Decarbonizing the Global Energy System:
Implications for Energy Technology and Security

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I. Introduction

Since the Intergovernmental Panel on Climate Change (IPCC) was formed in 1988, it has engaged a substantial proportion of those individuals with relevant scientific expertise in the process of forming reasonable judgments about the effects of aggregate human activity on the composition of the earth's atmosphere and about the resulting implications for global climate. It is now widely agreed that in concert with other so-called "greenhouse gases," carbon dioxide (CO_2) released from the burning of fossil fuels for energy is causing the earth's climate to change. Over the last century, the concentration of CO_2 in the atmosphere increased from about 300 to 375 parts per million by volume (ppmv), and global average surface temperature increased by 0.4 to 0.8 ^{o}C. In the absence of policies designed to substantially reduce global emissions, scenarios developed by the IPCC indicate that CO_2 concentrations will reach 550 to 1000 ppmv in 2100 and that global average surface temperature will increase by an additional 1.5 to 6 ^{o}C (IPCC 2001a).

The consequences of such a temperature increase and associated changes in precipitation patterns and other climate variables are a matter of greater uncertainty and disagreement. At the lower end of the range, it is possible that nothing of global consequence will occur, and that the regional and more localized effects will be moderate enough to be handled by natural adaptation. It also conceivable—particularly at the high end of the temperature range—that abrupt, nonlinear and fundamental changes could be triggered, such as a sudden change in large-scale ocean currents, with truly massive and potentially catastrophic consequences for human societies. The IPCC has identified the possibility of extreme danger, but has been and will remain unable to reach consensus on its exact character, magnitude, probability and timing.

That situation presents an extraordinary problem of risk management. It is feasible in principle but monumentally demanding to limit the atmospheric concentration of greenhouse gases resulting from aggregate human activity. Moreover, the will and capacity to do so would have to be generated in advance of scientific consensus about the danger to be avoided. If business continues as usual, however, any scientific consensus that might form about catastrophic climate change is likely to emerge only after it is too late to take action to avoid it.

Any effort to reduce emissions which restrains global economic output threatens the developing world with prolonged stagnation and hopelessness, setting the stage for increased civil conflict and international violence. Although the relevant relationships are not yet understood in detail, it is widely suspected that violence is generated by the sustained denial of economic opportunity. Thus, security in the globalized world economy ultimately depends on a more equitable pattern of economic development than has yet been achieved.

Meeting minimal standards of equitable economic growth, however, would require expanding the global economy by a factor of four to five over the next fifty years. To support this growth in economic activity, global energy production would have to double or triple during this time period, even with significant efficiency gains. Meeting this need primarily through today's fossil fuel-based energy system would make successfully addressing the climate change problem exceedingly difficult if not impossible. To hold greenhouse gas concentrations in the atmosphere to prudently low levels, the fraction of energy supplied by carbon-free sources would therefore have to increase very substantially, from about 15 percent today to 50-80 percent by 2050. Ensuring equitable development and poverty reduction through a path that does not obstruct efforts to prevent climate change is thus likely to be a major challenge faced by world policymakers in the coming years, one that has the potential to either reduce or greatly expand civil violence and intrastate conflict.

The shift from fossil fuels toward carbon-free sources also has serious implications for relations between states. The basis for producing and using energy would have to be transformed globally against the predictable resistance of current market dynamics and prevailing political attitudes. There are candidate technologies that would enable such a transformation to occur, but the effort to develop and deploy them on the time scale required would be an organizational feat far beyond any yet demonstrated. While in principle an energy transformation of the magnitude discussed here might be accomplished without expansion of nuclear power generation, in practice the world will have to ponder an eight-fold increase in that source. An increase of this magnitude would pose significant proliferation risks unless the entire nuclear fuel cycle was far protected against diversion and destructive application than it is today. Such greatly enhanced protection of nuclear materials and technologies would in turn require a degree of global collaboration that could not be accomplished without a fundamental change in prevailing security practices among the United States, China, Russia and India, at a minimum.

This daunting challenge presents a constructive opportunity. A massive, relentless and impersonal environmental threat that will affect populations worldwide in both developed and developing countries could potentially be an organizing focus for policy far more productive than, for example, the divisive fear of terrorism. The problem could provide both the context and the incentive for exploring deeper connections between security and economic development and for controlling the determinants of civil violence. If so, then energy production can be expected to become a central strategic concern capable of dominating policy and transforming international relationships.

The security implications of the climate change problem lie beyond the mandate of the IPCC and any other officially organized discussion at the moment. Although the proposed links are open to dispute, serious exploration of these and comparable implications would be worthwhile, and should be undertaken by those in a position to do so. To promote such exploration, this paper first briefly reviews the climate change challenge and suggests a goal prudent goal for stabilizing carbon dioxide concentrations, a goal far more ambitious than any the international community has yet been able to agree upon. Next, it summarizes current understanding of various carbon-free energy technologies to show that only five—biomass, nuclear fission, solar, wind, and decarbonized fossil fuel—have the potential to make a significant contribution by 2050, and that each alternative currently has significant drawbacks. The third section examines important intersections between the climate change problem and emerging sources of global insecurity. It highlights concerns about how action or inaction on climate change could exacerbate inequities that breed conflict, and also considers the challenges for non-proliferation that would arise from a significantly increased use of nuclear power. As reflected in the paper, atmospheric dynamics and energy producing technologies are much better understood than the dynamics of civil and international conflict, in part because much more extensive efforts have been made on the former topics. The paper argues that a dedicated attempt should be made to explore the asserted implications despite the unavoidable imbalance in the foundations of relevant knowledge.

II. The Climate Change Challenge

Setting a Prudent Stabilization Standard

In response to concerns that increasing concentrations of greenhouse gases—in particular, CO_2—might lead to harmful changes in climate, the United Nations Framework Convention on Climate Change (UNFCCC) was negotiated in Rio de Janeiro in 1992. The objective of the UNFCCC, as stated in Article 2, is to achieve "stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system" (UNFCCC, 1992).

The 1997 Kyoto Protocol strengthened the UNFCCC by establishing binding emission targets for the developed or "Annex I" countries, the aim of achieving an overall reduction in Annex I emissions equal to 5.2 percent below 1990 levels in the 2008-2012 period. The national emission reduction targets were determined by political bargaining and consensus-building, not science. There is widespread recognition that the Kyoto reductions, by themselves, would have only a small effect on future greenhouse gas concentrations. Thus, the Kyoto reductions are meaningful only insofar as they are a first step in a process toward deeper reductions that eventually include developing as well as developed countries.

Although the UNFCCC established stabilization of greenhouse gas concentrations the ultimate goal, the "level that would prevent dangerous anthropogenic interference" was not defined in the agreement or in subsequent annual meetings of the Conference of Parties. The IPCC has not endorsed a stabilization goal, nor is it likely to do so because of extraordinarily complex nature of climate change science. Understanding climate patterns and forecasting future changes and impacts requires analysis of a large number of interactive variables, a process that is inherently uncertain and subject to constant revision. Over the past decade, significant contributions have been made to the knowledge of climate change science and impacts, but the "level that would prevent dangerous anthropogenic interference" is no less uncertain as a consequence of this enormous effort. The question of where to set the stabilization level is thus as much a matter of prudential judgment as it is a matter of science.

Most studies of the effects of climate change have focused on a change in greenhouse concentrations equivalent to a doubling of the CO_2 concentration.[1] According to the

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[1] Most such studies use climate models in which the concentration of CO_2 is increased from the preindustrial concentration of 275 ppmv to 550 ppmv (or, sometimes, from 300 to 600 ppmv) and other gas concentrations are held constant. Because the concentrations of other greenhouse gases, such as methane, nitrous oxide, CFCs, and CFC substitutes, have and will continue to increase, the combined greenhouse effect (radiative forcing) of *all* greenhouse gases would be substantially greater than that due to CO_2 alone.

IPCC, an equivalent doubling would, over the long term, increase the global-average surface air temperature by 1.5 to 4.5 °C (IPCC 2001a). The wide range is due largely to uncertainties about how cloud cover, ocean currents, and vegetation 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. An appreciation of the magnitude of the expected changes in climate can be gained by noting that an increase in global temperature of 1.5 °C would exceed natural fluctuations over the last ten thousand years, and an increase of 4.5 °C would rival the increases that occurred during shifts from glacial to interglacial periods over the last two million years (Folland et al, 1990; Nicholls et al, 1996).

The European Union has argued that the increase in global average temperature should not exceed 2 °C, and therefore that stabilization at less than an equivalent doubling should guide global limitation and reduction efforts (AGBM, 1997).[2] Given the enormous uncertainties associated with climate change, any stabilization target should be seen as a tentative goal designed to guide long-term strategies to reduce emissions. Nevertheless, based on the current state of knowledge, an equivalent doubling of carbon dioxide is the highest stabilization target that can be considered both prudent and practical. Meeting this, or any other reasonable target will require a fundamental “decarbonization” of the global energy system during the next half century, in which traditional fossil fuels are replaced by energy sources that emit little or no CO_2.

Limits on Fossil Fuel Emissions

Fossil-fuel burning is the most important source of greenhouse gas emissions, but it is not the only source. To translate a stabilization goal into limits on future fossil-fuel burning, one must take into account greenhouse gases other than CO_2, and emissions of CO_2 from sources other than fossil-fuel burning.

An “equivalent doubling” is any combination of greenhouse-gas concentrations (above preindustrial levels) that would have the same effect on climate as a doubling of the CO_2 concentration. Because a doubling of the CO_2 concentration produces a radiative forcing[3] of 3.7 W/m^2, an equivalent doubling is any combination of gases that produces a combined radiative forcing of 3.7 W/m^2.

The term “equivalent doubling” means any combination of greenhouse gas concentrations that would produce a combined radiative forcing equivalent to a doubling of the CO_2 concentration alone. To stabilize greenhouse gas concentrations at an equivalent doubling, the CO_2 concentration very likely would have to be stabilized at about 450 ppmv.

[2] Although not stated explicitly, it is clear from the context that the EU was expressing support for stabilization at less than an equivalent doubling (i.e., including greenhouse gases other than CO_2) rather than an actual doubling of CO_2.

[3] “Radiative forcing” is the change in the energy balance of the climate system that would result from an instantaneous change in greenhouse-gas concentrations. In equilibrium, the Earth radiates infrared energy to space at the same average rate as it absorbs solar energy. If the CO_2 concentration were suddenly doubled, infrared radiation initially would be 3.7 W/m^2 less than solar absorption. Over time, the climate system would adjust (e.g., surface temperatures would increase) until the balance between infrared radiation and solar absorption was re-established.

Greenhouse gases other than CO_2 include methane, nitrous oxide, halocarbons, and sulfur hexafluoride, which today have a combined radiative forcing of about 0.9 W/m^2. Anthropogenic emissions of methane and nitrous oxide are due primarily to agricultural and waste-disposal activities. Strategies exist for controlling these emissions (Cole et al, 1996, Levine et al 1996), but significant reductions in anthropogenic emissions will be difficult in view of expected increases in population and per-capita agricultural production. Moreover, natural emissions of these gases may increase as a result of climate change (Lashof et al 1997, Melillo et al 1996). Although emissions of many halocarbons will be phased out in accord with the Montreal Protocol and its Amendments, substitute compounds are greenhouse gases. IPCC scenarios indicate that greenhouse gases other than CO_2 are likely to contribute a combined long-term radiative forcing of at least 1.0 W/m^2. Stabilization at an equivalent doubling (i.e. a total forcing of 3.7 W/m^2) would therefore require that CO_2 be limited to a radiative forcing of 2.7 W/m^2 and a concentration of about 450 ppmv.[4]

In order to stabilize the CO_2 concentration at 450 ppmv, total emissions must be reduced to about 5 PgC/y by 2050 and about half that level by 2100 (IPCC 2001a).[5] This includes emissions from all anthropogenic sources, not just fossil-fuel burning. In 2000, cement manufacture released 0.2 PgC/y (Marland et al, 2002); this can be expected to increase to about 0.5 PgC/y by 2050.[6] Net carbon emissions due to land-use changes (e.g., deforestation) have been variously estimated at 1.7 ± 0.7 PgC/y and 0.6-1.0 PgC/y during the 1980s, and about 1.6 Pg/y from 1990-95 (IPCC 2001a). Future land-use emissions are a matter of speculation; scenarios in the literature range from a net release of over 2 PgC/y to a net uptake of over 2 PgC/y in 2050, depending on rates of deforestation and reforestation and the carbon content of vegetation (Alacmo et al, 1994; Brown et al, 1996; Kirschbaum et al, 1996).[7] Changes in climate might cause large releases of carbon

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[4] The radiative forcing, ΔF, associated with a CO_2 concentration C is given approximately by $\Delta F = 5.35 \log_e(C/C_0)$ W/m^2, where C_0 is the preindustrial concentration (275 ppmv). The concentration that produces a forcing of 2.7 W/m^2 is given by $C = 275\, e^{2.7/5.35} \cong 450$ ppmv.

Note that aerosols and tropospheric ozone are ignored in this discussion of non-CO_2 greenhouse gases because their residence times in the atmosphere are very short. Unlike the “well-mixed” greenhouse gases, any effect of aerosols and tropospheric ozone on climate is regional and depends on the current rate of emission in that region. Reductions in coal burning would lead to immediate reductions in aerosol concentrations while having little effect on CO_2 concentrations for many decades. Moreover, efforts to control air pollution will lead to reductions in aerosol emissions and tropospheric ozone formation independent of reductions in carbon emissions as pollution-control technologies diffuse to developing countries.

[5] One petagram of carbon (PgC) is equal to 10^{15} grams or one billion metric tons of carbon, or 3.7 billion tons of carbon dioxide. For comparison, total CO_2 emissions by the United States and China in 2002 were 1.6 and 1.0 PgC, respectively.

[6] Per-capita cement production increased at an average rate of 3.5 percent per year over the last 50 years and 2 percent per year over the last 25 years (Marland et al, 2002). Even if per-capita production grows at only 1 percent per year over the next half century, total emissions (calcination only) would exceed 0.5 PgC/y by 2050. Opportunities to reduce calcination releases per ton of cement produced (e.g., by using waste lime) are limited.

[7] Note that some of these estimates use different base year (1990) emissions. When they are normalized to the same base year emissions, the range is of –2.2 to 2.5 PgC/y in 2050.

during the next century if mature forests die before they are replaced by new growth, if higher temperatures promote the decay of dead organic materials at high latitudes, or if drier conditions increase the frequency of forest fires; it is estimated that such processes could produce net emissions of 0.1–3.4 PgC/y during the next century in response to an equivalent doubling in greenhouse gas concentrations (Lashof et al, 1997; Mellio et al, 1996).[8] For simplicity we will assume that, in the context of stabilization at an equivalent doubling, absorption of carbon by reforestation and other carbon management programs will offset carbon releases from all non-fossil sources by 2050, but with an overall uncertainty of ± 2 PgC/y.

Thus, in order to stabilize greenhouse gas concentrations at an equivalent doubling, fossil-fuel carbon emissions must be limited to 5 ± 2 PgC/y in 2050 and 2.5 ± 1 PgC/y in 2100, equivalent to an energy consumption of about 300 ± 120 and 150 ± 60 EJ/y, respectively.[9] For comparison, in 2000 global fossil-fuel carbon emissions and energy consumption were 6.6 PgC/y and 360 EJ/y, respectively (EIA, 2004). Fossil-fuel combustion can continue to increase for another decade or two, but after that point it must begin a long and steady decline in order to stabilize CO_2 concentrations.

Requirements for Carbon-Free Energy

Scenarios of future world energy consumption generally show substantial growth over the next century, driven by increases in both population and per-capita consumption in developing countries. Figure 1 shows scenarios of future energy consumption from the IPCC Special Report on Emission Scenarios, assuming no new policies designed specifically to reduce carbon emissions.

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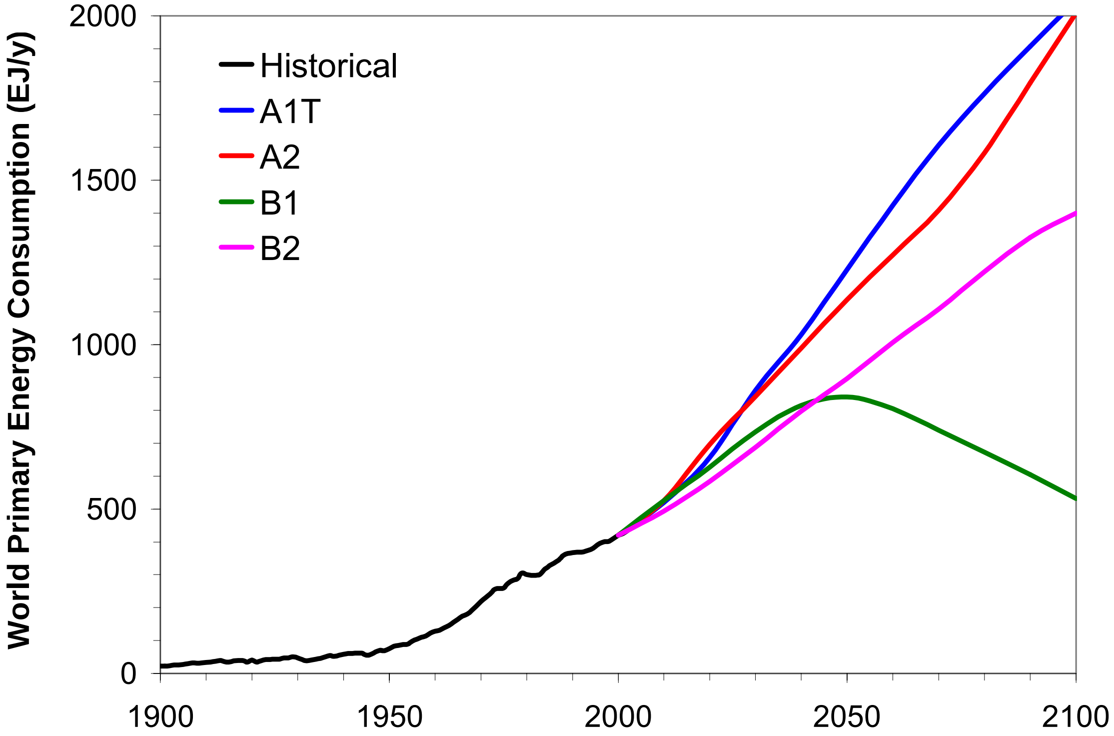
[8] This is the net release of CO_2 due to climate change, after subtracting the increase in carbon storage due to fertilization from increase CO_2 concentration. The increased uptake due to fertilization is included in the calculations of emission pathways that lead to stabilization.

[9] 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. About 25, 20, and 14 gC are released per kJ of thermal energy released from coal, oil, and gas, respectively. For the current mix of fossil fuels (30 percent coal, 45 percent oil, 25 percent gas), the average is about 19 gC/kJ of fossil energy; this might fall as low as 17 gC/kJ over the next several decades as users switch from coal to natural gas. Thus, 5 PgC would be equivalent to about 300 EJ.

Figure 1. IPCC Scenarios of World Energy Consumption



The four scenario families are developed in the *IPCC Special Report on Emissions Scenarios* (Nakićenović et al, 2000). The general assumptions for each are as follows:

- A1: Characterized by convergence among regions and increased cultural and social interactions. Assumes very rapid economic growth, a global population that peaks in mid-century and then declines, and the rapid introduction of new technologies. Includes a substantial reduction in differences in per capita income between regions. The variant shown here assumes an emphasis on non-fossil energy sources.
- A2: Characterized by self-reliance and preservation of local identities. Fertility levels converge slowly and global population increases continuously, nearly doubling from 2020 to 2100. Per capita economic growth and technological change are slower than in the other scenarios.
- B1: Emphasizes global solutions. Includes same population assumptions as A1, but with rapid changes toward a service- and information-oriented economy. Assumes resulting reductions in material intensity and the introduction of clean technologies.
- B2: Emphasizes local solutions. Assumes global population increases continuously but at a lower rate than A2, intermediate levels of economic development, and less rapid rates of technological change than in the A1 and B1 scenarios.

These scenarios generally make optimistic assumptions about the rate of economic growth in the least developed parts of the world. While these assumptions reflect aspirations more than actual growth trends in places like sub-Saharan Africa, they are appropriate reminders that more equitable patterns of development are an essential component of a sustainable global strategy. The SRES scenarios also make generally optimistic assumptions about improvements in energy efficiency, with average rates of decline in energy intensity[10] ranging from the long-term historical average to over twice that rate. In our view, gains in energy efficiency beyond those assumed in the most optimistic of these scenarios are unlikely without policy interventions that sharply increase energy prices.

The SRES scenarios project a doubling or tripling of total primary energy consumption over the next fifty years, from about 420 EJ/y in 2000 to 800–1200 EJ/y in 2050.[11] If fossil-fuel combustion was limited to 300 EJ/y in 2050 to permit stabilization at an equivalent doubling, then carbon-free energy sources would have to supply the difference: 500–900 EJ/y. The SRES scenarios, however, assume only 200–500 EJ/y of carbon-free energy in 2050, or two to four times less than required for stabilization at an equivalent doubling.

As noted above, these scenarios assume no new policies designed to reduce carbon emissions. Consumption of fossil fuels remains high in these scenarios primarily because it is assumed that the costs of fossil-fuel energy will remain low compared to carbon-free alternatives. Consumption of fossil fuels could be reduced, and production of carbon-free energy increased, either with carbon taxes or a system of tradable permits. Edmonds et al. (1998) calculate that a tax or permit price escalating to \$325–450/tC in 2050 and \$750–1200/tC in 2100 would be needed to stabilize CO_2 concentrations at 450 ppmv. The "ecologically driven" scenarios developed by Nakicenovic et al (1998), which result in a CO_2 concentration of about 450 ppmv in 2100, assume a carbon tax of \$150/tC in 2050 (in addition to energy taxes amounting to 100 percent in developing countries and 300 percent in developed countries) increasing to \$400/tC in 2100 (L Schrattenholzer, personal communication). Total energy consumption in these scenarios is about 600 EJ/y in 2050, with 250–300 EJ/y supplied by carbon-free sources.

Taxes of this magnitude are very high by current U.S. standards. Existing energy taxes are equivalent to \$30/tC in the United States (Baron, 1996); a tax of \$100/tC would more than triple the current price of coal delivered to U.S. utilities and increase the retail price of coal-fired electricity by about 30 percent.[12] Although such taxes need not have strong

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[10] "Energy intensity" is the amount of primary energy consumed per unit of GDP produced. Energy intensity has declined steadily over the last 50 years in most countries, due both to increased efficiency of energy use (e.g., more steel produced per GJ consumed) and structural changes in economies (e.g., a shift toward the production of software instead of steel).

[11] Renormalizing for a total energy consumption of 420 EJ/y in 2000, primary energy consumption in 2050 in the SRES scenarios ranges from 840, 900, 1140, and 1230 EJ/y in the B1, B2, A2, and A1T scenarios, respectively.

[12] Because coal is 75 percent carbon, a tax of \$100/tC would add \$75/t to the price of coal and \$0.026/kWh to the price of coal-fired electricity (assuming a heating value of 29 GJ/t and an average net conversion

negative economic effects if they are phased in slowly and the revenues are recycled efficiently (Repetto et al, 1997), opinion polls consistently indicate that a large majority of Americans would be unwilling to accept taxes of this magnitude to address the climate change problem (Kull, 1998). Developing countries are likely to be even less receptive to such taxes.

Thus, stabilization at an equivalent doubling will require 500–900 EJ/y of carbon-free energy by 2050 in the absence of carbon taxes or permits (i.e., at prices comparable to those of fossil fuels), or about 300 EJ/y with carbon taxes or permits (i.e., at prices two to three times higher). For comparison, in 2000 carbon-free sources supplied only about 60 EJ/y (EIA, 2004). Carbon-free energy supply must therefore grow by a factor of five to fifteen over the next 50 years (an average grow rate of 3–5 percent per year over this period), from 14 percent of total commercial supply to 50–80 percent 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. In these first two shifts, it took 50 years for the emerging source 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 stabilizing greenhouse gas concentrations at a reasonable level.

Sources of Carbon-Free Energy

Only two sources of carbon-free[13] energy—hydropower and nuclear fission—currently produce a significant fraction of world supply, with each accounting for about 28 EJ/y or 6.5 percent of commercial primary energy in 2002 (EIA, 2004). All other carbon-free sources—geothermal, wind, solar, and commercial biomass—together supplied only about 5.6 EJ/y in 2002 (EIA, 2004). Traditional biomass fuels are not included in this accounting; although they may provide up to 60 EJ/y, much of this is fuelwood that is harvested in a unsustainable manner, resulting in a net release of CO_2 (Hall, 1991). Carbon-free energy production has been grown at an average rate of only about 2 percent per year over the last 15 years—much less than the 4-5 percent per year growth needed to stabilize greenhouse-gas concentrations at an equivalent doubling without resort to high taxes. Moreover, most of the recent growth is due to an expansion of hydro and nuclear capacity, which is expected to taper off in the coming decades. Although additional hydro capacity potential exists in various countries, many of the more cost-effective sites have already been exploited. In addition, concerns about the potential environmental impacts have led to opposition to new dam construction in some areas. While there is significant potential for an expansion of nuclear power capacity worldwide, ongoing concerns over

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efficiency of 35 percent). For comparison, in 1997 the average price of coal delivered to U.S. utilities was \$29/t and the average retail price of electricity was \$0.085/kWh (EIA, 1999).

[13] The term “carbon-free” here refers to energy production with very low net emissions of CO_2 to the atmosphere. Of course, no energy source can be truly carbon-free if it involves structural materials (steel, cement, etc.) or fuels that are processed using energy derived from fossil fuels. This “embedded energy,” as it is sometimes called, is usually a small fraction of energy produced by the renewable and nuclear energy plants during their lifetimes.

reactor safety, waste disposal and nuclear weapons proliferation make its future uncertain. Growth in the developed world has slowed considerably, although nuclear power appears likely to expand in China and some other developing countries.

The list of potential carbon-free energy sources is long; in addition to those listed above, there is nuclear fusion, various forms of ocean energy, 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 in 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 1 at the end of Part II summarizes the current and potential contributions of various carbon-free energy sources.[14]

Sources Unlikely to Make Major Contributions by 2050

Hydropower

Hydropower currently is the leading source of carbon-free energy. In 2001, hydro produced about 2600 TWh[15] of electricity—17 percent of global electricity production and 6.5 percent of primary energy (EIA, 2004). Global hydroelectric production experienced strong growth from 1900 to 1970, but growth has slowed to about 2 percent per year over the last two decades. Future expansion is limited by the availability of economically attractive sites and, increasingly, by concerns about the environmental and social impacts of dams (March et al, 1999). It should also be noted that the reservoirs created by large-scale hydropower dams can produce significant quantities of methane, a potent greenhouse gas.

Scenarios of future energy supply assume that hydro will contribute less than 5000 TWh in 2050, and that its share of total energy supply will remain about the same or decline (Nakićenović et al, 2000). Without regard to environmental or economic constraints, global hydroelectric production potential is estimated at 15,000 to 19,000 TWh/y (Moreira et al, 1993). The historical experience in the United States, Europe, and Japan, where hydroelectric production has leveled off, indicates that 40 to 65 percent of this

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[14] While most of the carbon-free energy supply options considered here are for the electric power industry, it should be noted that their large-scale deployment may also allow for additional emission reductions in other sectors. In particular, in tandem with the development of new transportation technologies (i.e. hydrogen-powered fuel cell vehicles, "plug-in" electric-powered automobile networks for short-distance travel), increased generation of carbon-free electricity could produce significant reductions in oil consumption. At present it is unclear to what extent and over what time frame the deployment of such technologies will be feasible, however.

[15] A terawatt-hour (TWh) is a billion kilowatt-hours or 10^{12} watt-hours, and is equal to 0.0036 EJ.

technical potential could be exploited. Thus, hydro ultimately could produce no more than 10,000 TWh/y or 100 EJ_p/y.[16]

While large-scale hydropower is a mature industry, many small groups are working to develop and promote micro-hydropower technology for use in the developing world. Though it does not have the potential to meet a significant part of the world's energy needs, micro-hydro technology (defined loosely as hydropower installations generating less than 300 kW) have shown promise in providing modest electrification in rural areas of developing countries where the provision of grid power is prohibitively expensive.

Geothermal Energy

An enormous amount of heat—nearly 10^{13} 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 10^7 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 small—about 1000 EJ/y 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 resource.

Geothermal energy experienced rapid growth in the early 1980s; during the 1990s, however, production has grown at only 2 percent per year. In 2000, geothermal energy contributed about 0.7 EJ_p to world energy supply—49 TWh of electricity and about 0.6 EJ of direct-use heat (Koenig, 2003). Nearly all of this was extracted from high-temperature hydrothermal reservoirs.

Because heat is withdrawn from the surrounding rock much faster than it is replenished by conduction from below, geothermal energy is an exhaustible resource. The total amount of heat that could be extracted from high-temperature hydrothermal reservoirs is on the order of 5000 EJ_p—less than oil or gas resources.[17] Only a fraction of this could be extracted economically. Thus, hydrothermal energy is unlikely to 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 delivering that energy in a useful form and at an acceptable price. The basic concept is to drill two parallel wells several kilometers deep

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[16] The primary energy content of electricity from non-thermal sources, such as hydro and wind, is typically taken to be 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 the average thermal efficiencies expected several decades from now (40 percent), 1 TWh = 0.009 EJ_p, where "EJ_p" denotes "exajoules of primary energy."

[17] The accessible high-temperature (>150 °C) hydrothermal resource in the United States is estimated at 4000 to 6000 EJ (Muffler, 1979); based on this, the global resource is roughly 40,000 EJ. If one-fourth of the accessible resource could be extracted and used to produce electricity at half the average efficiency for thermal power plants, the contribution to world primary energy would be roughly 5,000 EJ_p. The amount that could be extracted economically would be smaller.

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 is 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 (Palmerini, 1993; Brown, 1996). 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 could supply a significant fraction of world energy demand by 2050.

Ocean Energy

Large amounts of energy are stored in the oceans in tides, currents, waves, heat, and salinity gradients. 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 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.

Tidal energy can be 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/y of electricity (Cavanagh et al, 1993). The total amount of energy dissipated by tides worldwide is over 200 EJ_p/Y, but only 5 to 10 EJ_p/y occurs at sites that are technically exploitable (i.e., with a mean tidal range greater than 3 m). Of this, perhaps 10 to 50 percent could be exploited at reasonable cost. Concern about adverse impacts of dams on the ecology of estuaries could further limit the development of this type of tidal power.

Energy in the tides could be extracted at lower environmental impact without a dam, using turbines placed in tidal currents, similar to run-of-the-river hydropower plants. Such techniques could be applied to areas of the open ocean having strong currents. The technology is at an early stage. One company that is developing prototype installations, Blue Energy Canada, has assessed the global potential at 450 GW, which is comparable to the current contributions of nuclear and hydro electricity.

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 naturally 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 (Druckers, 1996). Capital costs are likely to be very high, as would be the cost of insuring against storm damage.

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 of 10,000 EJ_p/y, but the amount that could be exploited (economics aside) is less than 100 EJ_p/y. 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. 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.

Energy is also stored in the form of salinity gradients. The difference in salinity between the Earth's river flow and the oceans is equal to 200 EJ_p/y. Available technologies to convert this energy into electricity are, however, extremely expensive.

Fusion Energy

Nuclear fusion—the joining of light nuclei to form more-stable heavy nuclei—is the energy source of the stars. 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. For fusion to occur, nuclei must be brought very close together—close enough to overcome the strong repulsive force of the positively charged nuclei. The two main approaches are inertial and magnetic confinement. In 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.

After break-even is achieved, 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. 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 significantly to the stabilization of greenhouse-gas concentrations.

Sources with the Potential to Make Major Contributions by 2050

This leaves five carbon-free energy sources that could potentially make a substantial contribution to world energy supply in 2050: fission, biomass, solar, wind, and decarbonized fossil fuels. Below we 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.

Fission Energy

Of the carbon-free sources that could make a major contribution to future energy supply, nuclear fission is the only one that is deployed commercially on a significant scale today. In 2002, fission reactors supplied almost 2600 TWh of electricity—17 percent of world electricity generation and 6.5 percent of commercial primary energy (EIA, 2003).

Like wind and solar photovoltaics, fission supplies only electricity; unlike wind and solar, however, fission can produce electricity at a steady rate. Although in principle fission can supply heat for industrial and residential use, accident concerns and other siting considerations have limited this application. And although the possibility of producing hydrogen from nuclear heat or electricity is often mentioned, this is likely to be more expensive than hydrogen produced from biomass or decarbonized fossil fuels.[18]

In nuclear-intensive energy scenarios (Nakićenović et al, 1998; IAEA, 1995; NEA, 1998b, MIT 2003), nuclear electricity production increases by a factor of three to five over the next 50 years, to 7,500-12,000 TWh/y in 2050, equivalent to 70-110 EJ_p/y. If this energy were supplied entirely by light-water reactors (LWRs) operating on a once-through fuel cycle with an average uranium requirement of 19 metric tons of uranium per TWh, cumulative consumption of uranium would be 5-6 million metric tons of uranium (MtU) through 2050; the reactors then in existence would require another 4-5 MtU for the remainder of their operating life (Bunn, et al 2005). The OECD estimates that total conventional uranium resources available at less than $130/kgU amount to 17 MtU (OECD, 2001); thus, conventional uranium resources can easily support a high-growth scenario for at least 50 years using a once-through cycle.

Over the longer term, heavy reliance on nuclear energy would require a transition to fuel cycles that use uranium more efficiently or that exploit unconventional uranium resources. The traditional solution is to recycle the unburned plutonium and uranium in breeder reactors. In this way, it is possible to decrease uranium requirements by a factor of 100, so that 17 MtU could provide over 10^6 EJ_p. Recycling plutonium raises concerns about the possible diversion of this material for weapons, however (see below). Less discussed is the possibility of using unconventional uranium resources. Undiscovered and low-grade terrestrial resources are likely to be many times larger than current OECD estimated resources (Bunn et al 2005). In addition, 4500 MtU is dissolved in the world's oceans; if this uranium could be extracted at a cost less than the breakeven cost for plutonium recycling, breeder reactors would be unnecessary even in the very long term.

Although fission's technical potential is substantial, its near-term prospects are not very favorable. Industry forecasts based on current market conditions range from a substantial decrease to a modest increase in installed capacity over the next 20 years, with fission's share of world electricity production falling to about 12 percent by 2022 (NEA 1998a; EIA, 2003b). The only region expected to experience significant growth in the near future is East Asia.

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 (Bodansky, 1996; National Research Council, 1992; EIA, 1990; EIA, 1995; Delene et al, 1988; Gielecki et al, 1994). The best U.S. nuclear plants,

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[18] Hydrogen can be produced from biomass gasification at a cost of $6-9/GJ, from natural gas at a cost of $7-10/GJ, and from coal at a cost of $8-9/GJ (Ogden et al, 1993). Carbon sequestration would add $0.2–1/GJ to the cost of H_2 produced from gas and $1–6/GJ for H_2 produced from coal (assuming sequestration at $10–60/tC). For comparison, the cost of electrolytic hydrogen, assuming electricity at a cost of $0.05-0.07/kWh, would be $17-25/GJ. A very-high-temperature reactor (outlet temperature = 900 °C) could potentially decrease this to $14-20/GJ, using either high-temperature electrolysis or a thermochemical process, for the same electricity cost of $0.05-0.07/kWh.

however, produce electricity at lower cost than the best coal-fired plants (EIA, 1990). In countries with well-run nuclear plants and expensive fossil fuels, such as Japan, nuclear is on average somewhat less expensive than fossil-generated electricity. The estimated cost of electricity from a new nuclear plant is estimated at \$0.05–0.07/kWh (Delene et al, 2000; MIT 2003). At the low end of this range, nuclear would be economically competitive with new coal- or gas-fired plants with carbon sequestration or a modest carbon tax.

Because nuclear technology is the most mature and least speculative of the carbon-free technologies, policy decisions could be made that would make nuclear energy more economically attractive relative to traditional fossil energy sources in order to encourage a larger, more rapid increase in nuclear capacity than would occur naturally under current market conditions. The experience of the nuclear power boom in the 1970s suggests a possible rate of construction in which global nuclear capacity doubled every ten years starting around 2020, so that there could be an eight-fold increase by 2050. If so, nuclear generation could be as high as 20,000 TWh/y or 200 EJ_p/y, about twice the amount assumed in most nuclear-energy intensive scenarios.

Economic considerations aside, the future of fission energy is clouded by concerns about accidents, waste disposal, and the spread of nuclear weapons. Below we review the current prospects in each of these areas. In part III, we consider additional steps that would be needed to address proliferation concerns if there was an eight-fold increase in nuclear energy use.

Accidents

The only major nuclear reactor accident occurred at the Chernobyl reactor in Ukraine in 1986. Discussions of nuclear reactor safety usually place this incident in a category by itself, however, because the design of the Chernobyl-type water-cooled, graphite-moderator (RBMK) reactors is inherently unsafe and would not have been licensed to operate outside of the former Soviet Union, and no new reactors of this type will be built. The only other serious accident occurred at the U.S. Three Mile Island (TMI) reactor in 1979. Although the reactor core was severely damaged, the amount of radioactivity released into the environment was too small to harm the surrounding population. This was the only accident in nearly 12,000 reactor-years of non-RBMK power plant operation in which the reactor core was damaged.

The accident at TMI triggered numerous improvements in reactor safety. Calculations indicate that the probability of core damage is less than 10^{-4} per reactor-year for current U.S. LWRs, and that the probability of a large release of radioactivity is about ten times smaller (USNRC, 1990). Although these probabilities are low, they are not low enough. At this rate, accidents resulting in core damage would occur once per decade in a world with 1,000 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 (Bodansky, 1996). 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.

It will be difficult, however, to demonstrate that extremely low levels of risk have been achieved. Even advanced LWRs depend on the proper operation of equipment, such as pumps and valves, to prevent accidents. Safety also depends on proper operation and maintenance, and it is difficult to estimate the likelihood of operator errors that could trigger or exacerbate an accident. For these reasons, a substantial expansion of nuclear power may require the development of "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. Design concepts have been put forward for passively safe LWRs, gas-cooled graphite-moderated reactors, and liquid-metal-cooled fast reactors, which would shut down automatically and prevent core damage for several days or longer without operator intervention or off-site electricity. Although passively safe reactors would be more expensive than conventional LWRs, shorter licensing and construction times, 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 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 50 to 100 years or more, the continued accumulation of wastes in the absence of a proven, permanent repository is seen as a barrier to the expansion of nuclear power in many countries.

Cost is not a major issue; geological disposal is expected to add only \$0.001/kWh to the price of nuclear-generated electricity in the United States. The availability of land also is not an issue—all nuclear wastes that would be generated worldwide this century (and beyond) could be stored in an area one-tenth the size of the Nevada Test Site (the site of over 800 underground nuclear explosions).[19] 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 there is a high level of scientific confidence that this can be achieved, it nevertheless may be difficult to overcome public opposition.

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 500 to 1,000,000 years, depending on the design of the

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[19] In a high-growth scenario, 3-4 Mt of spent LWR fuel would be discharged during the next century. Assuming a heat output (at time of emplacement) of 700 W per ton of spent fuel and a repository loading of 7 W/m^2, the waste would occupy 300-400 km^2. For comparison, NTS has an area of 3500 km^2, and Manhattan Island has an area of 60 km^2.

package, the thermal loading of the repository, the nature of the surrounding rock, and precipitation in the area (Bodansky, 1996). After the packages leak, it would take 1000 to 1,000,000 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 100 to 1000 times longer to reach the biosphere (National Research Council, 1983). 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 (Knight, 1998).

The U.S. National Academy of Sciences (National Research Council, 1995) and regulatory bodies in several countries have recommended that the radiation standards that currently are used to protect the public should apply to future individuals. These standards are very stringent: in the United States, the dose to an individual from all nuclear facilities must be less than 0.25 mSv/y—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 (McCombie, 1997; Summerling et al, 1998; Jean-Paul Schapira, personal communication). Although similar calculations show that maximum doses from the U.S. repository at Yucca Mountain would be a factor of 100 or more below suggested limits during the first 10,000 years (the time horizon proposed by the EPA for evaluating the performance of the repository), doses well in excess of such limits are possible after 50,000 years (USDOE, 1998; Craig, 1999). Whether this will prove to be a barrier to the licensing of Yucca Mountain remains to be seen.

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 an international standard comparable to the most restrictive national standards.

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 (Hollister et al, 1998, Nadis, 1996). 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 if additional research shows that it is safe and if geologic disposal proves unworkable (Waczewski, 1997).

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, 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. Likewise, the risks of waste disposal 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 is 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 (National Research Council, 1996).

Proliferation

All nuclear fuel cycles involve weapon-usable materials that can be separated using a relatively straightforward chemical process (Hebel et al, 1978). Although fresh LWR fuel cannot be used for weapons purposes, 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 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 (NAS, 1994; Mark, 1993). Because access to weapons-usable material is the principle barrier to the acquisition of nuclear weapons, the plutonium discharged from civilian reactors should receive the same degree of protection from theft or misuse as assembled nuclear weapons.

Under the Non-Proliferation Treaty, non-nuclear weapon state signatories 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 m long, has a mass of 650 kg, and would deliver a lethal dose of radiation to an unprotected person in a few minutes (NAS, 1994). A single assembly contains enough plutonium for a nuclear weapon, 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 to set an example for other countries to refrain from reprocessing and maintain 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. In contrast to spent fuel rods, which are easy to count and track, precise measurement of plutonium inventories in a reprocessing plant is difficult. The amount of plutonium in the spent fuel is uncertain and inventories are difficult to measure, leading to inevitable differences between the estimated amounts entering and exiting the plant. In a large plant, this “inventory difference” can amount to many bombs-worth of plutonium per year (Miller, 1990). 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. The fabrication, transport, and storage of plutonium fuels provide additional opportunities for theft or diversion.

Separation and recycle would decrease the availability of plutonium to future generations, who might otherwise mine stores of spent fuel for plutonium after radioactive decay has rendered the fuel much easier to handle. 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. In any case, this risk could be minimized by centralizing repositories in a few countries and by designing long-term safeguards to detect intrusion into repositories (Peterson, 1996; Peterson, 1999).

Biomass Energy

Biomass—wood, crop residues, dung, and other combustible wastes—is the main source of energy for a majority of the world’s population. Because most biomass fuels are not traded on world markets, consumption is highly uncertain and its contribution to total world energy demand typically is not included. Estimates range from 15 to 65 EJ/y, or 4-15 percent of world energy consumption (Nakićenović et al, 1998; Hall, 1991; Tillman, 1991; FAO, 1995).

The source of all biomass is photosynthesis, in which plants use solar energy to produce carbohydrates from CO_2 and water. The burning of biomass does not lead to a net emission of CO_2 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, most of which is harvested in an unsustainable manner, resulting in deforestation, loss of natural wildlife habitat, and a release of CO_2 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. Moreover, biomass typically is burned inefficiently, resulting in high levels of indoor and outdoor air pollution.

Biomass energy can, however, be a modern, environmentally benign energy source. In the United States, biomass supplied about 3 EJ_p in 1998, including about 60 TWh of electricity (EIA, 2000a; EIA 1998). Most of this was supplied by wood waste, and, to a lesser extent, agricultural waste, solid waste, landfill gas, and about 5 billion liters of ethanol produced from corn. Brazil produced about 13 billion liters of ethanol and 10 TWh of electricity from sugar cane in 1998 (EIA, 2000a; Rosillo-Calle et al, 1998).

Biomass has several advantages over other carbon-free energy sources. First, biomass is versatile. Biomass can be used to produce solid, liquid, and gaseous fuels as well as electricity; its ability to provide liquid transportation fuels is particularly important. Second, the technology for producing biofuels is relatively mature and can be deployed even in the poorest countries. Third, relatively modest advances in production or increases in fossil fuel prices could make biofuels economically competitive without carbon taxes. Biomass can be produced at estimated delivered costs of \$1.5-3/GJ (Carpentieri et al, 1993; Turhollow, 1994; Graham et al, 1995), compared to prices of \$1-2/GJ for coal and \$2.5-5/GJ for oil and natural gas over the last decade (EIA, 2003; BP Amoco, 1999). Using biomass feed at \$2.5/GJ, ethanol or methanol can be produced today at an estimated cost of \$0.25-0.3/L, which would compete with gasoline derived from oil at \$30-40 per barrel (Wyman, 1999; Wyman et al 1993).

The energy potential of biomass is large. Plants store energy at a rate of about 3000 EJ/y. 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; cropland, pasture, and managed forests store about 600 EJ/y. 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.

The energy value of all biomass wastes—crop residues, dung, wood waste, solid waste, and sewage—is about 130 EJ/y (Hall et al, 1993). 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 50-80 EJ/y in 2050 (Johansson et al, 1993).

In addition to wastes, energy crops could be grown on plantations. The amount of energy that could be supplied would depend on the amount of land and the average yield of the 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, average net yields in experimental plots are 150-250 GJ/ha·y. In tropical and subtropical regions, the leading candidates are Eucalyptus, with an average yield of 150-350 GJ/ha·y, and sugarcane, with an average yield of about 600 GJ/ha·y (Hall et al, 1993). Here we assume that average net yields of 200 GJ/ha·y can be achieved by 2050 over hundreds of millions of hectares of surplus and marginal land.

More difficult to estimate is the amount of land that realistically could be devoted to energy crops. In 1997, about 1500 Mha were classified as "arable" (i.e., cultivated in the last five years), of which about 1000 Mha were harvested (USDA, 2003). Estimates of potentially arable land—land on which rain-fed crops could achieve reasonable yields—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 into cropland. If conversion of natural lands is ruled out, 500-1000 Mha of potentially arable land would be available.

The availability of land for energy crops will depend on the balance between future growth in crop yields and grain consumption. If crop yields increase at a rate greater than consumption, the area harvested for food will shrink and large areas will be available for biomass plantations. If, on the other hand, increases in crop yields do not keep pace with consumption, cropland will increase and little land may be available for energy crops.

Past trends are encouraging: between 1961 and 2004, world production of cereals increased by 160 percent, while the area harvested increased only 5 percent. This was made possible by large increases in average cereal yield, from 1.4 t/ha in 1961 to 3.3 t/ha in 2004—an average increase of 2.1 percent per year (FAO, 2004).

Cereal consumption is expected to increase at an average rate of 1-2 percent per year over the next half century, driven by increases in population and per-capita grain utilization.[20] Whether growth in yields will continue to keep pace with growth in consumption is the subject of much debate (WRI, 1996). 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 (FAO, 2003). Biotechnology holds the promise of further increases. Pessimists note that most of the increase in yields was achieved before 1990; since then, yields have increased at an average rate of only 1.3 percent per year. 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/y, due to erosion, salinization, desertification, and urbanization (Evans, 1994; Kendall et al, 1994). 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.

If increases in yield keep pace with increases in consumption, then 500-1000 Mha would be available for energy crops and the energy potential would be 100-200 EJ/y. If grain consumption increases 1 percent per year faster than average yields over the next 50 years (e.g., consumption increases 2 percent per year while yields increase 1 percent per year),[21] the amount of land available for energy plantations would decrease by 700 Mha and the energy production potential would be 0-50 EJ/y. If crop yields increase 1 percent per year faster than consumption, an additional 500 Mha would be available and the energy production potential would be 200-300 EJ/y. Including wastes, commercial biomass could supply 50-400 EJ/y by 2050. For comparison, scenarios developed by Nakićenović et al (2000) assume that modern biofuels would supply 50–120 EJ/y in 2050 and 160–300 EJ/y in 2100.

A major uncertainty is whether very large quantities of biomass can be grown and harvested in a sustainable and environmentally acceptable manner. There is no question that this could be done in principle, but whether it can be accomplished in practice

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[20] The USDA has projected that world population will increase 30-100 percent by 2050 and per-capita consumption of cereals will increase 20-40 percent as diets improve and meat consumption rises. At per-capita incomes below $10,000/y, per-capita grain utilization has increased by about 90 kg/y for each doubling of per-capita GDP (USDA, 2003). Per-capita GDP is expected to grow at a rate of 1-2 percent per year from 2000 to 2050; per-capita grain utilization would therefore be expected to increase by 70-140 kg/y, or by a factor of 1.2 to 1.4.

[21] 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.

depends on a wide variety of economic, social, institutional factors. The history of agriculture, which has been characterized by widespread land abuse, is not encouraging. Furthermore, recent research into the causes of civil violence indicates that a world energy system based on large scale international trade in biomass fuels might be destabilizing for producing countries because primary commodity exports tend to create concentrated streams of income (this is discussed further below).

Biomass energy comes in many forms and is being pursued by many different groups. The US DOE is conducting several significant biomass initiatives. The Biochemical Engineering Research Group at the Oak Ridge National Laboratory is also conducting work in this area. ORNL maintains a list of biomass research initiatives and programs on the web at: http://bioenergy.ornl.gov/links.html

Solar Energy

Sunlight is the ultimate source of many of the forms of energy, including 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. In 2001 solar produced only about 9 TWh of electricity and perhaps 0.1 EJ of heat in solar thermal collectors—a tiny fraction of total world energy consumption.

The solar resource is huge. About 500,000 EJ falls on the continents each year. The resource is spread fairly uniformly, at least on an annual basis. Sunny areas, such as the southwestern United States or southern Spain, receive up to 9 $GJ/m^2 \cdot y$, while cloudy, northern areas, such as the northwestern United States or the United Kingdom, receive as little as about 4 $GJ/m^2 \cdot y$ (Boes et al, 1993, Everett, 1996).

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 (Brower, 1992). 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 1 percent of total U.S. energy demand in 2050.

Roof-mounted collectors can be used to heat air or water for residential or commercial use in existing buildings. In Israel and Cyprus, where fossil fuels are expensive but sunshine is plentiful, there is an average of roughly 1 m^2 of collector area per person, accounting for 10-15 percent of residential energy demand. Solar heat is expensive, however. Typical installed costs in Israel and Cyprus are \$350-400/m^2, equivalent to \$15-20/GJ of heat (ESIF, 1994). In the northeastern United States, where sunshine is less intense and labor costs are higher, solar heat would be twice as expensive. For comparison, the average U.S. residential price of natural gas has varied between \$5-10/GJ over the last decade. The economics of solar heat are even less favorable for industrial users, who require higher-temperature heat and who pay lower prices for conventional fuels. The potential for lowering the cost of solar heat is limited, because the technology is mature and uses common materials.

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 \$0.08-0.16/kWh (De Laquil et al, 1993). With additional improvements in efficiency and cost, solar thermal electric plants might possibly compete with new nuclear plants.

The solar technology with the greatest potential is photovoltaics, which convert sunlight directly into electricity. Photovoltaic cells require no focusing or tracking mechanisms (although these may be used), boilers, turbines, or cooling water; they generate no waste products, heat, or noise. Photovoltaics are highly reliable, have long lifetimes, and require 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.

The cost of photovoltaic modules has decreased tremendously, from \$100 per peak watt in 1975 to as low as \$4/W_p today for large purchases; the installed cost per peak watt of net AC output to the grid, including support structures, inverters, and so forth, is about \$6/W_p for large installations. An installed price of \$6/W_p corresponds to a cost of electricity of about \$0.2-0.5/kWh in high and low sun areas, respectively, which is far too expensive for widespread use. If installed prices fall to \$1/W_p, the cost of photovoltaic electricity would be \$0.04-0.1/kWh, depending on location, which could compete favorably with other sources of electricity. It will not be easy, however, to achieve such low costs. A cost of \$1/W_p corresponds to an installed price of \$50-100/m^2 for photovoltaic modules. The cost of the raw materials alone is unlikely to be less than \$30/m^2 (Kelly, 1993), and the price of installing common building materials, such as shingles or siding, is about \$30/m^2 (Consumer Reports, 1997).

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 40-200 percent. As mentioned above, the production of hydrogen is often mentioned as a means of storing and distributing solar energy, but solar electricity would have to be very inexpensive—less than \$0.02/kWh—for electrolytic hydrogen to be cheaper than hydrogen produced from the gasification of biomass or fossil fuels. 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 orbit around the earth, with the power transmitted in microwaves or lasers to fixed receiving antennae on earth. Because the orbital 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 average rate that it would at the sunniest locations on the earth’s surface. 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. Using current technology, launch costs alone would amount to \$100/W_p (Fetter, 2004). 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.

Research in solar energy is conducted, in one form or another, at virtually every major university in the country and in many private sector firms. The US Department of Energy has two major programs as part of its National Renewable Energy Laboratory: The Center for Buildings and Thermal Systems, and the National Center for Photovoltaics (NCPV).

Wind Energy

Wind power has been harnessed by humans for millennia, but only in the last decade has wind generated significant amounts of electricity. In 2004, wind produced about 50 TWh, mostly in Germany, Spain, the United States, Denmark, and India. Installed capacity increased from 1 GW_e in 1985 to 47 GW_e in 2004 (AWEA, 2005). The strong growth in wind power has been driven by subsidies and tax incentives, particularly in Europe.

Today, electricity is produced at a cost of \$0.05-0.08/kWh at sites with average wind power densities greater than 250 W/m^2 at a height of 10 m (EIA, 1997; Gipe, 1999). About 5 percent of the earth's land area has wind power densities this high; in theory, about 160,000 TWh/y (1400 EJ_p/y) could be generated with wind machines distributed over this area. Advances in technology might make it possible to generate electricity economically at off-shore sites or at sites with lower wind power densities. The use of sites with power densities between 150-250 W/m^2 would expand the production potential by a factor of three.

The amount of wind electricity 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, wind's contribution to regional electricity supply would be limited to perhaps 20 percent, unless large-scale energy storage or transmission is provided. Thus, the practical potential of wind electricity is about 12,000 TWh/y. A realistic upper limit for wind production in 2050 might be 4000 TWh/y (40 EJ_p/y)—roughly 10 percent projected world electricity production.

Although wind is unlikely to become a dominant energy source, it has the potential to contribute a substantial fraction to total energy demand. In the short term, at least, it is the most promising renewable electricity source.

The primary US government research entity in the area of wind power is the National Wind Technology Center at the DOE's National Renewable Energy Laboratory while Sandia National Laboratory also conducts significant research on wind power. As the market for commercial wind power equipment becomes increasingly developed and competitive, private sector research efforts are playing an increasing role as well. The state of California maintains a list of wind power links including both research facilities and commercial suppliers on the web at http://www.energy.ca.gov/links/wind.html.

Decarbonized Fossil Fuels

Recoverable, low-cost resources of conventional oil, gas, and coal are sufficient to meet world energy needs for at least another one hundred years. Moreover, enormous quantities of unconventional fossil fuels—methane hydrates, oil shales, and tar sands—could be extracted at higher prices or with improved technology. If one could safely and inexpensively "decarbonize" or remove and sequester the carbon contained in fossil fuels, they could continue to serve as a basis for world energy supply even while greenhouse gas concentrations are stabilized. If proven feasible and cost-effective, 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.

Capture

There are two main approaches for removing the carbon from fuels: post-combustion capture of CO_2, and chemical conversion of fossil fuels into hydrogen and CO_2. Capturing the CO_2 gas after combustion is practical only for large, centralized sources of CO_2, primarily coal-fired power plants. The technology for capturing CO_2 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 40-120 percent ($0.02-0.06/kWh), equivalent to $100-260 per ton of carbon emission avoided (Herzog, 1997; IEA, 1994; Herzog et al, 1997). 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 CO_2. 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 (Blok et al, 1997). 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, which are easier to transport and store than is hydrogen. The cost of such chemical conversions currently is very high, however—equivalent to $150-500 per ton of carbon emissions avoided.

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 CO_2 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 CO_2 is smaller because of the high concentration of CO_2 in the fuel gas. Even so, carbon-dioxide recovery is estimated to add $0.013-$0.026/kWh or 25-50 percent to the price of electricity, or $65-160 per ton of carbon emissions avoided (Herzog, 1998).

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 CO_2. 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. Such huge quantities of CO_2 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 (IEA, 1995a).

Oil and gas wells are probably the least expensive and the most reliable option for the storage of CO_2. Exploration and drilling costs would be low, and the prior existence of oil and gas deposits would ensure that CO_2 could be stored for millions of years if the original pressure of the reservoir is not exceeded. Total world capacity is estimated at 150-500 PgC, based on estimates of oil and gas resources. A small fraction of this storage potential (10-15 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 CO_2, which today is separated and vented to the atmosphere; injecting this CO_2 is an obvious application of sequestration. In 1996, Statoil of Norway began injecting CO_2 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, and the northeastern United States, where the cost to transport CO_2 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. Baring 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 to store CO_2 underground in deep saline aquifers. In the United States, for example, 65 percent of power-plant carbon emissions occurs close to deep aquifers (Bergman et al, 1996). Storage sites would be located at depths greater than 800 m, in order to maintain the CO_2 in a dense supercritical phase, and under an impermeable layer to prevent the escape of CO_2 or mixing with shallow aquifers used for drinking water or irrigation. The injected CO_2 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 PgC to more than nearly 3000 PgC (IEA, 1995b). The range is due partly to a lack of basic geological data, such as the volume, porosity, and permeability of aquifers, and partly to assumptions about how much CO_2 could be stored by unit volume and what types of aquifer structures would provide long-term storage.

It should be emphasized that carbon capture remains a highly speculative and unproven technology that could pose significant risks. In some cases the collected CO_2 would have to be transported or stored aboveground before being injected below. The transport and storage of CO_2 on land raises concerns about public safety and environment impacts from pipeline or well failures; however, it appears that these are likely to be no more difficult to address than those associated with the handling of natural gas. The most important challenge will be to ensure the permanence of CO_2 storage. At present the ability of underground storage to sequester CO_2 for many years is highly uncertain, and will have to be demonstrated before the technology can be deployed on a scale large enough to make a significant contribution to climate change mitigation. The prospect of a large-scale release of CO_2 into the atmosphere could be very dangerous, potentially leading to a sudden abrupt change in the global climate and, most importantly, to damage to human health and wildlife.

Another option is to inject CO_2 into the deep ocean. Since most of the CO_2 emitted into the atmosphere would dissolve in the ocean eventually, one could think of this as simply accelerating natural processes that would result from the burning of fossil fuels. The carbon sequestration potential of the oceans is huge—at least 1000 PgC. In contrast to underground aquifers, which can sequester carbon for millions of years, a significant fraction of the CO_2 injected into the deep ocean would return to the atmosphere over period of several hundred years.

The rate of return of CO_2 to the atmosphere would be determined primarily by depth of injection. At depths greater than 3700 m, the density of the CO_2 is greater than that of seawater and the CO_2 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 CO_2 would return to the atmosphere over a period of roughly 1000 years. Pipelines have not been laid at depths greater than 1000 m, 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. The fraction and rate of return can be significantly greater for CO_2 dispersed at depths of less than 2000 m, depending on ocean currents and topography near the point of injection, leading to higher atmospheric concentrations after 100 to 200 years. Careful site-specific studies would have to be completed to assure that the environmental benefits of reduced CO_2 concentrations would outweigh the costs and risks of ocean disposal.

As in the case of underground storage, the environmental impact of ocean disposal of CO_2 is highly 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 TgC/y (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 (Caulfield et al, 1997). Environmental effects can be minimized by injecting CO_2 at depths greater than 1000 m, since nearly all marine life is found above this level. The legal status of ocean disposal is also unclear. The 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.

The cost of disposal itself—that is, the cost of injecting CO_2 deep underground or into the ocean—is small compared to the costs of capture; estimates range from \$1-30/tC (Herzog et al, 1997; IEA, 1995b). More significant may be the cost of transportation to the disposal site. The most straightforward option is to transport the CO_2 via pipeline at high pressure as a liquid or supercritical fluid. For a large pipeline carrying 5-30 TgC/y (equivalent to the CO_2 emitted by 3 to 20 large coal-fired power plants), transport costs would be \$0.01-0.04/tC·km for either underground or ocean disposal (Skovholt, 1993; Summerfield et al, 1993; Hendriks, 1994). Transport and disposal by tanker is possible for ocean disposal, and may be cheaper at longer distances (Golumb, 1997). Depending on transport distance, total disposal costs would range from about \$10-60/tC.

Thus, the capture, transport, and disposal of hundreds of billions of tons of carbon is unlikely to be accomplished at an average cost of much less than \$100/tC, which 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.

The MIT Laboratory for Energy and the Environment's Carbon Management and Sequestration Program maintains a list of major sequestration research programs on the web at http://sequestration.mit.edu/links/index.html.

Carbon-Free Energy Sources: Summary

Only five energy sources are capable of providing a substantial fraction of the carbon-free energy required to stabilize greenhouse gas concentrations at an equivalent doubling: fission, biomass, solar, wind, and "decarbonized" fossil fuels. 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. Table 1 summarizes the situation.

Unfortunately, each of the five major alternatives currently has significant technical, economic, and/or environmental handicaps. Fission, which is the only one deployed on a large scale today, suffers from public-acceptance problems related to the risks of accidents, waste disposal, and the spread of nuclear weapons. Biomass has the potential to supply low-cost portable fuels, but large-scale use of energy crops could compete with food production and the preservation of natural ecosystems. Solar is benign but very expensive, and would require massive energy storage or intercontinental transmission to supply a large fraction of world energy. Wind is economically competitive in some areas today, but most of the resource is far from cities and would, like solar, require expensive storage or long-distance transmission to achieve a large fraction of the energy market. Fossil fuels are cheap and abundant, but the cost of capturing, transporting, and disposing of the CO_2 could be high and the environmental impacts are largely unknown. A broad-based program of energy research and development is needed to address these concerns, and to ensure that abundant, affordable, and acceptable substitutes for traditional fossil fuels will be available worldwide in the coming decades (PCAST, 1997).

Table 1. Current and potential contributions of carbon-free energy supply

	Primary Energy Production (EJ_p/y)			
Energy Source	2001	Potential by 2050	Long-term Potential	Natural flow or resource (EJ_p)
Hydroelectric	28	40–60	60–100	400/y
Geothermal	0.7	5–10	5–20	10,000,000
Ocean	0.006	0–1	1–5	2,000,000/y
Nuclear fusion	0	0	?	4,000,000,000+
Nuclear fission	28	70–220	500+	10,000,000
Biomass	4[*]	50–150	50–500	2,000/y
Solar	0.2	50–150	500+	3,000,000/y
Wind	0.6	20–50	100–250	40,000/y
Decarbonized fossil	0	150+	500+	250,000

[*] Commercial biomass only; traditional biomass is variously estimated at 15–65 EJ/y.

In short, addressing the climate change problem will require a mix of approaches. Stabilization of greenhouse emissions at an equivalent doubling will require 300 to 900 EJ/y of carbon-free energy by 2050. Given the technical, economic, and political barriers associated with each of the available energy supply options, no single source will be capable of meeting the global energy needs of the future. Any combination of taxes, technology developments, and other policy tools will have significant economic and social impacts in developing countries, which will need to be taken into account. In addition, given the future availability of other energy sources and the expected degree of technological development, stabilization of greenhouse gas emissions will almost certainly require that nuclear power be a part of the solution. This would in turn entail a major increase in nuclear power generation worldwide well above the current (in 2001) level of 28 EJ_p/y, a development that would present its own set of global environmental and security challenges.

III. The Relationship between Climate Change, Greenhouse Gas Emissions Mitigation, and Global Security

The previous discussion surveyed the need for carbon-free energy sources and the technologies available for meeting that need. Only one of these technologies—nuclear fission—has direct and relatively well understood security implications. These relate to the proliferation of nuclear weapons, and are discussed below. What has yet to be recognized or addressed in detail, however, are the various indirect and less well-understood security implications relating to both climate change and efforts to mitigate climate change, regardless of the specific approaches and technologies employed. These stem primarily from the impact that climate change and its mitigation are likely to have on the economic development of less developed nations.

The Link between Equitable Development and Civil Conflict

The IPCC reference scenarios all make the optimistic assumption that economic development will raise living standards in the poorest parts of the world until they eventually converge with those in the developed world. Unfortunately, convincing evidence to suggest that such a convergence is in fact occurring is lacking; rather, the gap has increased. According to the United Nations Development Programme, between 1970 and 1990, the ratio of the incomes of the wealthiest fifth of the world's population to the poorest fifth increased from 32 to 60. If current trends continue, the disparity is projected to increase to more than 100 by 2025 and to nearly 200 by 2050 (Hammond, 1998). This is hardly a reason to dismiss concerns about global warming, however, in part because the overall global economic growth rate is in line with IPCC projections even though the distribution of benefits is not, and in part because actual improvements in energy efficiency have been falling short of IPCC projections. Rather, it is an indication that the energy problem must be addressed in the context of another equally challenging security problem, because the control of civil violence and associated terrorism will ultimately require more equitable development patterns than have occurred over the past several decades.

Developing countries are more vulnerable than industrialized countries to the impacts of climate change for several reasons (Moss et al, 2001). Their economies are generally less diversified, leaving them fewer options for adaptation. They more often depend on primary agricultural products while being located in warm regions which stand to loose the most in agricultural terms from climate change. Furthermore, people in these countries tend to live more traditional lifestyles, which are more closely tied to their particular environment than do people in industrialized countries. These and other factors place the populations of developing countries in a position to be dangerously vulnerable to the impacts of even modest changes in climate (McCarthy et al, 2001). The same can generally be said for the poorest people within nations, be they industrialized or developing.

Failure to control climate change would significantly worsen environmental causes of conflict, such as shortages of natural resources (fresh water, arable land, etc.). For example, Thomas Homer-Dixon has identified a number of potential causal paths by which environmental change in developing countries may lead to conflict, including reduced agricultural production, economic decline, population displacement, and disruption of accepted social relations. These links can be shaped by variables such as regime repressiveness, perceived regime legitimacy, and political relations between key actors and coalitions (Homer-Dixon, 1991).

Though the relationship between development inequality and conflict is undoubtedly a complex one, recent studies tend to support the idea that weak states composed primarily of impoverished people are not simply a moral problem for a powerful nation like the United States, but also a security problem. This is especially true in the increasingly interconnected world of the 21st century, where terrorism and other asymmetric threats have replaced the interstate conflicts that characterized security concerns throughout the 20th century.

Intuitively, there is good reason to assume a connection between poverty and scarcity on the one hand, and civil conflict and violence on the other. This would appear to be a realistic assumption regardless of whether the conditions in question consist of absolute poverty (incomes below levels required for subsistence) or relative poverty (the perception of inequality irrespective of income). The existence of widespread hunger and desperation or resentment and frustration among populations appears likely to increase competition for scarce resources, to exacerbate existing social, ethnic, racial, and religious tensions, to encourage political and social movements to utilize and foster such tensions to mobilize supporters, and, ultimately, to lead to violence. Demonstrating this relationship and establishing causal linkages has proven a challenging task for scholars, however. The implications of unequal economic development for security are complex (Steinbruner and Forrester, 2003). Quantitative research in this area by the State Failure Task Force based at the University of Maryland Center for International Development and Conflict Management indicates that over the past 50 years the outbreak of conflict has been associated with low levels of openness to trade, high infant mortality, and low levels of democracy (Goldstone et al, 2000; Gurr et al, 2001). In a related result, it also appears that conflict is often associated with poor economic performance (Collier et al, 2002).

Other quantitative work conducted by Paul Collier and others at the World Bank has pointed to a strong link between conflict and dependence on primary commodity exports (Collier, 2000, Collier et al, 2001). This line of thought has come to be known as the “greed” theory of conflict, as distinguished from more traditional “grievance” theories. The idea here is that conflict can be thought of as a form of business which can be expected to flourish in cases where there are commodity export streams to hijack and other forms of productive economic activity are scarce.

James Fearon and David Laitin of Stanford University have lent further credence to this general approach. They have found that the apparent influence of varying levels of democracy on the incidence of conflict disappear when differences in state strength, economic development and economic growth are taken into account (Fearon et al, 2003). Work by Nicholas Sambanis indicates that greed and grievance both play major roles in the development of conflict and that a proper understanding requires appropriate categorization of conflicts according to their origin in ethnicity or economics (Sambanis, 2001; Sambanis, 2003).

Contemporary quantitative studies such as these can be combined to produce a rough profile of the factors that are conducive to civil conflict (Jones, 2004). Agreed risk factors include a history of conflict, a low level of economic development, being the homeland for ethnic diasporas, a small population, a thinly dispersed population, and a weak central government. Factors which seem to be consistently relevant, but which work in more complex ways include democratic governance, abundance of natural resources, economic inequality, and divided ethnicity.

In a less quantitative vein, work by Carol Graham on the relationship between economic performance and subjective well-being also has implications here (Graham et al, 2001). Graham has found that people's satisfaction with their economic lot depends more on their performance relative to their perceived comparison group than it does with their absolute level of income. While rapid economic growth can go some way toward offsetting the dissatisfaction engendered by radical inequality, people in high growth economies are particularly frustrated when this growth slows. In a highly connected world where the comparison group for the average person in the developing world comes to include members of the industrialized world, and where economic growth needs to be tempered by the need to maintain a livable atmosphere, these feelings of frustration must be anticipated and taken seriously.

Finally, Amy Chua provides a relevant way of thinking about economic change, political change, and the emergence of violence (Chua, 2003). Chua documents a series of cases where economic liberalization has collided with democratization to create an environment conducive to violence. She observes that unrestrained capitalism has, in many cases, concentrated economic power in the hands of an ethnic minority. Examples include ethnic Chinese in Southeast Asia, people of European decent in Latin America, and Indians in East Africa. These groups tend to become targets of resentment on the part of the broader population. In this environment, Chua observes that the introduction of democratic rule empowers this broader population leading to potentially deadly conflict between the economic and political power centers. She notes the emergence of Milosovic in Serbia, Mugabe in Zimbabwe, and the Hutu leadership in Rwanda as examples of this dynamic. She also analyzes the terrorist threat against the United States in these terms, casting the US in the role of the economically dominant ethnic minority and modern communications technology as the democratizing force that is empowering the resentful masses.

The Need for Equitable Mitigation Strategies

If not implemented with care, the measures employed to address the global climate change problem could have significant negative impacts on incomes and contribute to social tensions that may lead to violence. For example, efforts to decrease the use of fossil fuels or increase the use of higher-cost renewable sources could raise electricity prices and slow the expansion of electricity supply. Actions to address climate change could produce broader societal changes as well. Chua's research implies the potential for violence that could result if a change in fuel consumption patterns or prices were to alter economic relations between an ethnic minority and the rest of society. In addition, in countries where low-carbon energy resources are found in areas that are poor or populated by distinct ethnic or social groups, national efforts to develop these resources could galvanize opposition to such development or lead to charges of inequitable distribution of benefits. This could in turn worsen conflicts between central governments and local ones or indigenous peoples. Such potential can be seen in the case of the Indonesian province of Aceh on the island of Sumatra, where exploitation of the region's rich oil and natural gas deposits has figured prominently in the conflict between the government and the local separatist movement.

The work by Collier et al also has particularly disturbing implications for a future world where much of the industrialized world's energy needs are met with fuels derived from biomass. The plants required to produce this fuel would most likely be grown in tropical nations where growing seasons are long, water is plentiful, and land prices are low. In such a scenario, grower countries would be made even more dependent on primary agricultural exports, along with the concentrated streams of income and conflicts that they tend to produce.

According to most studies, mitigation policies such as carbon taxes and other measures that increase the cost of energy are also likely to impose proportionally greater burdens on poorer households (Symons et al, 1994; O'Donoghue, 1997; Brendemoen et al, 1994; Cornwell et al, 1996; Aasness et al, 1996; Harrison et al, 1999; Barker et al, 1998). These studies show that revenue recycling can be effectively used to eliminate the regressive nature of such taxes. While redistributive mechanisms exist within states, though, it would be more challenging to design international protections against the regressive effects of policies that raise energy prices on the global market.

Constructive Opportunities for International Cooperation

In the climate change debate, it is generally recognized that to be widely acceptable and effective, mitigation measures must also be basically fair. Most of the additional CO_2 currently circulating in the atmosphere originated in industrialized countries that have used the energy derived from its production to build wealthy, flexible economies. Less developed countries are understandably hesitant to commit to restrictions on their emissions of CO_2 until they have reached a similar level of development. It is clear that the climate will not support the kind of emissions that would be associated with the full industrialization of the 80 percent of the world's population currently living in non-OECD countries.

As noted in the introduction, raising global living standards to a more equitable level would most likely require a threefold increase in global energy production over the next fifty years. Under business-as-usual conditions, such an increase would necessarily entail a huge increase in global CO_2 emission levels, even under an optimistic assumption of future declines in carbon intensity. Without a corresponding commitment to dramatically reduce the use of fossil fuels, a global poverty amelioration effort would thus greatly exacerbate the climate change problem. The resulting climate-related impacts would then likely feed back on the entire effort, providing incentives for renewed conflict and violence and in time diminishing or even eliminating the impact of the original antipoverty program. At the same time, however, global policies that deny the right to equal development are bound to breed resentment and discord.

To address this concern, policies will need to be designed to provide opportunities for sustainable development on the part of poorer nations without breaking the global carbon budget. The 1998 UNDP *Human Development Report* stated, “Poor countries need to accelerate their consumption growth – but they need not follow the path taken by the rich and high-growth economies over the past half century.” (UNDP, 1998) However, the responsibility for making such alternative growth paths feasible and attractive may well lie equally with industrialized and developing nations. Equity concerns such as these are increasingly being integrated into the analyses of the climate change problem (Ramakrishna, 1992; Shue, 1995; Mintzer and Leonard, 1994; Munasinghe, 2000; Lipietz, 1995; Rowlands, 1995; Runnalls, 1997; Jamieson, 2000; Murthy et al., 1997; Rajan, 1997; Schelling, 1997; Byrne et al., 1998; Najam and Sagar, 1998; Parikh and Parikh, 1998; Tolba, 1998; Agarwal et al., 2000). The likely impact of these concerns on the formation of more and less effective control regimes has also received considerable study. There exists an extensive literature in this area from both economic and political science perspectives. This literature has been reviewed in some detail by the IPCC (Metz et al, 2001, pp 620-630).

Policies which promote technology transfer between nations can help offset the regressive aspects of mitigation policies, while bringing other types of benefits. Policy impacts on technology development and transfer is treated in considerable depth in the IPCC Special Report on Technology Transfer (IPCC, 2000). The Special Report also provides a major review of work relating to the potential for technology transfer to ease the adoption of clean technologies.

Technology transfer can lower the costs of transition to less carbon intensive technology in at least two major ways. First, clean technology transferred at low or no cost can allow developing countries to make use of this technology without the prohibitively high levels of investment which would be required to develop the technology indigenously or to import the technology under normal market conditions.

Second, market and infrastructure conditions may make a low-carbon technology cost effective in the developing world before it is cost effective in the industrialized world. Photovoltaic panels, for example, are currently cost effective for some applications in places that do not have access to grid-based power systems. However, electricity from photovoltaics is still relatively far from being competitive with grid based power. Bringing such technologies to market in places where power needs are modest and existing infrastructure is limited offers the possibility of creating mass markets for these technologies. The cost reductions associated with mass markets may then drive the cost of the technology down to the point where it is competitive in the industrialized world as well.

In recent years, technological learning curves have emerged as a promising area of research with respect to the nature of technology development and adoption. The basic empirical insight here is that the price of a new technology tends to fall as a function of past production of that technology. The decrease is generally exponential, asymptotically approaching a mature level. This approach produces a certain degree of predictability in prices and can be used to justify policy based expenditures on technology which is not yet competitive in an effort to drive the price down to a level competitive with existing technologies. It also implies that technology portfolio decisions can be persistent: a decision to invest in one technology may drive its cost down to the point where it is no longer cost effective to develop an alternative technology.

This approach has recently been used in various integrated assessment models of climate change (van der Zwaan et al, 2002) leading to significant insights regarding policy choices relative to technological change. Notable examples include MESSAGE (Messner, 1997), MARKAL (Seebregts, 2000), ERIS (Kyperos 2000), Goulder and Mathai (1998), Goulder and Schneider (1999) and DEMETER (van der Zwaan, 2002).

This discussion indicates the fine balance that must be maintained if the world is to address successfully the twin problems of armed conflict and global climate change. Both represent important and serious challenges to future global security that must be confronted; at the same time, however, an intensive effort to address either problem in isolation can make the other worse. There is thus a strong case to be made for a global recognition of the interdependence of both issues, and for tackling them simultaneously and with complementary measures and approaches.

Climate change mitigation is one among many indirect factors that can influence the potential for civil conflict. The empirical studies provide a useful starting point for analysis, but significant work needs to be done to provide a workable framework for predicting the impact of energy policy decisions on civil conflicts. This could then be integrated with an expanded analysis of the implications of poverty reduction for fossil fuel consumption and global climate change.

International Management of Nuclear Energy

It will clearly be easier to meet global energy demands while reducing future greenhouse gas emissions to an acceptable level if one component of the strategy involves a significant expansion of nuclear power. However, because nuclear facilities, technologies and materials can also be used to build nuclear weapons, expanding the use of nuclear energy substantially -- particularly in non-nuclear weapon states -- would require unprecedented forms of international cooperation to make sure that the proliferation risks do not outweigh the benefits.

As noted earlier, nuclear power is the most mature of the carbon-free technologies and is the only one currently deployed on a significant scale. While each of the other technologies show promise, they are all highly speculative at this time, and it would be unwise to count on enough expansion in each area that a significant increase in nuclear power would not be needed to stabilize greenhouse emissions at an equivalent doubling by 2050. Even if an optimistic assumption of sustainable source biomass energy production is made (e.g., on the order of 100 EJ/y), another 200 to 800 EJ/y would need to be provided by the remaining carbon-free sources likely to be available. Solar and wind power currently account for less than 1 EJ/y. The role of decarbonized fossil fuels with CO_2 disposal is also highly uncertain, and as their development will require advances in technology and reductions in cost they cannot be depended upon to provide a large share of the future energy supply.

Nuclear power also has significant advantages over other carbon-free energy sources. Nuclear power plants can be situated almost anywhere, unlike solar, wind, and fossil fuel plants with CO_2 disposal, which would only be available in countries and areas with these resources. In addition, only a portion of such resources will be located in areas where construction of electricity transmission is feasible and affordable. There is also an important qualitative difference between the operation of nuclear plants and renewables: the former can provide reliable "baseload" power during most hours throughout the year on a scale sufficient to replace fossil-fired electricity, while the latter provide only intermittent power and could not supply more than about 10 percent of electricity supply without large-scale energy storage or intercontinental electricity transmission, neither of which is affordable using current technologies.

If one contemplates an expanded role for nuclear energy, then one would want nuclear energy to make enough of a contribution to the global warming problem to outweigh the risks. For example, one study proposes as an analytical benchmark an eight-fold increase in global nuclear capacity (to 3,000 GW) by 2075 (Feiveson, 2004). Using the middle range of the estimates given in Table 1 of the various technology's potential contributions by 2050 suggests that an even more rapid increase in global nuclear capacity might be needed. If 600 EJ/y of carbon-free energy is needed by 2050, if 150 EJ/y is assumed to come from decarbonized fossil fuel and 250 EJ/y is assumed to be the combined contribution of biomass, solar, and wind technologies, then the remaining 200 EJ/y would need to come from nuclear fission. Providing this energy would require a total nuclear capacity of about 2,500 GW.

Barring major and unanticipated leaps in energy production methods and technologies, a future low-carbon global energy system will thus be one in which nuclear power expands significantly above current levels. The number of countries reliant on nuclear power will increase as well, especially fast-growing countries that currently depend upon fossil fuels to meet much of their energy needs. Whereas countries with current nuclear power programs either already have nuclear weapons or are industrialized democracies with a strong commitment to nonproliferation, the countries whose future energy needs are growing most rapidly are a much more diverse group. China and India are expected to greatly increase their nuclear energy use. This option may also become attractive for other countries with rapidly growing populations that currently use little or no nuclear power, including Indonesia and Pakistan. Such a large, rapid, and diverse global expansion would heighten concerns about accidents, materials management, and secure waste disposal. There would need to be a much more open international discussion about best practices for handling these problems, as well as a concerted effort to develop and exchange inherently safer nuclear technologies that could keep the risk of accidents as low as it is today even with an eight-fold increase in nuclear power production.

A major increase in nuclear power use would also exacerbate concerns about proliferation. If nuclear power grows substantially, recycle may become necessary or economically attractive. In this case, additional technical and institutional barriers would be needed to prevent, deter, or 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; and fuel cycles that minimize the production of high-quality plutonium, such as the thorium fuel cycle (Galperin et al, 1997; Kasten, 1998).

The Role of Internationalization

The Non-Proliferation Treaty (NPT) and the IAEA safeguards system is the basis of the current international regime for preventing the spread of nuclear weapons while guaranteeing member states the right to use nuclear technology for peaceful purposes. The NPT has been highly successful overall: nearly all states with any type of nuclear program have joined, so that "essentially all nuclear facilities in nonnuclear countries … are under IAEA safeguards" (Feiveson, 2004). However, the NPT does have limitations. Three key states with nuclear programs (India, Pakistan and Israel) are not parties to the treaty, while another (North Korea) withdrew in 2003. Nuclear weapon states parties to the NPT are not required to have any IAEA safeguards on their civilian or military nuclear programs. Both the Iraqi nuclear program before 1991 and the more recent experience in North Korea demonstrate that IAEA safeguards are not always sufficient to prevent countries from embarking on programs of nuclear weapons research and development, and that some governments can (for a time at least) evade the scrutiny of the IAEA.

In response to the Iraqi experience, the IAEA strengthened the safeguards by deciding to use more vigorously the investigative powers that it already had under the existing safeguards system (INFCIRC/153) and by developing an additional protocol (INFCIRC/540) that increased reporting requirements and access for IAEA inspectors (Scheinman, 2005). Key countries with nuclear power ambitions have yet to adopt this voluntary additional protocol, however; as of March 1, 2005 about half of the NPT signatories had signed an additional protocol agreement but only about a third of NPT signatories had agreements that had entered into force.

The IAEA safeguards budget has been chronically underfunded. For nearly twenty years until 2003, member states imposed a "zero-real-growth" budgetary policy on the IAEA, so funding remained essentially flat even as the amount of material to be safeguarded increased dramatically (doubling in one six-year period), the range of relevant technologies expanded, and the safeguards process grew more stringent. A significant increase in nuclear energy use would require a corresponding international commitment to fully fund the safeguards system and would intensify internal debates about the efficient, effective, and equitable allocation of resources, especially as the group of countries with major nuclear programs grows more diverse.

Under the NPT's guarantee of access to peaceful nuclear technology, non-nuclear-weapon states are permitted to own and operate declared facilities capable of producing plutonium and HEU, and can produce, stockpile, and use these materials so long as they are under IAEA safeguards. Critics are concerned that 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 fuel-fabrication plants. In response, President Bush has proposed a fundamental change in NPT bargain, such that states which do not already possess full-scale, functioning enrichment and reprocessing plants would no longer be able to buy them, but would instead be promised reliable access at reasonable cost to fuel for their civilian reactors (Bush, 2004). This approach would make the global nuclear control regime even more discriminatory than it already is, and thus is unlikely to be acceptable, especially at a time when many of the non-nuclear weapon states do not believe that the nuclear weapon states are fulfilling their Article VI disarmament commitments.[22]

The Director General of the IAEA has proposed an alternative approach that would reduce proliferation risks while expanding access to peaceful nuclear technology and creating a more equitable system overall. The proposal builds on the NPT and IAEA safeguards system, but adds several new elements. It would restrict all processing of weapon-usable materials (separated plutonium and high enriched uranium) to facilities under multinational control. It proposes that all nuclear energy systems should be proliferation-resistant by design, including the accelerated conversion of all HEU reactors to LEU reactors. It advocates consideration of multilateral arrangements for the management and disposal of spent fuel and radioactive waste. It stresses the need for all countries to end the production of fissile material for nuclear weapons and to make further progress on nuclear arms reductions. Incentives for proliferation would be reduced through an inclusive effort to address all countries' security concerns by developing a new collective security system that does not depend on nuclear weapons or deterrence. Once in force, this new framework would be a "peremptory norm" of international law without a right of withdrawal (ElBaradei, 2003).

As a first step toward working out the practical details of this vision, an Expert Group has reviewed various multilateral approaches to the nuclear fuel cycle (IAEA Expert Group, 2005). This group notes that the civilian nuclear industry may soon begin a worldwide expansion due to the growing global demand for electricity; concerns about price, supply, and pollution associated with traditional fuels; and the challenge of global warming — but they make no assumptions about how large or rapid the expansion of nuclear energy use might be. They assess a range of near-term multilateral options for uranium enrichment, spent fuel reprocessing, and spent fuel disposal in terms of their ability to simultaneously provide "assurance of nonproliferation" and "assurance of supply and services." They recommend ways to make multilateral options more attractive than purely national options, but argue that multilateral management of sensitive fuel cycle activities could not be made mandatory for NPT members in good standing without changing Article IV of the treaty. Such a fundamental change would only be possible in the context of a broader negotiating framework, such as the vision outlined by Director General ElBaradei.

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[22] The British have advanced a more modest version of this proposal in which states which violate their safeguards obligations would have their fuel cycle rights rescinded (Wolfsthal, 2004). If this was seen as a purely punitive way to deny non-compliant states access to nuclear technology, it would have only limited effect on the larger problem. If, on the other hand, states such as North Korea and Iran were allowed to have nuclear fuel cycle capabilities under tight international control, it might set a useful precedent and provide practical experience with multilateral options.

Using a nuclear-intensive approach to satisfy energy demands for equitable economic development while stabilizing greenhouse gas concentrations at an equivalent doubling would likely involve a much more rapid and extensive expansion of civilian nuclear programs than the IAEA experts group had in mind. A novel approach to integrated international control of the entire fuel cycle would involve the centralization of all sensitive nuclear facilities in a few heavily guarded "energy parks," preferably under international control. Electricity could be sent out directly from the parks. Alternatively, long-life reactor cores could be sealed and exported to far-away users who would plug them into their electrical generation system, operate them for 15-20 years, then return the sealed core with the spent fuel to a central international repository (Feiveson, 2004).[23] There would be a number of difficult technical, institutional, and political problems involved in any approach that is so different from current practice. Given the magnitude of the global warming problem, though, a serious effort should be made not only to assess incremental expansion of existing arrangements but also to think creatively about the new reactor designs and novel institutional arrangements that would be maximally proliferation-resistant even in a world where nuclear power contributed fifty-percent of more of world energy supply.

IV. Conclusion

At the moment human societies are tolerating the risk of catastrophic climate change. Actions being taken under the Kyoto protocol will not be sufficient to meet the standard of prudent protection most reasonably derived from the IPCC assessment. That course of action is clearly a judgment made by default, however, rather than by considered consensus. It seems evident that the circumstances described by the IPCC will eventually compel yet more extensive deliberation yet broader in scope than they were mandated to undertake. It seems particularly evident that the security implications of the problem will have to be more systematically explored and that substantial reconceptualization can be expected to emerge from that effort.

In principle the magnitude of risk associated with climate change might rival or exceed that of any form of warfare. That fact is not currently considered to be a strategic risk in that malign intent, the traditional preoccupation of security policy, is generally not attributed to the dynamics of nature. There are many reasons to believe, however, that the threat of dangerous processes as distinct from calculating enemies is likely to emerge under the circumstances of globalization as a more compelling concern of security policy. If so, then risk of catastrophic climate change is likely to become a leading instance and the implications for prevailing security policy outlined above will have to be examined in serious detail.

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[23] The author notes that although preferred, international control of energy parks is not essential. Encouragement of energy parks would presumably reduce the potential for diversion of materials and facilitate IAEA monitoring even if they remained under national control.

As noted, the situation offers constructive opportunity as well as looming danger. The massive and relatively rapid transformation of global energy production and usage required to meet a much higher standard of environmental protection is apparently feasible in technical and financial terms. The major impediments have to do with prevailing attitudes, the concepts of interest derived from them and the various institutions organized to pursue those interests. As everyone can readily recognize, those are formidable barriers indeed, but they are not implacably rooted in the physics or in the economics of the problem. What we do understand about the physics of the problem in the broadest sense of that term suggests that prevailing human attitudes and institutions will be compelled by circumstance to undertake far more extensive adjustment than is currently considered practical. Fortunately, and perhaps ironically, as best it can be anticipated most of that adjustment is likely itself to be constructive in character. Basically it requires intimate collaboration rather than belligerent confrontation across all the many divisions of jurisdiction and culture that currently dominate relevant policies.

Whether engagement with the problem proves to be constructive or otherwise, however, it will certainly be important. One can argue that all existing institutions that have any applicable capability have an obligation to bring it to bear. Certainly those that aspire to think should begin to do so.

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