Full title: Decarbonizing the Global Energy System

Author: Steve Fetter
School of Public Affairs
University of Maryland
College Park, MD 20742-1821 USA
sfetter@wam.umd.edu
301-405-6355; FAX: 301-403-8107

Key words: Climate change, nuclear energy, renewable energy, carbon sequestration

Running title: Decarbonizing the Energy System

Abstract To stabilize greenhouse gas concentrations at an equivalent doubling, CO_2 emissions must be limited to 5 PgC y^{-1} in 2050, compared to 8 PgC y^{-1} today. This will require the decarbonization of world energy supply, in which fossil fuels, which today account for 85% of energy supply, are replaced by carbon-free sources. Only five sources are capable of supplying a substantial fraction of the required carbon-free supply: biomass, fission, solar, wind, and decarbonized fossil fuels. Other sources are either too limited, too expensive, or too unproven to make a substantial contribution by 2050. Each of the major alternatives has significant economic, technical, or environmental handicaps. Biomass can supply affordable portable fuels, but would require vast areas of land, in competition with agriculture and natural ecosystems. Fission is a mature technology, but suffers from public-acceptance problems related to the risks of accidents, waste disposal, and proliferation. Solar is environmentally benign but expensive and would require massive storage or transmission. Wind is economically competitive at windy sites, but attractive sites are limited. Fossil fuels are cheap and abundant, but the cost of CO_2 capture and disposal may be high and the environmental impacts unknown.

CONTENTS

INTRODUCTION

In response to concerns that increasing concentrations of greenhouse gases—in particular, CO_2—might lead to harmful changes in climate, the Framework Convention on Climate Change was negotiated in Rio de Janeiro in 1992. The objective of the Convention, 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" (1). Although the Convention established stabilization as a goal, the "level that would prevent dangerous anthropogenic interference" remains undefined.

Most studies of climate change and its impacts focus on a doubling of the CO_2 concentration from the pre-industrial level of 275 ppmv to 550 ppmv. According to the Intergovernmental Panel on Climate Change, the scientific body established to advise parties to the Convention on such matters, a doubling would, over the long term, increase the global-average surface air temperature by 1.5 to 4.5 °C, with a best estimate of 2.5 °C (2). 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 (3, 4).

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 of the CO_2 concentration should guide global limitation and reduction efforts (5).[1] Although this is reasonable based on current estimates of climate change and its impacts, stabilization below an equivalent doubling would require reductions in emissions far beyond existing commitments or proposals. In particular, it would require a fundamental transformation or "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. Here I review the scale and the timing of this transformation and prospects for various carbon-free energy sources.

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 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

---

[1] 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.

concentration. Since a doubling of the CO_2 concentration produces a radiative forcing[2] of 4.4 W m^{-2}, an equivalent doubling is any combination of gases that produces a combined radiative forcing of 4.4 W m^{-2}.

Greenhouse gases other than CO_2 include methane, nitrous oxide, and halocarbons.[3] Anthropogenic emissions of methane and nitrous oxide are due primarily to agricultural and waste-disposal activities. Strategies exist for controlling these emissions (6, 7), but it is unlikely that global emissions can be reduced significantly taking into consideration expected increases in population and per-capita consumption. Moreover, natural emissions of these gases may increase as a result of climate change (8, 9). If rates of emission of methane and nitrous oxide remain constant at today's levels, the combined radiative forcing of these gases would increase from 0.65 W m^{-2} today to about 1.0 W m^{-2} (10). Although emissions of many halocarbons will be phased out in accord with the Montreal Protocol and its Amendments, substitute compounds are greenhouse gases. Scenarios developed by the IPCC result in a radiative forcing of 0.3 to 0.4 W m^{-2} for halocarbons in 2100, compared to about 0.3 W m^{-2} today (10). Gasses other than CO_2 are therefore likely to contribute a combined long-term radiative forcing of about 1.3 W m^{-2}. For stabilization at an equivalent doubling, CO_2 would be limited to a forcing of 3.1 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 5–6 PgC y^{-1} by 2050 and about 3 PgC y^{-1} by 2100 (10–12). The rate at which stabilization is achieved has little effect on this result. This includes emissions from all anthropogenic sources, not just fossil-fuel burning. In 1996, cement manufacture released 0.2 PgC y^{-1} (17); this can be expected to increase to about 0.5 PgC y^{-1} by 2050.[5] Schimel et al (10) assume that land use

---

[2] "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 4.4 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.

[3] Aerosols can be ignored in this context. Although aerosols may have a significant cooling effect that partially offsets the warming due to greenhouse gases, their residence times in the atmosphere are very short compared to greenhouse gases (days versus decades). Thus, unlike greenhouse gases, any effect of aerosols 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 (and the associated cooling effect) while having little effect on CO_2 concentrations for many decades. Moreover, efforts to control air pollution and acid deposition will lead to reductions in aerosol emissions independent of reductions in coal burning as pollution-control technologies diffuse to developing countries.

[4] The radiative forcing, ΔF, associated with a CO_2 concentration C is given by $\Delta F = 6.3 \log_e(C/C_0)$ W m^{-2}, where C_0 is the preindustrial concentration (275 ppmv). The concentration that produces a forcing of 3.1 W m^{-2} is given by $C = 275\ e^{3.1/6.3} =$ 450 ppmv. The uncertainty in these estimates is on the order of ±0.4 W m^{-2} or ± 30 ppmv.

[5] Per-capita cement production increased at an average rate of 3.5% y^{-1} over the last 50 years and 2% y^{-1} over the last 25 years (17). Even if per-capita production grows at only 1% y^{-1} over the next half century, total emissions (calcination only) would reach 0.5 PgC y^{-1} by 2050.

changes resulted in net average emissions of 1.1 ± 0.7 PgC y^{-1} during the 1980s, but a more recent evaluation by Houghton (13) gives net emissions of 2.0 ± 0.8 PgC y^{-1} over the same period. Future emissions are a matter of speculation; values in the literature range from a net release of over 2 PgC y^{-1} to a net uptake of over 2 PgC y^{-1} in 2050, depending rates of deforestation and reforestation and the carbon content of vegetation (14, 15).[6] Changes in climate might cause large releases of carbon during the next century if mature forests die before they are replaced by new forests, if higher temperatures promote the decay of dead organic materials at high latitudes, or if drier conditions increase the frequency of forest fire. For an equivalent doubling, it is estimated that such processes could produce net emissions of 0.1–3.4 PgC y^{-1} during the next century (8, 9, 16).[7] For simplicity I will assume that, in the context of stabilization at an equivalent doubling, net emissions from land-use change and climate change will be roughly zero by 2050, but with a large uncertainty.

Thus, in order to stabilize greenhouse gas concentrations at an equivalent doubling, fossil-fuel carbon emissions must be limited to 5 ± 2 PgC y^{-1} in 2050 and 2.5 ± 1 PgC y^{-1} in 2100, equivalent to an energy consumption of about 300 ± 120 and 150 ± 60 EJ y^{-1}, respectively.[8] For comparison, 1997–98 fossil-fuel carbon emissions and energy consumption were 6.4 PgC y^{-1} and 340 EJ y^{-1}, respectively (17, 18). Fossil-fuel combustion can continue to increase for another decade or two, but after that point it must begin a long and steady decline.

REQUIREMENTS FOR CARBON-FREE ENERGY

World energy consumption is expected to grow substantially over the next century, driven by increases in both population and per-capita consumption in developing countries. Figure 1 shows several scenarios of future energy consumption (19–22). These are “reference” scenarios—that is, they assume no special policies to decrease energy consumption or carbon emissions (but they do take into account expected improvements in energy efficiency and price increases caused by the depletion of oil and gas resources). With the exception of the “IS92c” scenario, which assumes essentially no population growth and limited oil and gas resources, total primary energy consumption is expected to double or triple over the next fifty years, from about 400 EJ y^{-1} in 1998 to 750–1250 EJ y^{-1} in 2050. If fossil-fuel consumption was limited to 300 EJ y^{-1} in 2050 to

---

Opportunities to reduce calcination releases per ton of cement produced (e.g., by using waste lime) are limited.

[6] Note that some of these estimates use different base year (1990) emissions. When they are normalized to the same base year emissions (1.1 PgC y^{-1}), the range is of –2.2 to 2.5 PgC y^{-1} in 2050.

[7] 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 (10-12).

[8] 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 is equivalent to about 300 EJ.

permit stabilization at an equivalent doubling, then carbon-free energy sources would have to supply the difference: 400–900 EJ y^{-1}, at prices not much higher than the expected prices for fossil fuels at that time.

Energy consumption, and requirements for carbon-free energy, could be reduced by various interventions not included in the reference scenarios. These could take the form of taxes on energy or fossil fuels, emission quotas or tradable permits, subsidies for energy-efficiency improvements, or energy-efficiency standards. Economists generally regard a tax as the most efficient mechanism. Edmonds et al (23) calculate that a tax of \$100 tC^{-1}, escalating to \$325–450 tC^{-1} in 2050 and \$750–1200 tC^{-1} in 2100, would be needed to stabilize CO_2 concentrations at 450 ppmv, depending on the prices of various energy-supply alternatives. The "ecologically driven" scenarios developed by Nakicenovic et al (20), which result in a CO_2 concentration of about 450 ppmv in 2100, assume a carbon tax of \$150 tC^{-1} in 2050 (in addition to energy taxes amounting to 100 percent in developing countries and 300 percent in developed countries) increasing to \$400 tC^{-1} in 2100 (20; L Schrattenholzer, personal communication). Total energy consumption in these scenarios is about 600 EJ y^{-1} in 2050, with 250–300 EJ y^{-1} 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^{-1} in the United States (24); a tax of \$100 tC^{-1} 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%.[9] Although such taxes need not have strong negative economic effects if they are phased in slowly and the revenues are recycled efficiently (26), polls consistently indicate that a large majority of Americans would be unwilling to accept taxes of this magnitude to address the climate change problem (27). Developing countries are likely be even less receptive to such taxes.

Thus, stabilization at an equivalent doubling will require roughly 600 EJ y^{-1} of carbon free energy by 2050 at prices comparable to those of fossil fuels, or 300 EJ y^{-1} at prices two to three times higher (with substantial carbon taxes on fossil fuels). For comparison, in 1998 carbon-free sources supplied less than 60 EJ y^{-1} (18). Carbon-free energy supply must therefore grow by a factor of five to ten over the next 50 years (an average grow rate of 3–5% y^{-1} over this period), from 15 percent of total commercial supply to 50–75 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.

---

[9] Since coal is 75% carbon, a tax of \$100 tC^{-1} would add \$75 t^{-1} to the price of coal and \$0.026 kWh^{-1} to the price of coal-fired electricity (assuming a heating value of 29 GJ t^{-1} and an average net conversion efficiency of 35%). For comparison, in 1997 the average price of coal delivered to U.S. utilities was \$29 t^{-1} and the average retail price of electricity was \$0.085 kWh^{-1} (25).

SOURCES OF CARBON-FREE ENERGY

Only two sources of carbon-free[10] energy—hydropower and nuclear fission—currently produce a significant fraction of world supply, with each accounting for about 27 EJ y^{-1} or 7 percent of commercial primary energy in 1998 (18). All other carbon-free sources—geothermal, wind, solar, and commercial biomass—together supplied only about 4 EJ y^{-1} in 1998 (18). Traditional biomass fuels are not included in this accounting; although they may provide up to 60 EJ y^{-1}, much of this is fuelwood that is harvested in a unsustainable manner, resulting in a net release of CO_2 (28). Carbon-free energy production has been growing recently at only about 2% y^{-1}—much less than the 5% y^{-1} rate needed to stabilize greenhouse-gas concentrations at an equivalent doubling without resort to very high taxes. Moreover, most of the recent growth is due to an expansion of nuclear and hydro capacity, which is expected to taper off in the coming decades.

The list of potential carbon-free energy sources is long; in additional to those listed above, there is 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 before 2050. The sources with the greatest potential in this time period are nuclear fission, solar photovoltaic, decarbonized fossil fuels, and, to a lesser extent, wind and commercial biomass. Table 1 summarizes the current and potential contributions of various carbon-free energy sources.

Sources Unlikely to Make a Major Contribution

Hydropower. Hydropower currently is the largest carbon-free source of commercial energy. In 1998, hydro produced about 2600 TWh[11] of electricity—19 percent of global electricity production and 7 percent of primary energy (18). Global hydroelectric production experienced strong growth from 1900 to 1970, but growth has slowed to about 2 percent per year over the last decade. Future expansion is limited by the availability of economically attractive sites and, increasingly, by concerns about the environmental and social impacts of dams (29). 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 (20).

---

[10] 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.

[11] A terawatt-hour (TWh) is a billion kilowatt-hours or 10^{12} watt-hours, and is equal to 0.0036 EJ. The primary energy content of electricity from non-thermal sources, such as hydro and wind, is the energy needed to produce the same amount of electricity in a thermal plant. At today's average efficiency (33%), 1 TWh = 0.011 EJ_p; at the average thermal efficiencies expected several decades from now (40%), 1 TWh = 0.009 EJ_p.

Without regard to environmental or economic constraints, global hydroelectric production potential is estimated at 15,000 to 19,000 TWh y^{-1} (30). The historical experience in the United States, Europe, and Japan, where hydroelectric production has leveled off, indicates that 40 to 65 percent of this technical potential ultimately could be exploited. Thus, hydro ultimately could produce no more than 10,000 TWh y^{-1} or 100 EJ_p y^{-1}.

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 very small—about 1000 EJ y^{-1} 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% of the total resource.

Geothermal energy experienced rapid growth in the early 1980s; during the 1990s, however, production has grown at only 2% y^{-1}. In 1998 geothermal contributed about 0.6 EJ_p to world energy supply—41 TWh of electricity and about 0.15 EJ of direct-use heat (18, 31). 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.[12] 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 to parallel wells several kilometers deep into the rock and to fracture the rock between the wells. Water injected down one well is forced through the fissures in the hot rock and pumped to the surface via the other well. The technology is in the experimental stage and commercial feasibility 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 (31, 33). 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.

---

[12] The accessible high-temperature (>150 °C) hydrothermal resource in the United States is estimated at 4000 to 6000 EJ (32); 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.

Ocean energy. Large amounts of energy are stored in the oceans in tides, 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 is harnessed by building a dam across an estuary having a large tidal range. Because of its similarity to hydropower, the technology is fairly mature. Several small tidal-power facilities currently are in operation, producing about 0.6 TWh y^{-1} of electricity (34). The total amount of energy dissipated by tides worldwide is over 200 EJ_p y^{-1}, but only 5 to 10 EJ_p y^{-1} 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. The desire to avoid adverse impacts on the ecology of estuaries could further limit the development of tidal power.

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 (35). 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 10,000 EJ_p y^{-1}, but the amount that could be exploited (economics aside) is less than 100 EJ_p y^{-1}. 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%, 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 also is 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^{-1}. Available technologies to convert this energy into electricity are extremely expensive, however.

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 a 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 to the stabilization of greenhouse-gas concentrations.

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

Biomass Energy

Biomass—wood, crop 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. Estimates range from 15 to 65 EJ y^{-1}, or 4-15% of world energy consumption (20, 28, 36-37).

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% 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 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 (18, 38). 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 (18, 39).

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 transportation fuels is particularly important. Second, the technology for producing biofuels is mature and is available 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^{-1} (40-42), compared to prices of \$1-2 GJ^{-1} for coal and \$2.5-5 GJ^{-1} for oil and natural gas over the last decade (25, 43). Using biomass feed at \$2.5 GJ^{-1}, ethanol or methanol can be produced today at an estimated cost of \$0.25-0.3 L^{-1}, which would compete with gasoline derived from oil at \$30-40 per barrel (44, 45). Further technical improvements could make biomass-derived alcohol competitive at oil prices below \$25 per barrel.

The energy potential of biomass is large. Plants store energy at a rate of about 3000 EJ y^{-1}. 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^{-1}. 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^{-1} (46). 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^{-1} in 2050 (47).

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^{-1} y^{-1}. In tropical and subtropical regions, the leading candidates are Eucalyptus, with an average yield of 150-350 GJ $ha^{-1}y^{-1}$, and sugarcane, with an average yield of about 600 GJ $ha^{-1}y^{-1}$ (46). Here I assume that average net yields of 200 GJ ha^{-1} y^{-1} 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 (48). Estimates of potentially arable land—land on which rain-fed crops could achieve reasonable yields, in addition to those currently under cultivation—range from 500 to 2500 Mha. Most of this land is in sub-Saharan Africa and Latin America. The wide range of values reflects incomplete knowledge of soil and climate conditions, differing evaluations of the potential of poor soils or steep terrain to support crop production, and differing views about the desirability and feasibility of converting natural forests and swamps 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 will shrink and large areas will be available for biomass plantations. If, on the other hand, increases in yields do not keep pace with increases in consumption, cropland will increase and little land may be available for energy crops.

Past trends are encouraging: between 1961 and 1996, world production of cereals increased by 140%, while the area harvested increased only 9%. This was made possible by large increases in average cereal yield, from 1.4 t ha^{-1} in 1961 to 3.0 t ha^{-1} in 1997 (37). It is unclear whether growth in yields will continue to keep pace with growth in consumption. Cereal consumption is expected to increase at an average rate of 1-2% y^{-1} over the next half century, driven by increases in population and per-capita grain utilization.[13]

---

[13] Population is expected to increase 30-100% by 2050 and per-capita consumption of cereals will increase 20-40% as diets improve and meat consumption rises. At per-capita incomes below \$10,000 y^{-1}, per-capita grain utilization has increased by about 90 kg y^{-1} for each doubling of

How much grain yields will increase in the future is the subject of much debate (49). 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 (37). Biotechnology holds the promise of further increases. Pessimists note that most of the increase in yields was achieved before 1984; since then, yields have increased at an average rate of only 1.3% y^{-1}. 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^{-1}, due to erosion, salinization, desertification, and urbanization (50, 51). 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^{-1}. If grain consumption increases 1% y^{-1} faster than average yields over the next 50 years (e.g., consumption increases 2% y^{-1} while yields increase 1% y^{-1}),[14] the amount of land available for energy plantations would decrease by 700 Mha and the energy production potential would be 0-50 EJ y^{-1}. If yields increase 1% y^{-1} faster than consumption, an additional 500 Mha would be available and the energy production potential would be 200-300 EJ y^{-1}. Including wastes, commercial biomass could supply 50-400 EJ y^{-1} by 2050. For comparison, scenarios developed by Nakićenović et al (20) assume that modern biofuels would supply 50–120 EJ y^{-1} in 2050 and 160–300 EJ y^{-1} 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 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.

Fission Energy

Of the carbon-free sources that could make a major contribution to future energy supply, fission is the only one that is deployed commercially on a significant scale today. In 1998, fission reactors supplied over 2300 TWh of electricity—17 percent of world electricity generation and over 6 percent of commercial primary energy (18).

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

---

per-capita GDP (48). Per-capita GDP is expected to grow at a rate of 1-2% y^{-1} from 2000 to 2050; per-capita grain utilization would therefore be expected to increase by 70-140 kg y^{-1}, or by a factor of 1.2 to 1.4.

[14] 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.

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-generated electricity is sometimes mentioned, electrolytic hydrogen would be considerably more expensive than hydrogen produced from biomass or decarbonized fossil fuels.[15]

Fission's energy production potential depends on the fuel-cycle technology used and the size of exploitable uranium resources. It is estimated that 15-125 Mt of uranium could be extracted from terrestrial ores at a cost of less than \$260 kg^{-1} (53, 54). The type of reactor in widest use, the light-water reactor (LWR), requires about 200 t GW_ey^{-1} if operated on a once-through fuel cycle, in which the spent fuel is treated as waste (53). In nuclear-intensive energy scenarios (20, 55, 56) generating capacity rises from about 350 GW_e today to 1100-1700 GW_e in 2050, with nuclear supplying 70-110 $\text{EJ}_p\ \text{y}^{-1}$ and 30-40% of world electricity supply. If this energy is supplied entirely by LWRs operating on a once-through fuel cycle, cumulative consumption of uranium would be 5-7 Mt; the reactors then in existence would require another 4-6 Mt for the remainder of their operating life. 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 25 Mt could provide over $10^6\ \text{EJ}_p$. 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, particularly the 4500 Mt that is dissolved in the world's oceans. Recent studies indicate that uranium could be extracted from seawater for as little as \$100 kg^{-1} (57; Seguchi and Foos, personal communications), in which case plutonium recycling and breeder reactors would remain economically unattractive indefinitely.

Although fission's technical potential is substantial, its near-term prospects are not very favorable. Forecasts 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 less than 10 percent by 2020 (53, 58). 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 and unpredictable construction times. 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 (59-64). The best U.S. nuclear plants, however, produce electricity at lower cost than the best coal-fired plants (61). 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. New plants should have lower operating expenses.

---

[15] According to Ogden & Nitsch (52), hydrogen can be produced from biomass gasification at a cost of \$6-9 GJ^{-1}, from natural gas at a cost of \$7-10 GJ^{-1}, and from coal at a cost of \$8-9 GJ^{-1}. Carbon sequestration would add \$0.2–1 GJ^{-1} to the cost of H_2 produced from gas and \$1–6 GJ^{-1} for H_2 produced from coal (assuming sequestration at \$10–60 tC^{-1}). The cost of electrolytic hydrogen, assuming nuclear-generated electricity at a cost of \$0.03-0.07 kWh^{-1}, would be \$15-30 GJ^{-1}.

Studies indicate that in many countries new nuclear plants should be economically competitive with new coal- and gas-fired plants, producing electricity for \$0.03–0.07 kWh^{-1} (63, 65-66).

Economic considerations aside, the future of fission energy is clouded by concerns about accidents, waste disposal, and the spread of nuclear weapons. Below I review the prospects in each of these areas.

Accidents. The most serious accident outside of the former Soviet Union occurred at the Three Mile Island (TMI) reactor in 1979. Although the reactor core was seriously damaged, the amount of radioactivity released into the environment was too small to harm the surrounding population. This was the only accident in about 9,000 reactor-years of 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 (67). 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 (59). 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 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 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^{-1} 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).[16] 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 package, the thermal loading of the repository, the nature of the surrounding rock, and precipitation in the area (59). 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 (68). 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 (69).

The U.S. National Academy of Sciences (70) 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^{-1}—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 (71, 72; 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 (73, 74). 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,

---

[16] 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.

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 (75, 76). 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 (77).

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 (78).

Proliferation. All nuclear fuel cycles involve weapon-usable materials that can be separated using a relatively straightforward chemical process (79). Although fresh LWR fuel cannot be used for weapons purposes, spent LWR fuel is 1% 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 (80, 81). 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, all but a handful of states have promised not to acquire nuclear weapons and have agreed to accept safeguards on peaceful nuclear activities to verify that nuclear materials are not being diverted or misused. As long as the fuel remains intact, it is relatively easy to detect diversion of the plutonium-bearing spent fuel, because international inspectors can simply tag and count the number of fuel assemblies. Spent fuel also is very difficult to steal, both because of its unwieldy size and because it is highly radioactive. A spent fuel assembly from a typical LWR is 4 m long, has a mass of 650 kg, and would deliver a lethal dose of radiation to an unprotected person in a few minutes (80). 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 because it maintains nuclear materials in forms that are relatively invulnerable to misuse. At current and foreseeable uranium prices, it is also the least expensive fuel cycle.

The main alternative to the once-through cycle involves the separation and recycling of the plutonium and uranium in the spent fuel. 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 (82). 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, however, 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 (83, 84).

If nuclear power grows substantially, recycle may become necessary or economically attractive. In this case, additional technical and institutional barriers could be introduced to deter and detect theft or diversion. This could include novel reactor concepts, such as lifetime cores; new reprocessing techniques that do not involve the separation of pure plutonium; and fuel cycles that minimize the production of high-quality plutonium, such as the thorium fuel cycle (85, 86). Diversion also could be inhibited by internationalizing certain parts of the nuclear fuel cycle. A serious shortcoming of the current regime is that non-nuclear-weapon states are permitted to own and operate facilities capable of producing plutonium and HEU, and can produce, stockpile, and use these materials so long as they are under safeguards. But safeguards may be unable to detect the diversion of significant quantities of these materials in a timely manner from facilities that handle the materials in bulk form, such as reprocessing and fuel-fabrication plants. It would be far easier to deter or detect diversions by states if such activities were managed directly by an international agency. Similar arrangements could be extended to the storage and use of fresh plutonium fuels, or even spent fuel. National reactors might be permitted to burn only low-enriched fuels, with the spent fuel turned over to international reprocessing or storage centers; reactors burning plutonium fuels would be managed by an international authority.

Solar Energy

Sunlight is the ultimate source of many of the forms of energy discussed above: biomass and fossil fuels, hydro, wind, wave, and ocean thermal energy. Here "solar" refers only to the direct use of sunlight to produce heat or electricity. In 1998 solar produced about 3 TWh of electricity and perhaps 0.5 EJ of heat in solar thermal collectors.

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} y^{-1}, while cloudy, northern areas, such as the northwestern United States or the United Kingdom, receive as little as about 4 GJ m^{-2} y^{-1} (87, 88).

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 (89). Today, however, less than 1% 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% 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. To produce solar heat at \$5 GJ^{-1} (the current retail price of natural gas in the United States), installed costs must be less than \$200 m^{-2} in sunny areas and less than \$100 m^{-2} in less-sunny areas such as New York or London. Although the collectors themselves are produced in the United States for about \$150 m^{-2} (90), installed costs are several times higher (88). 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; the technology is mature and uses common materials. If energy prices double or quadruple, however, solar could provide a substantial fraction of the energy used for heat—perhaps 10 percent of total energy demand.

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^{-1} (91). With additional improvements in efficiency and cost, solar thermal electric plants might compete favorably with new nuclear plants in sunny locations.

The solar technology with the greatest potential is photovoltaics. Photovoltaic cells convert sunlight directly into electricity. They require no focusing or tracking mechanisms (although 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 very little maintenance. Photovoltaic cells can be wired together to form units of any size, from a fraction of a watt to hundreds of megawatts. They can be integrated into the design of exterior building surfaces.

The cost of photovoltaic modules has decreased tremendously, from \$100 per peak watt in 1975 to as low as \$4 W_p^{-1} 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 roughly double the cost of the photovoltaic modules (92, 93). At this price, photovoltaic electricity remains far too expensive for widespread use. At an installed price of \$1 W_p^{-1}, photovoltaic systems would produce electricity at a cost of \$0.04-0.1 kWh^{-1}, depending on location, in which case they would compete favorably with other sources of electricity. It may not be easy to reduce the price of photovoltaic systems to \$1 W_p^{-1}, which 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} (93), and the price of installing common building materials, such as shingles or siding, is about \$30 m^{-2} (94).

Even if prices fall to levels that would be economically competitive with other sources, solar would be limited to 10-20% 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%. 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^{-1}—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 geosynchronous orbit around the earth, with the power transmitted in microwaves to fixed receiving antennae on earth. Because the array would receive sunlight at a constant rate, without interference from the atmosphere or clouds, a photovoltaic module in orbit would on average produce electricity at about five times the rate that it would at the sunniest locations on the earth's surface. This constant and predictable supply would, moreover, eliminate the need for energy storage. Although conceptually appealing, these advantages are unlikely to compensate for the enormous costs of placing and maintaining equipment in orbit. At current prices, launch costs alone would amount to \$100 to \$500 W_p^{-1}.[17] 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.

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 1998, wind produced 13 TWh, mostly in the United States, Germany, and Denmark (18). Installed capacity increased from 1 GW_e in 1985 to 12 GW_e in 1999—an average growth rate of nearly 20% y^{-1}.

Today, electricity is produced at a cost of \$0.05-0.08 kWh^{-1} at sites with average wind power densities greater than 250 W m^{-2} at a height of 10 m (97, 98). About 5% of the earth's land area has wind power densities this high; in theory, about 160,000 TWh y^{-1} (1400 EJ_p y^{-1}) 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.

---

[17] Photovoltaic cells weighing only 5 g W_p^{-1} (0.12 mm thick) have been produced for use on a solar-power aircraft (95). Launch costs currently range from \$20 to \$100 per gram for geosynchronous orbit (96). Thus, launch costs would amount to \$100 to \$500 W_p^{-1}, or about \$75 to \$370 W^{-1} in orbit. Assuming that launch costs are amortized over 30 y at a rate of 10% y^{-1}, launch costs would add \$0.8-\$4 kWh^{-1} to the price of electricity.

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%, unless large-scale energy storage or transmission is provided. Thus, the practical potential of wind electricity is about 12,000 TWh y^{-1}. A realistic upper limit for wind production in 2050 might be 4000 TWh y^{-1} (40 EJ_p y^{-1})—roughly 10% 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 the most promising renewable energy source.

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 somewhat 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.

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. The first is to capture the CO_2 gas after combustion. This 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% ($0.02-0.06 kWh^{-1}), equivalent to $100-260 per ton of carbon emission avoided (99-101). 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% greater than that of natural gas and five times greater than that of coal (102). Even at these high prices, hydrogen could be an attractive fuel in the long term because it can be converted efficiently in fuel cells into electricity with virtually no pollution. Coal also can be converted into hydrogen-rich fuels, such as methane or methanol, that are easier to transport and store than is hydrogen. The cost of such chemical conversions is very high, however—equivalent to $150-500 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^{-1} or 25-50% to the price of electricity, or \$65-160 per ton of carbon emissions avoided (99).

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 (103).

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 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%) 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 store CO_2 underground in deep saline aquifers. In the United States, for example, 65% of power-plant carbon emissions occurs close to deep aquifers (104). 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 (105). The wide range is partly due to a lack of basic geological data, such as the volume, porosity, and permeability of aquifers, and partly due to assumptions about how much CO_2 could be stored by unit volume and about what types of aquifer structures would be provide long-term storage. The transport and storage of CO_2 on land raises concerns about public safety and environment impact from pipeline or well failures, but these should not be more difficult to address than those associated with the handling of natural gas.

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 a 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% 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.

The environmental impact and legal status of ocean disposal are uncertain. Sequestration will increase the acidity of seawater; depending on the dispersal mechanism, the decrease in pH could be biologically significant over large volumes of water. For example, the injection of 10 TgC y^{-1} (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 (106). Environmental effects should be minimal as long as CO_2 is injected at depths greater than 1000 m, since nearly all marine life is found above this level. In any case, dumping of wastes in the oceans is regulated by international law, and issuance of the required permits would take into account possible effects on deep-sea marine life and the availability of land-based disposal alternatives.

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^{-1} (101, 105). 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^{-1} (equivalent to the CO_2 emitted by 3 to 20 large coal-fired power plants), transport costs would be \$0.01-0.04 tC^{-1} km^{-1} for either underground or ocean disposal (107-109). Transport and disposal by tanker is possible for ocean disposal, and may be cheaper at longer distances (110). Depending on transport distance, total disposal costs would range from about \$10-60 tC^{-1}.

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^{-1}, 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.

CONCLUSIONS

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: biomass, fission, 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.

Unfortunately, each of the five major alternatives currently has significant technical, economic, and/or environmental handicaps. 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. 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. 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 certain 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 ensure that abundant, affordable, and acceptable substitutes for traditional fossil fuels will be available worldwide in the coming decades (111).

LITERATURE CITED

1. United Nations Framework Convention on Climate Change, May 1992, http://www.unfccc.de
2. Kattenberg A, Giorgi F, Grassl H, Meehl GA, Mitchell JFB, et al. 1996. Climate models—projections of future climate. In *Climate Change 1995; The Science of Climate Change*, ed. JT Houghton, LG Meira Filho, BA Callander, N Harris, A Kattenberg, K Maskell, 285-357. Cambridge: Cambridge Univ. Press. 572 pp.
3. Folland, CK, Karl TK, Vinnikov, KYA. 1990. Observed climate variations and change. In *Climate Change: The IPCC Scientific Assessment*, ed. JT Houghton, GJ Jenkins, JJ Ephraums, 195-238. Cambridge: Cambridge Univ. Press. 365 pp.
4. Nicholls N, Gruza GV, Jouzel J, Karl TR, Ogallo LA, et al. 1996. Observed climate variability and change. See Ref. 2, pp. 133-192
5. Ad-hoc Group on the Berlin Mandate, ***Implementation of the Berlin Mandate: Comments from Parties, addendum***, FCCC/AGBM/1997/MISC.2/Add.1, 27 April 1997, http://www.unfccc.de/resource/docs/1997/agbm/misc02a1.htm
6. Cole V, Cerri C, Minami K, Mosier A, Rosenberg N, et al. 1996. Agricultural options for mitigation of greenhouse gas emissions. In *Climate Change 1995; Impacts, Adaptations and Mitigation of Climate Change: Scientific-Technical Analyses*, ed. RT Watson, MC Zinyowera, RH Moss, 745-772. Cambridge: Cambridge Univ. Press. 879 pp.
7. Levine MD, Akbari H, Busch J, Dutt G, Hogan K, et al. 1996. Mitigation options for human settlements. See ref. 6, pp. 713-743
8. Lashof DA, DeAngelo BJ, Saleska SR, Harte J. 1997. Terrestrial ecosystem feedbacks to global climate change. *Annu. Rev. Energy Environ*. 22:75-118
9. Melillo JM, Prentice IC, Farquhar GD, Schulze ED, Sala OE. 1996. Terrestrial biotic responses to environmental change and feedbacks to climate. See Ref 2, pp. 445-481
10. Schimel D, Alves D, Enting I, Heimann M, Joos F, et al. 1996. Radiative forcing of climate change. See Ref. 2, pp. 65-131
11. Enting IG, Wigely TML, Heimann M. 1994. Future emissions and concentrations of carbon dioxide: key ocean/atmospheric/land analyses. CSIRO Division of Atmospheric Research Technical Paper 31, Victoria, Australia
12. Wigley TML, Richels R, Edmonds JA. 1995. Economic and environmental choices in the stabilization of CO_2 concentrations: choosing the “right” emissions pathway. *Nature* 379:240-243
13. Houghton RA. 1999. The annual net flux of carbon to the atmosphere from changes in land use 1850-1990. *Tellus*. 51B:298-313
14. Alacamo J, Bowman A, Edmonds J, Grubler A, Morita T, Sugandhy A. 1994. An evaluation of the IPCC IS92 emission scenarios. In *Climate Change 1994; Radiative Forcing of Climate Change and An Evaluation of the IPCC IS92 Emission Scenarios*, ed. JT Houghton, LG Meira Filho, J Bruce, H Lee, BA Callander, et al., 237-304. Cambridge: Cambridge Univ. Press. 339 pp.
15. Brown S, Sathaye J, Cannell M, Kauppi P. 1996. Management of forests for mitigation of greenhouse gas emissions. See Ref 6, pp. 773-797
16. Kirschbaum MUF, Fischlin A, Cannell MGR, Cruz RVO, Galinski W, et al. 1996. Climate change impacts on forests. See Ref. 6, pp. 95-129
17. Marland G, Boden TA, Andres RJ, Brenkert AL, Johnston CA. 1999. Global, Regional, and

National Fossil Fuel CO_2 Emissions, Carbon Dioxide Information Analysis Center, Oak Ridge National Lab., Oak Ridge, Tenn., http://cdiac.esd.ornl.gov/trends/emis/em_cont.htm

18. Energy Information Administration. 2000. International Energy Annual 1998. U.S. Department of Energy, Washington, DC
19. Leggett J, Pepper WL, Swart RJ. 1992. Emission scenarios for IPCC: an update. In *Climate Change 1992: The Supplementary Report to the IPCC Scientific Assessment*, ed. JT Houghton, BA Callander, SK Varney, 69-95. Cambridge: Cambridge Univ. Press. 200 pp.
20. Nakićenović N, Grübler A, McDonald A, eds. 1998. Global Energy Perspectives. Cambridge: Cambridge Univ. Press. 299 pp
21. Shell International Ltd. 1996. *The Evolution of the World's Energy Systems*. London: Shell International.
22. Schmalensee R, Stoker TM, Judson RA. 1998. World carbon dioxide emissions: 1950-2050. Rev. Econ. Stat. 80:15-27
23. Edmonds J, Dooley J, Kim S. 1998. *Long-term Energy Technology: Needs and Opportunities for Stabilizing Atmospheric CO_2 Concentrations*, American Council for Capital Formation, Washington, DC.
24. Baron R. 1996. *Economic/fiscal Instruments: Taxation.* "Policies and Measures for Common Action" working paper, OECD, Paris
25. Energy Information Agency. 1999. *U.S. Energy Prices*. http://www.eia.gov/emeu/steo/pub/4tab.htm
26. Repetto R, Austin D. 1997. *The Costs of Climate Protection: A Guide for the Perplexed.* Washington, DC: World Resources Institute, Washington, DC.
27. Kull S. 1998. *Americans on Global Warming: A Study of U.S. Public Attitudes.* Program in International Policy Attitudes, Univ. Maryland, College Park, MD.
28. Hall DO. 1991. Biomass energy. *Energy Policy*. 19:711-737.
29. March PA, Fisher RK. 1999. It's not easy being green: environmental technologies enhance conventional hydropower's role in sustainable development. *Annu. Rev. Energy Environ.* 24:173-88
30. Moreira JR, Poole AD. 1993. Hydropower and its constraints. *In Renewable Energy: Sources for Fuels and Electricity,* ed. TB Johansson, H Kelly, AKN Reddy, RH Williams, 73-119. Washington, DC: Island Press. 1160 pp.
31. Palmerini CG. 1993. Geothermal energy. See Ref. 30, pp. 549-591
32. Muffler PLJ, 1979. *Assessment of Geothermal Resources of the United States***.** Circular 790, US Geological Survey, Washington, DC.
33. Brown G. 1996. Geothermal energy. In *Renewable Energy: Power for a Sustainable Future***,** ed. G Boyle, 353-392. Oxford: Oxford Univ. Press, 479 pp.
34. Cavanagh JE, Clarke JH, Price R. 1993. Ocean energy systems. See Ref. 30, pp. 513-547.
35. Druckers D. 1996. Wave energy. See Ref. 33, pp. 315-352.
36. Tillman DA. 1991. *The Combustion of Solid Fuels and Wastes*. New York: Academic Press.
37. Food and Agriculture Organization. 1995. *FAOSTAT-PC*. Rome: FAO
38. Energy Information Agency. 1998. Renewable Energy Annual 1998. U.S. Department of Energy, Washington, DC
39. Rosillo-Calle F, Cortez LAB. 1998. Towards proalcohol II: a review of the Brazilian bioethanol programme. *Biomass Bioenergy* 14(2):115-24

40. Carpentieri AE, Larson ED, Woods J. 1993. Future biomass-based electricity supply in north-east Brazil. *Biomass and Bioenergy* 14:149-173
41. Turhollow A. 1994. The economics of energy crop production. *Biomass and Bioenergy* 6(3):229-241
42. Graham RL, Lichtenberg E, Roningen VO, Shapouri H, Walsh ME. 1995. The economics of biomass production in the United States. *Proc. Biomass Conf. of the Americas: Energy, Environment, Agriculture, and Industry, 2nd, Portland, OR.* http://www.esd.ornl.gov/bfdp/papers/bioam95/graham3.html
43. BP Amoco. 1999. *BP Amoco Statistical Review of World Energy 1999.* http://www.bpamoco.com/worldenergy
44. Wyman CE. 1999. Biomass ethanol: technical progress, opportunities, and commercial challenges. *Annu. Rev. Energy Environ.* 24:189-226
45. Wyman CE, Bain RL, Hinman ND, Stevens DJ. 1993. Ethanol and methanol from cellulosic biomass. See Ref. 30, pp. 865-923
46. Hall DO, Rosillo-Calle F, Williams RH, Woods J. 1993. Biomass for energy: supply prospects. See Ref. 30, pp. 593-651
47. Johansson TB, Kelly H, Reddy AKN, Williams RH. 1993. A renewables-intensive global energy scenario. See Ref. 30, pp. 1071–1142
48. U.S. Department of Agriculture, *World Agriculture: Trends and Indicators.* http://jan.mannlib.cornell.edu/data-sets/international/89024
49. World Resources Institute. 1996. Food and agriculture. In *World Resources 1996–97*, 225-246. Oxford: Oxford Univ. Press. 365 pp.
50. Evans M. 1994. Agriculture and environment: a review, 1972–1992. *Ambio* 23(3):194
51. Kendall HW, Pimentel D. 1994. Constraints on the expansion of the global food supply. *Ambio* 23(3):200.
52. Ogden JM, Nitsch J. 1993. Solar hydrogen. See Ref. 30, pp. 925-1009.
53. Nuclear Energy Agency, International Atomic Energy Agency. 1998. *Uranium 1997*. p. 60.
54. Holdren JP, Pachauri RK. 1992. Energy. In *An Agenda of Science for Environment and Development into the 21st Century*. Cambridge: Cambridge Univ. Press
55. International Atomic Energy Agency. 1995. *Nuclear Power: An Overview in the Context of Alleviating Greenhouse Gas Emissions*. Rep. IAEA-TECDOC-793, IAEA, Vienna.
56. Nuclear Energy Agency. 1998. *Nuclear Power and Climate Change*. Rep. NEA#0846, Paris
57. Hiraoka T. 1994. Nuclear Electricity Generation by Seawater Uranium. *J. Atomic Energy Soc. Japan* 36(7):644-645
58. Energy Information Administration. 2000. *International Energy Outlook 1999.* U.S. Department of Energy, Washington, DC. http://www.eia.doe.gov/oiaf/ieo99/home.html
59. Bodansky D. 1996. *Nuclear Energy: Principles, Practices, and Prospects.* Woodbury, NY: American Institute of Physics. 396 pp.
60. National Research Council. 1992. *Nuclear Power: Technical Options and Institutional Options for the Future.* Washington, DC: National Academy Press. 215 pp.
61. Energy Information Administration. 1990. *Electric Plant Cost and Power Production Expenses, 1988.* Rep. DOE/EIA-0455(88), U.S. Depart. of Energy, Washington, DC.
62. Energy Information Administration. 1995. *Analysis of Nuclear Plant Operating Costs: A 1995 Update.* U.S. Depart. of Energy, Washington, DC.
63. Delene JG, Williams KA, Shapiro, BH. 1988. Nuclear Energy Cost Data Base. Rep.

DOE/NE-0095, U.S. Depart. of Energy, Washington, DC.

64. Mark Gielecki and James G. Hewlett, "Commercial Nuclear Electric Power in the United States: Problems and Prospects," ***Monthly Energy Review*** (Washington, DC: Energy Information Administration, August 1994).
65. Organization for Economic Cooperation and Development. 1989. *Projected Costs of Generating Electricity from Power Stations For Commissioning in the Period 1995-2000*. OECD, Paris
66. Organization for Economic Cooperation and Development. 1993. *Projected Costs of Generating Electricity: 1992 Update*. OECD, Paris
67. U.S. Nuclear Regulatory Commission. 1990. *Severe Accident Risks: An Assessment for Five Nuclear Power Plants*. Rep. NUREG-1150, Nuclear Regulatory Commission, Washington, DC.
68. National Research Council. 1983. *A Study of the Isolation system for Geologic Disposal of Radioactive Wastes*. Washington, DC: National Academy Press
69. Knight JL. 1998. Use of natural analogues in waste disposal. *Interdisciplinary Science Reviews* 23(3):233-241
70. National Research Council. 1995. *Technical Bases for Yucca Mountain Standards*. Washington, DC: National Academy Press
71. McCombie C. 1997. Nuclear waste management worldwide. *Physics Today* 50(6):60-62
72. Sumerling T, Smith P. 1998. Disposal of nuclear fuel waste. *Interdisciplinary Science Reviews* 23(3):228–230
73. US Dep. Energy, Off. Civil. Radioactive Waste Manage. 1998. *Viability Assessment of a Repository at Yucca Mountain*, Dec. DOE/RW-0508. http://www.ymp.gov/va.htm
74. Craig PP. 1999. High-level nuclear waste: the status of Yucca Mountain. *Annu. Rev. Energy Environ*. 24:461-86
75. Hollister CD, Nadis S. 1998. Burial of radioactive waste under the seabed. *Scientific American* 276(1):60-65
76. Nadis S. 1996. The sub-seabed solution. *Atlantic Monthly* 278(4):28-39
77. Waczewski J. 1997. Legal, political, and scientific response to ocean dumping and sub-seabed disposal of nuclear waste. *Journal of Transnational Law & Policy* 7(1). http://www.law.fsu.edu/journals/transnational/issues/7-1/wacz.html
78. National Research Council. 1996. *Nuclear Waste: Technologies for Separations and Transmutation.* Washington, DC: National Academy Press
79. Hebel LC, Christensen EL, Donath FA, Falconer WE, Lidofsky LJ, et al. 1978. Report to the American Physical Society by the study group on nuclear fuel cycles and waste management. *Reviews of Modern Physics* 50(1):S1-186.
80. National Academy of Sciences, Committee on International Security and Arms Control. 1994. *Management and Disposition of Excess Weapons Plutonium*. Washington, DC: National Academy Press. 288 pp.
81. Mark JC. 1993. Explosive properties of reactor-grade plutonium. *Science & Global Security* 4(1):111–128
82. Miller MM. 1990. *Are IAEA Safeguards on Plutonium Bulk-handling Facilities Effective?* Nuclear Control Institute, Washington, DC. http://www.nci.org/mmsgrds.htm
83. Peterson PF. 1996. Long-term safeguards for plutonium in geologic repositories. *Science and Global Security* 6(1):1-26

84. Peterson PF. 1999. Issues for detecting undeclared post-closure excavation at geologic repositories. *Science and Global Security* 8(1):1-39
85. Galperin A, Reichert P, Radkowsky A. 1997. Thorium fuel for light water reactors—reducing the proliferation potential of nuclear power fuel cycle. *Science and Global Security* 6(3):265-290
86. Kasten PR. 1998. Review of the Radkowsky thorium reactor concept. *Science and Global Security* 7(3):237-269
87. Boes EC, Luque A. 1993. Photovoltaic concentrator technology. See Ref. 30, pp. 361-401
88. Everett B. 1996. Solar thermal energy. See Ref. 33, pp. 41-88
89. Brower M. 1992. *Cool Energy: Renewable Solutions to Environmental Problems*. Cambridge, MA: MIT Press
90. Energy Information Administration. 1998. *Renewable Energy Annual 1997, Vol. I.* Washington, DC: U.S. Dep. Energy
91. De Laquil III P, Kearney D, Geyer M, Diver R. 1993. Solar-thermal electric technology. See Ref. 30, pp. 213-296.
92. Boyle G. 1996. Solar Photovoltaics. See Ref. 33, pp. 89-136
93. Kelly H. 1993. Introduction to photovoltaic technology. See Ref. 30, pp. 297-336
94. Consumer Reports. 1997. Shingles and siding. *Consumer Reports* 62(8):27-33
95. Piellisch R. 1991. Solar powered flight. *Sunworld*, March-April, pp. 17–20.
96. Hopkins JB. 1994. Orbital and planetary launch services. http://www.ksc.nasa.gov/facts/faq13.txt
97. Energy Information Administration. 1997. *Renewable Energy Annual 1996.* Washington, DC: U.S. Dep. Energy
98. Gipe P. 1999. Overview of Worldwide Wind Generation. http://rotor.fb12.tu-berlin.de/overview.html
99. Herzog HJ. 1998. The Economics of CO_2 Capture. Fourth International Conference on Greenhouse Gas Control Technologies, Interlaken, Switzerland. http://web.mit.edu/energylab/www/hjherzog/economics.PDF
100. International Energy Agency. 1994. *Carbon Dioxide Capture from Power Stations.* IEA Greenhouse Gas R&D Programme, Stoke Orchard, UK. http://www.ieagreen.org.uk/sr2p.htm
101. Herzog H, Drake E, Adams E. 1997. *Carbon Dioxide Capture, Reuse, and Storage Technologies for Mitigating Global Climate Change*. Massachusetts Institute of Technology, Cambridge, MA. http://web.mit.edu/energylab/www/hjherzog/White_Paper.pdf
102. Blok K, Williams RH, Katofsky RE, Hendriks CA, Hydrogen production from natural gas, sequestration of recovered CO_2 in depleted gas wells and enhanced natural gas recovery. *Energy* 22(2/3):166
103. International Energy Agency. 1995. *Carbon Dioxide Utilisation.* IEA Greenhouse Gas R&D Programme, Stoke Orchard, UK. http://www.ieagreen.org.uk/sr4p.htm
104. Bergman PD, Winter EM. 1996. Disposal of carbon dioxide in deep saline aquifers in the U.S. US/Japan Joint Technical Workshop, State College, PA.
105. International Energy Agency. 1995. *Carbon Dioxide Disposal from Power Stations.* IEA Greenhouse Gas R&D Programme, Stoke Orchard, UK. http://www.ieagreen.org.uk/sr3p.htm

106. Caulfield JA, Auerbach DI, Adams EE, Herzog HJ. 1997. Near-field impacts of reduced pH from ocean CO_2 disposal. *Energy Conversion and Management* 38:S343–S348
107. Skovholt O. 1993. CO_2 transportation system. *Energy Conversion and Management* 34(9-11):1095–1103
108. Summerfield IR, Goldthorpe SH, Williams N, Sheikh A. 1993. Costs of CO_2 disposal options. *Energy Conversion and Management* 34(9-11):1105–1112
109. Hendriks CA. 1994. *Carbon Dioxide Removal from Coal-fired Power Plants* Dordrecht, Netherlands: Kluwer Academic Press
110. Golumb D. 1997. Transport systems for ocean disposal of CO_2 and their environmental effects. *Energy Conversion and Management.*
111. President's Committee of Advisors on Science and Technology, Panel on Energy Research and Development. 1997. *Report to the President on Federal Energy Research and Development for the Challenges of the Twenty-first* Century, Washington DC, Office of Science and Technology Policy

TABLE 1 Current and potential contributions of carbon-free energy sources to world primary energy supply.

	Primary Energy Production ($EJ_p\ y^{-1}$)			
Energy Source	1998	Potential by 2050	Long-term Potential	Natural flow or resource (EJ_p)
Hydroelectric	29	40–60	60–100	400 y^{-1}
Geothermal	0.6	5–10	5–20	10,000,000
Ocean	0.006	0–1	1–5	2,000,000 y^{-1}
Nuclear fusion	0	0	?	4,000,000,000+
Biomass	4*	50–150	50–500	2,000 y^{-1}
Nuclear fission	25	70–150	500+	10,000,000
Solar	0.5	50–150	500+	3,000,000 y^{-1}
Wind	0.14	20–50	100–250	40,000 y^{-1}
Decarbonized fossil	0	150+	500+	250,000

*Commercial biomass only; traditional biomass is variously estimated at 15–65 EJ y^{-1}.

Figure 1 Scenarios of future world commercial primary energy consumption by the Intergovernmental Panel on Climate Change (IS92), the World Energy Council (WEC), Shell Oil, and Schmalensee et al.