncertainties about the fertilization of plant growth, is indicated for the 450 ppm case by the narrow red lines. Also shown are emissions for a more gradual approach to 450 ppm and for a more rapid approach to 500 ppm (the light red and blue lines, respectively). Two features of this figure are worthy of attention.

First, carbon-dioxide emissions must peak no later than 2020. This conclusion is insensitive to assumptions about other greenhouse gases, the rate at which stabilization is achieved, or model parameters. After peaking, carbon-dioxide emissions must decline to levels below the current rate of emission (about 7.5 PgC/yr) by 2050, and to no more than half that rate by 2100.

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[16] If rates of emission remain constant at today's levels, concentrations would rise from 1.76 to about 1.90 ppm for methane and from 0.315 to about 0.41 ppm for nitrous oxide. Radiative forcing would increase from 0.49 to 0.53 W/m^2 for methane and from 0.16 to 0.50 W/m^2 for nitrous oxide. Results of MAGICC computer model with methane and nitrous oxide emissions (natural plus anthropogenic) set at 535 and 13.6 Mt/yr. T.M.L. Wigley, S.C.B. Raper, M. Salmon, and M. Hulme, ***MAGICC: Model for the Assessment of Greenhouse-gas Induced Climate Change*** (Norwich, UK: Climate Research Unit, University of East Anglia, April 1997).

Second, the stabilized concentration of carbon dioxide is determined primarily by the rate of emission in the second half of the next century. A slower approach to stabilization would require immediate reductions in emissions, but would permit only slightly higher emissions over the long term. Conversely, a more rapid approach to stabilization would allow 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 larger 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 10 to 20 years, as long as they are reduced below the current level by 2050.

This observation has important policy implications. The stabilization target can, to a first approximation, be translated into a target for total carbon emissions in 2050. Near-term reductions in emissions 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.[17]

Other carbon emissions. Anthropogenic carbon-dioxide emissions are due mostly to fossil-fuel burning, but deforestation and cement manufacture also make significant contributions. During the 1980s, it is estimated that tropical deforestation released an average of 1.6 PgC/yr and that regrowth of temperate forests absorbed 0.5 PgC/yr, for a net rate of emission of 1.1 ± 0.7 PgC/yr.[18]

Future emissions from land-use changes are a matter of speculation. Reference scenarios developed by the IPCC and others assume rates ranging from 0 to 2 PgC/yr in 2050.[19] On the other hand, scenarios that assume strong policy efforts to slow tropical deforestation and implement reforestation programs result in a net uptake of carbon of 0.5 to 2.2 PgC/yr in 2050.[20] All scenarios converge on near-

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[17] 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, near-term reductions and a more gradual approach to stabilization might make sense.

[18] D. Schimel, et al., "Radiative Forcing of Climate," in Houghton, et al., eds., ***Climate Change 1995: The Science of Climate Change,*** pp. 78–79.

[19] J. Alacamo, 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.

[20] Alacamo, 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, Zinyowera, and Moss, eds., ***Climate Change 1995: Impacts, Adaptations and Mitigation of Climate Change***, p. 775.

zero net rates of emission in 2100, because the potential for either deforestation or reforestation has been exhausted.

It is possible that climate change itself might cause large transient releases of carbon during the next century. For example, mature forests may die before they are replaced by new forests, and the amount of carbon stored in northern soils may decrease as higher temperatures promote decay. It is estimated that such processes might result in the release of 0 to 240 PgC over the next century, at rates of up to 3 PgC/yr during the middle of the next century.[21]

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 PgC. By 2050, this could be expected to increase to at least 0.5 PgC/yr.

Fossil-fuel emissions. Emissions of carbon from fossil-fuel burning have risen steadily over the last half century, from about 1.4 PgC in 1945 to 6.2 PgC in 1995—an average growth rate of 3 percent per year.[22] Including other sources of carbon, total anthropogenic emissions were about 7.5 ± 0.9 PgC in 1995.

In order to stabilize greenhouse gas concentrations at an equivalent doubling, fossil-fuel emissions of carbon dioxide must be limited to 6 ± 2 PgC/yr in 2050 and 2.8 ± 1.2 PgC/yr in 2100. These limits take into account the long-term contribution of other greenhouse gases, other sources of carbon dioxide, and uncertainties in these and other parameters.[23]

Limits on carbon emissions can be translated into limits on traditional fossil energy supply by noting that 1 EJ of fossil energy releases 17 to 20 TgC, depend-

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[21] Miko U.F. Kirschbaum and Andreas Fischlin, “Climate Change Impacts on Forests,” in Watson, Zinyowera, and Moss, eds., ***Climate Change 1995: Impacts, Adaptations and Mitigation of Climate Change***, p. 104.

[22] 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.

[23] The best estimates of 6.0 and 2.8 PgC/yr in 2050 and 2100 represent the mean of seven carbon-cycle models for stabilization at 475 ppm early in the 22nd century. The uncertainty in the long-term forcing due to greenhouse gases other than carbon dioxide introduces an uncertainty (90-percent confidence interval) of 1.1 and 0.6 PgC/yr in emissions in 2050 and 2100. Differences between models produce uncertainties of 1.0 and 0.7 PgC/yr; uncertainties in model parameters (fertilization and ocean update) produce uncertainties of 1.0 and 0.6 PgC/yr in the Wigely model. Varying the rate at which stabilization is achieved introduces uncertainties of about 0.3 PgC/yr. For stabilization at an equivalent doubling, I assume that biospheric emissions due to deforestation and climate feedbacks would be offset by absorption due to reforestation, with an uncertainty of ±1 PgC/yr in 2050 and ±0.5 PgC/yr. Emissions from cement manufacture are assumed to be 0.5 PgC/yr in 2050 and 2100. The overall uncertainties of ±2 and ±1.2 PgC/yr assume that the various errors are independent and combine randomly.

ing on the mix of coal, oil, and gas. The limits on fossil-fuel carbon emissions therefore translate into 330 ± 110 EJ/yr in 2050, and 150 ± 70 EJ/yr in 2100.

Future Energy Demand

The demand for energy will grow substantially over the next century, driven by increases in both population and per-capita consumption in developing countries. Figure 3 shows several scenarios of future energy consumption. These scenarios generally assume no policy-driven market interventions, such as carbon taxes, but they do 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 range from 590 to 1260 EJ/yr in 2050, and from 620 to 2800 EJ/yr in 2100.

By subtracting the limits on fossil-fuel supply from the total energy demand, we derive requirements for non-carbon-emitting energy supply.[24] These are given in table 1 for stabilization at an equivalent doubling of carbon dioxide. Note that the supply of energy from sources that do not emit carbon must grow from 53 EJ/yr in 1995 to roughly 600 EJ/yr by 2050—an average growth rate of nearly 5 percent per year.

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. Non-carbon-emitting sources must grow from 14 percent of total commercial supply to 50–80 percent of total supply in 2050.

The transition to non-carbon-emitting 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, took place from 1925 to 1975. In these first two shifts, it took 50 years for the dominate source to go from 10 to 60 percent of total supply. The third major shift, from fossil fuels to non-carbon-emitting sources, will occur from 2000 to 2050—if, that is, we decide to take seriously the task of preventing dangerous interference with the climate system.

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[24] The difference between total demand and fossil supply could be narrowed by reductions in demand caused by market interventions. The effects of carbon taxes are beyond the scope of this paper.

Non-carbon-emitting Energy Sources

In 1995, non-fossil sources supplied about 53 EJ of primary commercial energy: 27 EJ from hydropower, 25 EJ from nuclear fission, and 1.2 EJ from geothermal, wind, biomass, and solar. Another 54 EJ was supplied by noncommercial biomass—fuelwood and dung—but much of the fuelwood was harvested in a unsustainable manner, resulting in deforestation and a net release of carbon dioxide.

For stabilization at an equivalent doubling, non-carbon-emitting sources must supply 600 ± 300 EJ/yr of primary commercial energy by 2050. Only five sources are capable of supplying a substantial fraction this non-carbon supply: solar, fission, decarbonized coal, and, to a lesser extent, biomass and wind. Other potential sources are either too limited (hydropower and hot-water geothermal), too expensive (ocean thermal and wave energy), or too unproven (fusion and hot-rock geothermal) to make a substantial contribution by 2050.

Each of the major alternatives currently has significant economic, technical, and/or environmental handicaps. Solar is environmentally benign, but the cost of photovoltaic electricity is currently more than five times greater than that of coal-fired electricity. Moreover, solar would require massive and inexpensive energy storage if it is to supply more than 10 percent of energy demand. 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 and environmental impact of capturing, transporting, and disposing of the carbon dioxide could be high. Biomass also has the potential to supply low-cost portable fuels, but generating large quantities of biofuels would require vast areas of land, in competition both with agriculture and the preservation of natural ecosystems. Wind is already economically competitive at windy sites close to cities or existing transmission lines, but attractive sites are limited.

The most pressing need, therefore, is research and development aimed at reducing the liabilities of the major alternatives. Last year, the U.S. government spent a little more than $1 billion on energy R&D, compared with the $500 billion spent on energy in the United States ($60 billion of which went for imported oil). Total energy R&D—private as well as public—amounted to less than 1 percent of energy expenditures, compared with an average of 3.5 percent for all U.S. industries.

In the past, it has taken about 20 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 by 2015, 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 mentioned above, including nuclear fission.

The Potential Role of Fission

Fission is the only potential major non-carbon source that is deployed commercially on a significant scale today. In 1995, fission supplied 17 percent of the world's electric power and 6.5 percent of commercial primary energy. Over the next 50 to 100 years, fission could be expanded to provide over half of the world's electric power and a third of the non-carbon-emitting energy supply required to stabilize greenhouse gas concentrations at an equivalent doubling.[25] This is unlikely to happen, however, unless concerns about accidents, waste disposal, and proliferation are resolved.

Most people in the nuclear energy community do not seem to believe that fission's problems are real, in the sense that the problems are regarded as political rather than technical in nature. In their view, current reactor designs are very safe, waste-disposal risks are infinitesimal, proliferation risks are purely theoretical, and costs have been inflated by unjustified licensing delays. They believe that sound technical solutions are already in hand, but worry that the current lack of support for fission might cause expertise to atrophy, particularly in the United States.

Most people in the anti-nuclear community seem to believe that the liabilities of nuclear energy are so great and so intractable that no amount of R&D could solve them. In their view, fission is simply "beyond the pale." They oppose government-sponsored research on fission, believing that it would only divert resources from renewables and prop up an industry that otherwise is headed toward extinction.

The Clinton administration and the Congress seem to agree that fission either does not deserve or does not require government support for research and development. Federal funding for fission-energy R&D has declined from nearly $2

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[25] In scenarios developed by the IAEA and the WEC, nuclear contributes up to 2000 GWe or 150 EJ/yr of primary energy by 2050, and 6000 GWe or 450 EJ/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); World Energy Council and International Institute of Applied Systems Analysis, ***Global Energy Perspectives to 2050 and Beyond*** (London: WEC, 1995).

billion in FY78 to a mere $46 million in FY98, with no funds allocated for new reactor concepts. Industry spending has also declined greatly.

Thus, proponents and opponents of fission and budget-cutting politicians have combined to inhibit innovative thinking about the future of fission. This is regrettable, given the potential contribution that fission could make to reducing carbon emissions and stabilizing concentrations of greenhouse gases.

This may be changing. In a recent report on U.S. energy research and development, the President's Committee of Advisors on Science and Technology argued that "given the desirability of stabilizing and reducing greenhouse gas emissions, it is important to establish fission energy as a widely viable and expandable option if this is at all possible. A properly focused R&D effort to address the problems of nuclear fission power—economics, safety, waste, proliferation—is therefore appropriate."[26] The key recommendation is the creation of a Nuclear Energy Research Initiative, funded initially at $50 million per year and increasing over five years to $100 million per year, to fund R&D on safer and lower-cost reactor designs, new waste-disposal techniques, and proliferation-resistant fuel cycles.

The focus of the proposed program is perfect, but the scale of the effort may be too modest. For comparison, the recommended funding for renewables—mostly biomass, solar, and wind—rises from $410 to 570 million per year over the five-year period.[27] Moreover, the Panel recommended that funding for fusion energy—a source which almost certainly will not make a significant contribution to energy supply before 2050—be increased from $250 to 320 million per year. As another point of comparison, the U.S. government spent about $6 billion, in addition to the billions spent by industry, to help develop the light-water reactor.[28] 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.

What types of fission R&D should be supported? First, R&D is needed on reactor designs that are immune to operator error or equipment failures. Current designs are safe if they are built and operated properly, and advanced versions of

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[26] 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-19.
[27] PCAST, ***Report to the President***, p. ES-33. Also includes geothermal, hydro, and storage for intermittent sources.
[28] PCAST, ***Report to the President***, p. 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.

these designs are even safer. Unfortunately, examples of poor management of nuclear plants are abound.

The goal should be to build reactors that cannot produce off-site fatalities, regardless of what happens inside the plant. The Westinghouse AP 600, which is nearing design certification, might meet that standard. There should be room in an expanded energy R&D program to support industry-government partnerships on additional advanced designs, such as the Simplified BWR, the HTGR, or the Safe Integral Reactor. The concept of small, factory-built modular reactors with lifetime cores in especially interesting.

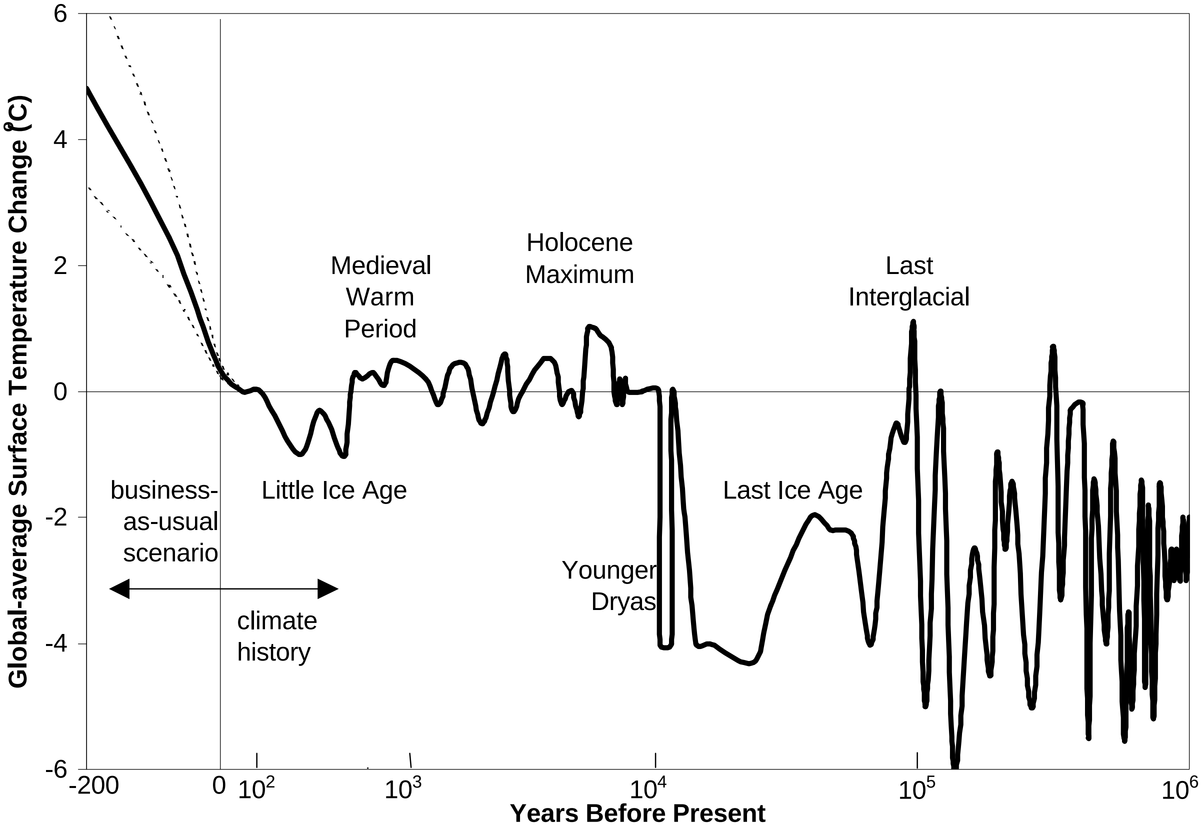
There is no reason to fund research on breeder reactors for at least the next thirty years. Breeder reactors will be economically attractive only if the price of uranium becomes so high that their increased efficiency of uranium use compensates for their higher capital cost. However, low-cost uranium resources are sufficient to support a very large increase in fission energy over the next century. Exploration, which has virtually ceased over the last 20 years because of low uranium prices, would undoubtedly uncover substantial additional resources if prices rose significantly. It may be possible to extract uranium from seawater for less than $250 per kilogram, in which case breeder reactors may never be necessary or economical. In any case, it would be foolish to tie the expansion of fission over the next 50 or so years to breeder reactors or reprocessing.

Second, the federal government should support R&D on alternative fuel-cycle concepts designed to minimize proliferation risks in a world with many more reactors, and with reactors in many more countries. This could include novel reactor concepts, such as lifetime cores; new reprocessing techniques that do not involve the separation of pure plutonium; fuel cycles that minimize the production of high-quality plutonium, such as the thorium fuel cycle; the indefinite use of seawater uranium on a once-through fuel cycle; and institutional solutions, such as the consolidation or international control of facilities that handle plutonium fuels.

Third, the federal government should support R&D on alternative waste disposal concepts. Today, R&D is limited to a single concept—deep geologic disposal—and, in the United States, to a single site—Yucca Mountain. If current waste-disposal concepts experience significant technical or political setbacks, fission is unlikely to expand substantially. Alternatives to Yucca Mountain should be developed—short-term alternatives, such as interim storage, as well as long-term alternatives, including disposal in granite and in the deep sea bed.

Conclusion

Meeting the objective of the Framework Convention on Climate Change—to prevent dangerous interference with the climate system—will require a fundamental transformation in the nature of world energy supply, beginning in the next 10 to 20 years. Over the next 50 years, the supply of energy by sources that do not emit carbon dioxide must increase ten-fold, from 14 percent to over 50 percent of total supply. All of the possible non-carbon-emitting sources have serious drawbacks that must be resolved if they are to play a major role in future energy supply. In the case of fission, we must begin an energetic R&D program to address concerns about accidents, waste-disposal, and proliferation.



<u>Figure 1</u>. Global-average surface temperature change over the last million years, and projected change to 2200 under a "business-as-usual" scenario.

Source: L.A. Frakes, Climates throughout Geologic Time (Amsterdam: Elsevier, 1979).

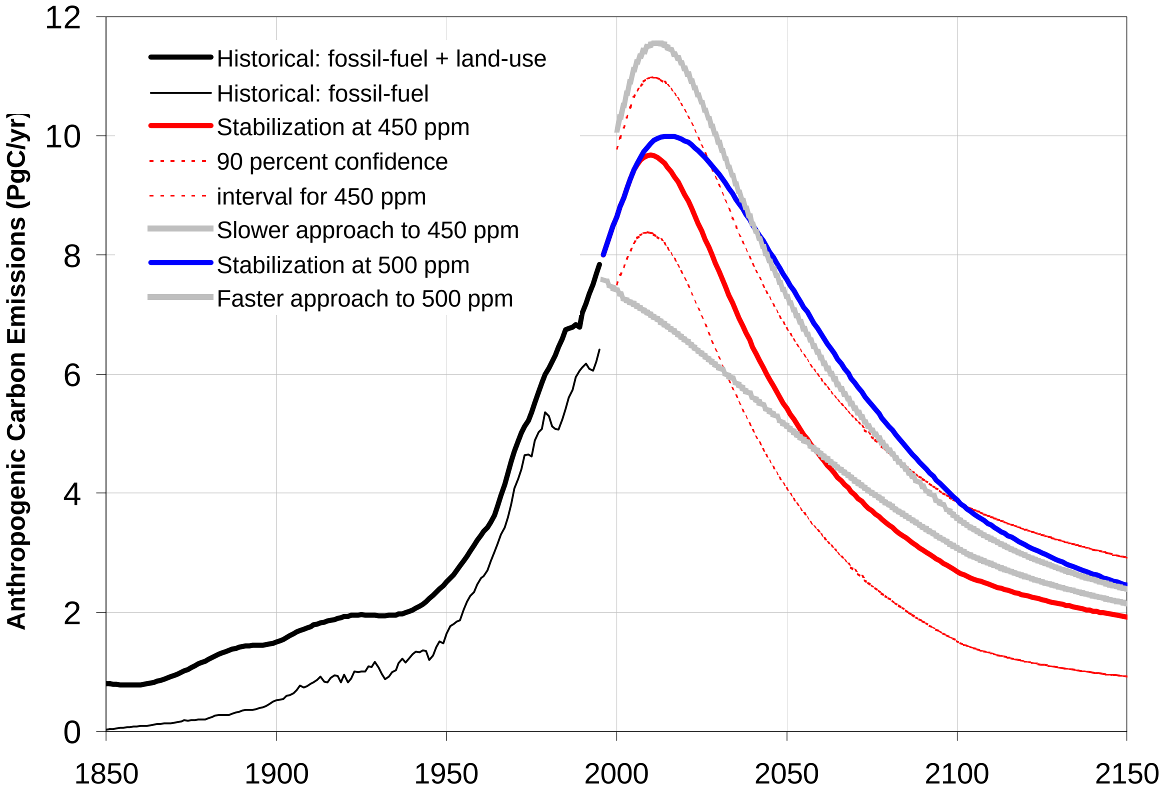


Figure 2. Historical emissions of carbon from fossil-fuel burning and land-use changes, and emission pathways that stabilize carbon dioxide concentrations at 450 and 500 ppm in the period 2100 to 2150.

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.

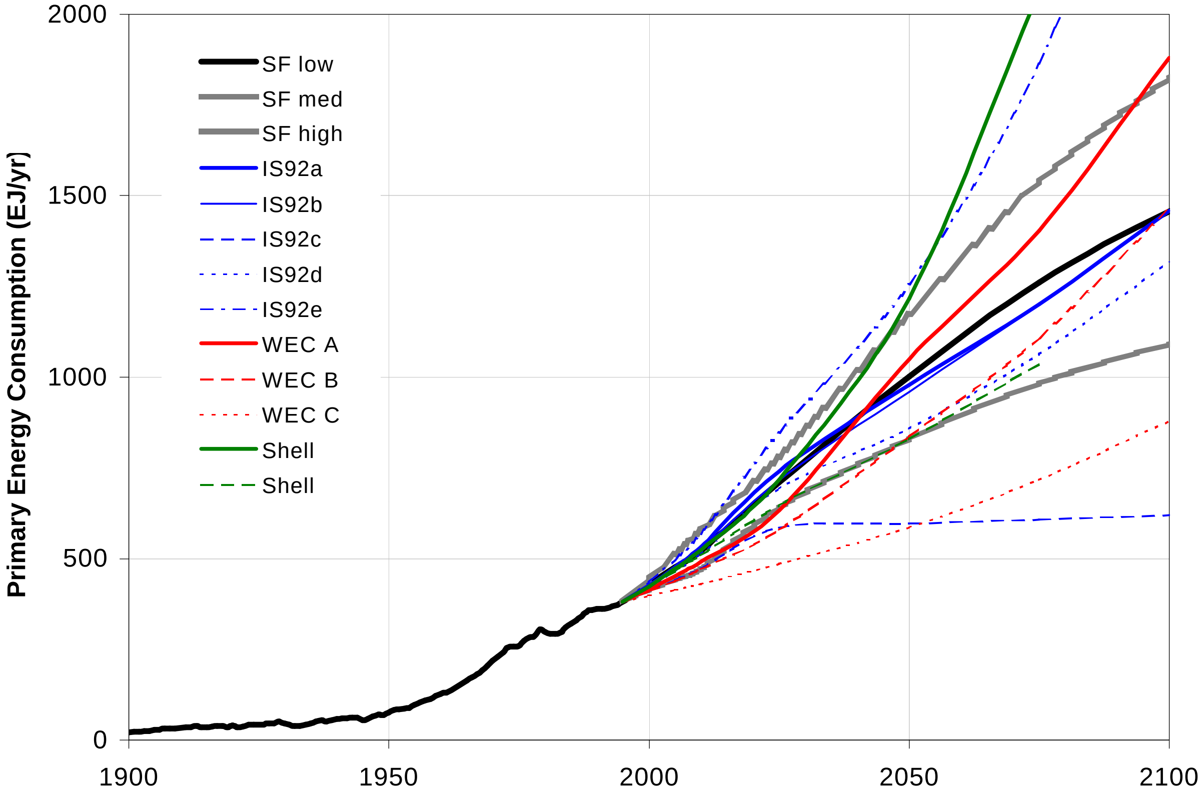


Figure 3. Scenarios of future world commercial primary energy consumption by Fetter (SF), the Intergovernmental Panel on Climate Change (IS92), the World Energy Council (WEC), and Shell Oil.

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 1. World commercial primary energy supply, traditional fossil supply for stabilization at an equivalent doubling of carbon dioxide, required non-CO_2-emitting energy supply (or demand reductions), and average growth rate of non-CO_2-emitting supply.

	Commercial Primary Energy Supply (EJ/yr)			Growth Rate
Year	Total	Limit on Fossil	Non-CO_2-emitting	of Non-CO_2 Supply (%/yr)
1995	382	329	53	2
2050	930 ± 280	330 ± 110	600 ± 300	3–5
2100	1450 ± 600	150 ± 70	1300 ± 600	1–2

Sources: Figures 2–3 and author's calculations.