19 Renewable Energy: Current and Potential Issues

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The United States faces energy shortages and increasing energy prices within the next few decades (Duncan, 2001). Coal, petroleum, natural gas, and other mined fuels provide 75% of U.S. electricity and 93% of other U.S. energy needs (USBC, 2001). On average, every year each American uses about 93,000 kWh, equivalent to 8000 L of oil, for all purposes, including transportation, heating, and cooling (USBC, 2001). About 12 kWh (1 L of gasoline) costs as much as \$0.50, and this cost is projected to increase significantly in the next decade (Schumer, 2001).

The United States, having consumed from 82% to 88% of its proved oil reserves (API, 1999), now imports more than 60% of its oil at an annual cost of approximately \$75 billion (USBC, 2001). General production, import, and consumption trends and forecasts suggest that within 20 years the United States will be importing from 80% to 90% of its oil. The U.S. population of more than 285 million is growing each year, and the 3.6 trillion kWh of electricity produced annually at a cost of \$0.07 to \$0.20 per kWh are becoming insufficient for the country's current needs. As energy becomes more scarce and more expensive, the future contribution of renewable energy sources will be vital (USBC, 2001).

Fossil fuel consumption is the major contributor to the increasing concentration of carbon dioxide (CO_2) in the atmosphere, a key cause of global warming (Schneider et al., 2000). Global warming reduces agricultural production and causes other biological and social problems (Schneider et al., 2000). The United States, with less than 4% of the world population, emits 22% of the CO_2 from burning fossil fuels, more than any other nation. Reducing fossil fuel consumption may slow the rate of global warming (Schneider et al., 2000).

Diverse renewable energy sources currently provide only about 8% of U.S. needs and about 14% of world needs (Table 19.1), although the development and use of renewable energy is expected to increase as fossil fuel supplies decline. Several different technologies are projected to provide the United States most of its renewable energy in the future: hydroelectric systems, biomass, wind power, solar thermal systems, photovoltaic systems, passive energy systems, geothermal systems, biogas,

TABLE 19.1
Fossil and Solar Energy Use in the United States and the World (in kWh and quads)

	United States		World	
Form of Energy	**kWh × 109**	**Quads**	**kWh × 109**	**Quads**
Petroleum	10,973.1	37.71[a]	43,271.7	148.70[b]
Natural gas	6431.1	22.10[a]	24,414.9	83.90[b]
Coal	6314.7	21.70[a]	27,295.8	93.80[b]
Nuclear power	2249.4	07.73[a]	6984.0	24.00[b]
Biomass	1047.6	03.60[a]	8439.0	29.00
Hydroelectric power	989.4	03.40[a]	7740.6	26.60[b]
Geothermal	93.1	00.32[b]	291.0	01.00
Biofuels (ethanol)	26.2	00.09[c]	52.4	00.18
Wind energy	11.6	00.04	232.8	00.80
Solar thermal	11.6	00.04	11.6	00.04
Photovoltaics	11.6	00.04	11.6	00.04
Total consumption	28,159.4	96.77	118,745.4	408.06

Note: A quad is a unit of energy equal to 1 quadrillion British thermal units.
[a] Adapted from USBC (2001).
[b] Adapted from DOE/EIA (2001).
[c] Adapted from Pimentel (2001).

ethanol, methanol, and vegetable oil. In this chapter, we assess the potential of these various renewable energy technologies for supplying the future needs of the United States and the world in terms of land requirements, environmental benefits and risks, and energetic and economic costs.

HYDROELECTRIC SYSTEMS

Hydropower contributes significantly to world energy, providing 6.5% of the supply (Table 19.1). In the United States, hydroelectric plants produce approximately 989 billion kWh (1 kWh = 860 kcal = 3.6 MJ), or 11% of the nation's electricity, each year at a cost of $0.02 per kWh (Table 19.2; USBC, 2001). Development and rehabilitation of existing dams in the United States could produce an additional 60 billion kWh/year (Table 19.3).

Hydroelectric plants, however, require considerable land for their water storage reservoirs. An average of 75,000 ha of reservoir land area and 14 trillion L of water are required per 1 billion kWh/year produced (Table 19.2; Pimentel et al., 1994; Gleick and Adams, 2000). Based on regional estimates of U.S. land use and average annual energy generation, reservoirs currently cover approximately 26 million ha of the total 917 million ha of land area in the United States (Pimentel, 2001). To develop the remaining best candidate sites, assuming land requirements similar to those in past developments, an additional 17 million ha of land would be required for water storage (Table 19.3). Despite the benefits of hydroelectric power, the plants cause

TABLE 19.2
Land Resource Requirements and Total Energy Inputs for Construction of Facilities That Produce 1 Billion kWh of Electricity per Year

Electrical Energy Technology	Land Required (ha)	Energy (input–output ratio)	Cost per kWh ($)	Life in Years
Hydroelectric power	75,000[a]	1:24	0.020[b]	30
Biomass	200,000	1:7	0.058[c]	30
Parabolic troughs	1,100[d]	1:5	0.070–0.090[e]	30
Solar ponds	5,200[f]	1:4	0.150	30
Wind power	13,700[g]	1:5[h]	0.070	30
Photovoltaics	2,800[i]	1:7[i]	0.120–0.200	30
Biogas	—[j]	1:1.7–3.3[k]	0.020[k]	30
Geothermal	30	1:48	0.064[l]	20
Coal (nonrenewable)	166[m]	1:8	0.030–0.050[n]	30
Nuclear power (nonrenewable)	31[m]	1:5	0.050	30
Natural gas (nonrenewable)	134[n]	1:8	0.030–0.050[n]	30

[a] Based on a random sample of 50 hydropower reservoirs in the United States, ranging in area from 482 to 763,000 ha (FERC 1984; ICLD 1988).
[b] Pimentel et al. (1994).
[c] Production costs based on 70% capacity factor (John Irving, Burlington Electric, Burlington, VT, personal communication, 2001).
[d] Calculated from DOE/EREN (2001).
[e] DOE/EREN (2001).
[f] Based on 4000-ha solar ponds plus an additional 1200 ha for evaporation ponds.
[g] From Smith and Ilyin (1991).
[h] Adapted from Nelson (1996).
[i] Calculated from DOE (2001).
[j] No data available.
[k] William Jewell, Cornell University, Ithaca, NY, personal communication, 2001.
[l] DOE/EIA (1991).
[m] Smil (1994).
[n] Bradley (1997).

major environmental problems. The impounded water frequently covers valuable, agriculturally productive, alluvial bottomland. Furthermore, dams alter the existing plants, animals, and microbes in the ecosystem (Ligon et al., 1995; Nilsson and Berggren, 2000). Fish species may significantly decline in river systems because of these numerous ecological changes (Brown and Moyle, 1993). Within the reservoirs, fluctuations of water levels alter shorelines, cause downstream erosion, change physiochemical factors such as water temperature and chemicals, and affect aquatic communities. Sediments build up behind the dams, reducing their effectiveness and creating another major environmental problem.

TABLE 19.3
Current and Projected U.S. Gross Annual Energy Supply from Various Renewable Energy Technologies, Based on the Thermal Equivalent and Required Land Area

	Current (2000)			Projected (2050)		
Energy technology	kWh × 109	Quads	Million hectares	kWh × 109	Quads	Million hectares
Biomass	1047.6	3.600[a]	75[b]	1455.0	5	102[b]
Hydroelectric power	1134.9	3.900[a]	26[c]	1455.0	5	33
Geothermal energy	87.3	0.300[a]	0.400	349.2	1.2	1
Solar thermal energy	<11.6	<0.040	<0.010	291.0	10	11
Photovoltaics	<11.6	<0.040	<0.010	3201.0	11	3
Wind power	11.6	0.040[a]	0.500	2037.0	7	8
Biogas	<0.3	<0.001	<0.001	145.5	0.5	0.01
Passive solar power	87.5	0.300[d]	0	1746.0	6	1
Total	2392.2	82.210	101.921	10,679.7	45.7	159.01

[a] USBC (2001).
[b] This is the equivalent land area required to produce 3 metric tons/ha, plus the energy required for harvesting and transport.
[c] Total area based on an average of 75,000 ha per reservoir area per 1 billion kWh/year produced.
[d] Pimentel et al. (1994).

BIOMASS ENERGY SYSTEMS

Although most biomass is burned for cooking and heating, it can also be converted into electricity. Under sustainable forest conditions in both temperate and tropical ecosystems, approximately 3 dry metric tons per hectare per year of woody biomass can be harvested sustainably (Birdsey, 1992; Repetto, 1992; Trainer, 1995; Ferguson, 2001). Although this amount of woody biomass has a gross energy yield of 13.5 million kcal, approximately 33 L of diesel fuel per hectare, plus the embodied energy, are expended for cutting and collecting the wood for transport to an electric power plant. Thus, the energy input–output ratio for such a system is calculated to be 1:22. The cost of producing 1 kWh of electricity from woody biomass is about $0.058, which is competitive with other systems for electricity production (Table 19.2). Approximately 3 kWh of thermal energy is expended to produce 1 kWh of electricity, an energy input–output ratio of 1:7 (Table 19.2; Pimentel, 2001). Per capita consumption of woody biomass for heat in the United States amounts to 625 kg per year. In developing nations, use of diverse biomass resources (wood, crop residues, and dung) ranges from 630 kg per capita (Kitani, 1999) to approximately 1000 kg per capita (Hall, 1992). Developing countries use only about 500 L of oil equivalents of fossil energy per capita, compared with nearly 8000 L of oil equivalents of fossil energy used per capita in the United States.

Woody biomass could supply the United States with about 1.5 × 1012 kWh (5 quads thermal equivalent) of its total gross energy supply by the year 2050, provided that approximately 175 million ha were available (Table 19.3). A city of 100,000 people using the biomass from a sustainable forest (3 t/ha/year) for electricity would require approximately 200,000 ha of forest area, based on an average electrical demand of slightly more than 1 billion kWh (electrical energy [e]) (860 kcal = 1 kWh) (Table 19.2).

The environmental effects of burning biomass are less harmful than those associated with coal, but more harmful than those associated with natural gas (Pimentel, 2001). Biomass combustion releases more than 200 different chemical pollutants, including 14 carcinogens and 4 cocarcinogens, into the atmosphere (Alfheim and Ramdahl, 1986; Godish, 1991). Globally, but especially in developing nations where people cook with fuelwood over open fires, approximately 4 billion people suffer from continuous exposure to smoke (World Bank, 1992; WHO/UNEP, 1993; Reddy et al., 1997). In the United States, wood smoke kills 30,000 people each year (EPA, 2002). However, the pollutants from electric plants that use wood and other biomass can be controlled.

WIND POWER

For many centuries, wind power has provided energy to pump water and to run mills and other machines. Today, turbines with a capacity of at least 500 kW produce most commercially wind-generated electricity. Operating at an ideal location, one of these turbines can run at maximum 30% efficiency and yield an energy output of 1.3 million kWh (e) per year (AWEA, 2000a). An initial investment of approximately $500,000 for a 500 kW capacity turbine (Nelson, 1996), operating at 30% efficiency, will yield an input–output ratio of 1:5 over 30 years of operation (Table 19.2). During the 30-year life of the system, the annual operating costs amount to $40,500 (Nelson, 1996). The estimated cost of electricity generated is $0.07/kWh (e) (Table 19.2).

In the United States, 2502 MW of installed wind generators produce about 6.6 billion kWh of electrical energy per year (Chambers, 2000). The American Wind Energy Association (AWEA, 2000b) estimates that the United States could support a capacity of 30,000 MW by the year 2010, producing 75 billion kWh (e) per year at a capacity of 30%, or approximately 2% of the annual U.S. electrical consumption. If all economically feasible land sites were developed, the full potential of wind power would be about 675 billion kWh (e) (AWEA, 2000b). Offshore sites could provide an additional 102 billion kWh (e) (Gaudiosi, 1996), making the total estimated potential of wind power 777 billion kWh (e), or 23% of current electrical use.

Widespread development of wind power is limited by the availability of sites with sufficient wind (at least 20 km per hour) and the number of wind machines that the site can accommodate. In California's Altamont Pass Wind Resource Area, an average of one 50 kW turbine per 1.8 ha allows sufficient spacing to produce maximum power (Smith and Ilyin, 1991). Based on this figure, approximately 13,700 ha of land is needed to supply 1 billion kWh/year (Table 19.2). Because the turbines themselves occupy only approximately 2% of the area, most of the land can be used for vegetables, nursery stock, and cattle (DP Energy, 2002; NRC, 2002). However, it may be impractical to produce corn or other grains because the heavy equipment used in this type of farming could not operate easily between the turbines.

An investigation of the environmental impacts of wind energy production reveals a few hazards. Locating the wind turbines in or near the flyways of migrating birds and wildlife refuges may result in birds colliding with the supporting towers and rotating blades (Kellet, 1990). For this reason, Clarke (1991) suggests that wind farms be located at least 300 m from nature reserves to reduce the risk to birds. The estimated 13,000 wind turbines installed in the United States have killed fewer than 300 birds per year (Kerlinger, 2000). Proper siting and improved repellant technology, such as strobe lights or paint patterns, might further reduce the number of birds killed.

The rotating magnets in the turbine electrical generator produce a low level of electromagnetic interference that can affect television and radio signals within 2–3 km of large installations (IEA, 1987). Fortunately, with the widespread use of cable networks or line-of-sight microwave satellite transmission, both television and radio are unaffected by this interference.

The noise caused by rotating blades is another unavoidable side effect of wind turbine operation. Beyond 2.1 km, however, the largest turbines are inaudible even downwind. At a distance of 400 m, the noise level is about 56 decibels (IEA, 1987), corresponding roughly to the noise level of a home airconditioning unit.

SOLAR THERMAL CONVERSION SYSTEMS

Solar thermal energy systems collect the sun's radiant energy and convert it into heat. This heat can be used directly for household and industrial purposes or to produce steam to drive turbines that produce electricity. These systems range in complexity from solar ponds to electricity-generating parabolic troughs. In the material that follows, we convert thermal energy into electricity to facilitate comparison with other solar energy technologies.

Solar Ponds

Solar ponds are used to capture radiation and store the energy at temperatures of nearly 100°C. Constructed ponds can be converted into solar ponds by creating a layered salt concentration gradient. The layers prevent natural convection, trapping the heat collected from solar radiation in the bottom layer of brine. The hot brine from the bottom of the pond is piped out to use for heat, for generating electricity, or both.

For successful operation of a solar pond, the salt concentration gradient and the water level must be maintained. A solar pond covering 4000 ha loses approximately 3 billion L of water per year (750,000 L/ha/year) under arid conditions (Tabor and Doran, 1990). The solar ponds in Israel have been closed because of such problems. To counteract the water loss and the upward diffusion of salt in the ponds, the dilute salt water at the surface of the ponds has to be replaced with fresh water and salt added to the lower layer.

The efficiency of solar ponds in converting solar radiation into heat is estimated to be approximately 1:4 (i.e., 1 kWh of input provides 4 kWh of output), assuming a 30-year life for the solar pond (Table 19.2). Electricity produced by a 100 ha (1 km^2) solar pond costs approximately \$0.15 per kWh (Kishore, 1993).

Some hazards are associated with solar ponds, but most can be avoided with careful management. It is essential to use plastic liners to make the ponds leak-proof and prevent contamination of the adjacent soil and groundwater with salt. The degradation of soil quality caused by sodium chloride can be avoided by using an ammonium salt fertilizer (Hull, 1986). Burrowing animals must be kept away from the ponds by buried screening (Dickson and Yates, 1983).

Parabolic Troughs

Another solar thermal technology that concentrates solar radiation for large-scale energy production is the parabolic trough. A parabolic trough, shaped like the bottom half of a large drainpipe, reflects sunlight to a central receiver tube that runs above it. Pressurized water and other fluids are heated in the tube and used to generate steam, which can drive turbogenerators for electricity production or provide heat energy for industry.

Parabolic troughs that have entered the commercial market have the potential for efficient electricity production because they can achieve high turbine inlet temperatures (Winter et al., 1991). Assuming peak efficiency and favorable sunlight conditions, the land requirements for the central receiver technology are approximately 1100 ha per 1 billion kWh/year (Table 19.2). The energy input–output ratio is calculated to be 1:5 (Table 19.2). Solar thermal receivers are estimated to produce electricity at a cost of approximately \$0.07–\$0.09 per kWh (DOE/EREN, 2001).

The potential environmental impacts of solar thermal receivers include the accidental or emergency release of toxic chemicals used in the heat transfer system (Baechler and Lee, 1991). Water scarcity can also be a problem in arid regions.

PHOTOVOLTAIC SYSTEMS

Photovoltaic cells have the potential to provide a significant portion of future U.S. and world electrical energy (Gregory et al., 1997). Photovoltaic cells produce electricity when sunlight excites electrons in the cells. The most promising photovoltaic cells in terms of cost, mass production, and relatively high efficiency are those manufactured using silicon. Because the size of the unit is flexible and adaptable, photovoltaic cells can be used in homes, industries, and utilities. However, photovoltaic cells need improvements to make them economically competitive before their use can become widespread. Test cells have reached efficiencies ranging from 20% to 25% (Sorensen, 2000), but the durability of photovoltaic cells must be lengthened and production costs reduced several times to make their use economically feasible.

Production of electricity from photovoltaic cells currently costs \$0.12–\$0.20 per kWh (DOE, 2000). Using massproduced photovoltaic cells with about 18% efficiency, 1 billion kWh/year of electricity could be produced on approximately 2800 ha of land, which is sufficient to supply the electrical energy needs of 100,000 people (Table 19.2; DOE, 2001). Locating the photovoltaic cells on the roofs of homes, industries, and other buildings would reduce the need for additional land by an estimated 20% and reduce transmission costs. However, because storage systems such as batteries cannot store energy for extended periods, photovoltaics require conventional backup systems.

The energy input for making the structural materials of a photovoltaic system capable of delivering 1 billion kWh during a life of 30 years is calculated to be approximately 143 million kWh. Thus, the energy input–output ratio for the modules is about 1:7 (Table 19.2; Knapp and Jester, 2000).

The major environmental problem associated with photovoltaic systems is the use of toxic chemicals, such as cadmium sulfide and gallium arsenide, in their manufacture (Bradley, 1997). Because these chemicals are highly toxic and persist in the environment for centuries, disposal and recycling of the materials in inoperative cells could become a major problem.

HYDROGEN AND FUEL CELLS

Using solar electric technologies for its production, gaseous hydrogen produced by the electrolysis of water has the potential to serve as a renewable fuel to power vehicles and generate electricity. In addition, hydrogen can be used as an energy storage system for various electric solar energy technologies (Winter and Nitsch, 1988; MacKenzie, 1994).

The material and energy inputs for a hydrogen production facility are primarily those needed to build and run a solar electric production facility, like photovoltaics and hydropower. The energy required to produce 1 billion kWh of hydrogen is 1.4 billion kWh of electricity (Ogden and Nitsch, 1993; Kreutz and Ogden, 2000). Photovoltaic cells (Table 19.2) currently require 2800 ha per 1 billion kWh; therefore, a total of 3920 ha would be needed to supply the equivalent of 1 billion kWh of hydrogen fuel. The water required for electrolytic production of 1 billion kWh per year equivalent of hydrogen is approximately 300 million L/year (Voigt, 1984). On a per capita basis, this amounts to 3000 L of water per year. The liquefaction of hydrogen requires significant energy inputs because the hydrogen must be cooled to about –253°C and pressurized. About 30% of the hydrogen energy is required for the liquefaction process (Peschka, 1992; Trainer, 1995).

Liquid hydrogen fuel occupies about three times the volume of an energy equivalent of gasoline. Storing 25 kg of gasoline requires a tank weighing 17 kg, whereas storing 9.5 kg of hydrogen requires a tank weighing 55 kg (Peschka, 1987, 1992). Although the hydrogen storage vessel is large, hydrogen burns 1.33 times more efficiently than gasoline in automobiles (Bockris and Wass, 1988). In tests, a Plymouth liquid hydrogen vehicle, with a tank weighing about 90 kg and 144 L of liquid hydrogen, has a cruising range in traffic of 480 km with a fuel efficiency of 3.3 km/L (MacKenzie, 1994). However, even taking into account its greater fuel efficiency, commercial hydrogen is more expensive at present than gasoline. About 3.7 kg of gasoline sells for about $1.20, whereas 1 kg of liquid hydrogen with the same energy equivalent sells for about $2.70 (Ecoglobe, 2001).

Fuel cells using hydrogen are an environmentally clean, quiet, and efficient method of generating electricity and heat from natural gas and other fuels. Fuel cells are electrochemical devices, much like storage batteries, that use energy from the chemical synthesis of water to produce electricity. The fuel cell provides a way to burn hydrogen using oxygen, capturing the electrical energy released (Larminie and Dicks, 2000). Stored hydrogen is fed into a fuel cell apparatus along with oxygen from the atmosphere, producing effective electrical energy (Larminie and Dicks, 2000). The conversion of hydrogen into direct current (DC) using a fuel cell is about 40% efficient.

The major costs of fuel cells are the electrolytes, catalysts, and storage. Phosphoric acid fuel cells (PAFCs) and proton exchange membrane fuel cells (PEMs) are the most widely used and most efficient. PAFCs have an efficiency of 40%–45%, compared to diesel engine efficiency of 36%–39%. However, PAFCs are complex and have high costs because they operate at temperatures of 50°C–100°C (DOE, 1999). A fuel cell PEM engine costs $500/kW, compared to $50/kW for a gasoline engine (DOE, 1999), leading to a total price of approximately $100,000 for an automobile running on fuel cells (Ogden and Nitsch, 1993). These prices are for specially built vehicles, and the costs should decline as they are massproduced. There is high demand for fuel cell-equipped vehicles in the United States (Larminie and Dicks, 2000).

Hydrogen has serious explosive risks because it is difficult to contain within steel tanks. Mixing with oxygen can result in intense flames because hydrogen burns more quickly than gasoline and diesel fuels (Peschka, 1992). Other environmental impacts are associated with the solar electric technologies used in hydrogen production. Water for the production of hydrogen may be a problem in arid regions of the United States and the world.

PASSIVE HEATING AND COOLING OF BUILDINGS

Approximately 20% (5.5 kWh × 1012 [19 quads]) of the fossil energy used each year in the United States is used for heating and cooling buildings and for heating hot water (USBC, 2001). At present only about 0.3 quads of energy are being saved by technologies that employ passive and active solar heating and cooling of buildings (Table 19.3), which means that the potential for energy savings through increased energy efficiency and through the use of solar technologies for buildings is tremendous. Estimates suggest that the amount of energy lost through poorly insulated windows and doors is approximately 1.1 × 1012 kWh (3.8 quads) each year—the approximate energy equivalent of all the oil pumped in Alaska per year (EETD, 2001).

Both new and established homes can be fitted with solar heating and cooling systems. Installing passive solar systems in new homes is less costly than retrofitting existing homes. Based on the cost of construction and the amount of energy saved, measured in terms of reduced heating and cooling costs over 10 years, the estimated returns of passive solar heating and cooling range from $0.02 to $0.10/kWh (Balcomb, 1992).

Improvements in passive solar technology are making it more effective and less expensive than in the past (Bilgen, 2000). Current research in window design focuses on the development of "superwindows" with high insulating values and "smart" or electrochromic windows that can respond to electric current, temperature, or sunlight to control the admission of light energy (Roos and Karlsson, 1994; DOE, 2000).

Although none of the passive heating and cooling technologies requires land, they are not without problems. Some indirect problems with land use may arise, concerning such issues as tree removal, shading, and rights to the sun (Simpson and McPherson, 1998). Glare from collectors and glazing may create hazards to automobile drivers and airline pilots. Also, when houses are designed to be extremely energy efficient and airtight, indoor air quality becomes a concern because of indoor air pollutants. However, well-designed ventilation systems with heat exchangers can take care of this problem.

GEOTHERMAL SYSTEMS

Geothermal energy uses natural heat present in Earth's interior. Examples are geysers and hot springs, like those at Yellowstone National Park in the United States. Geothermal energy sources are divided into three categories: hydrothermal, geopressured-geothermal, and hot dry rock. The hydrothermal system is the simplest and most commonly used one for electricity generation. The boiling liquid underground is utilized through wells, high internal pressure drives, or pumps.

In the United States, nearly 3000 MW of installed electric generation comes from hydrothermal resources, and this figure is projected to increase by 1500 MW within the next 20 years (DOE/EIA, 1991, 2001).

Most of the geothermal sites for electrical generation are located in California, Nevada, and Utah (DOE/EIA, 1991). Electrical generation costs for geothermal plants in the West range from \$0.06 to \$0.30 per kWh (Gawlik and Kutscher, 2000), suggesting that this technology offers potential to produce electricity economically. The U.S. Department of Energy and the Energy Information Administration (DOE/EIA, 1991, 2001) project that geothermal electric generation may grow three- to fourfold during the next 20–40 years. However, other investigations are not as optimistic and, in fact, suggest that geothermal energy systems are not renewable because the sources tend to decline over 40–100 years (Bradley, 1997; Youngquist, 1997; Cassedy, 2000). Existing drilling opportunities for geothermal resources are limited to a few sites in the United States and the world (Youngquist, 1997).

Potential environmental problems with geothermal energy include water shortages, air pollution, waste effluent disposal, subsidence, and noise (DOE/EIA, 1991). The wastes produced in the sludge include toxic metals such as arsenic, boron, lead, mercury, radon, and vanadium (DOE/EIA, 1991). Water shortages are an important limitation in some regions (OECD, 1998). Geothermal systems produce hydrogen sulfide, a potential air pollutant; however, this product could be processed and removed for use in industry (Bradley, 1997). Overall, the environmental costs of geothermal energy appear to be minimal relative to those of fossil fuel systems.

BIOGAS

Wet biomass materials can be converted effectively into usable energy with anaerobic microbes. In the United States, livestock dung is normally gravity fed or intermittently pumped through a plug-flow digester, which is a long, lined, insulated pit in the Earth. Bacteria break down volatile solids in the manure and convert them into methane gas (65%) and carbon dioxide (35%) (Pimentel, 2001). A flexible liner stretches over the pit and collects the biogas, inflating like a balloon. The biogas may be used to heat the digester, to heat farm buildings, or to produce electricity. A large facility capable of processing the dung from 500 cows costs nearly \$300,000 (EPA, 2000).

The Environmental Protection Agency (EPA, 2000) estimates that more than 2000 digesters could be economically installed in the United States.

The amount of biogas produced is determined by the temperature of the system, the microbes present, the volatile solids content of the feedstock, and the retention time. A plug-flow digester with an average manure retention time of about 16 days under winter conditions (−17.4°C) produced 452,000 kcal/day and used 262,000 kcal/day to heat the digester to 35°C (Jewell et al., 1980). Using the same digester during summer conditions (15.6°C) but reducing the retention time to 10.4 days, the yield in biogas was 524,000 kcal/day, with 157,000 kcal/day used for heating the digester (Jewell et al., 1980). The energy input–output ratios for the digester in these winter and summer conditions were 1:1.7 and 1:3.3, respectively. The energy output of biogas digesters has changed little over the past two decades (Sommer and Husted, 1995; Hartman et al., 2000).

In developing countries such as India, biogas digesters typically treat the dung from 15 to 30 cattle from a single family or a small village. The resulting energy produced for cooking saves forests and preserves the nutrients in the dung. The capital cost for an Indian biogas unit ranges from $500 to $900 (Kishore, 1993). The price value of one kWh of biogas in India is about $0.06 (Dutta et al., 1997). The total cost of producing about 10 million kcal of biogas is estimated to be $321, assuming the cost of labor to be $7/h; hence, the biogas has a value of $356. Manure processed for biogas has little odor and retains its fertilizer value (Pimentel, 2001).

BIOFUELS: ETHANOL, METHANOL, AND VEGETABLE OIL

Petroleum, essential for the transportation sector and the chemical industry, makes up approximately 40% of total U.S. energy consumption. Clearly, as the supply diminishes, a shift from petroleum to alternative liquid fuels will be necessary. This analysis focuses on the potential of three fuel types: ethanol, methanol, and vegetable oil. Burned in internal combustion engines, these fuels release less carbon monoxide and sulfur dioxide than gasoline and diesel fuels; however, because the production of most of these biofuels requires more total fossil energy than they produce as a biofuel, they contribute to air pollution and global warming (Pimentel, 2001).

Ethanol production in the United States using corn is heavily subsidized by public tax money (Pimentel, 2001). However, numerous studies have concluded that ethanol production does not enhance energy security, is not a renewable energy source, is not an economical fuel, and does not ensure clean air. Furthermore, its production uses land suitable for crop production (Weisz and Marshall, 1980; Pimentel, 1991; Youngquist, 1997; Pimentel, 2001). Ethanol produced using sugarcane is more energy efficient than that produced using corn; however, more fossil energy is still required to produce a liter of ethanol than the energy output in ethanol (Pimentel et al., 1988).

The total energy input to produce 1000 L of ethanol in a large plant is 8.7 million kcal (Pimentel, 2001). However, 1000 L of ethanol has an energy value of only 5.1 million kcal and represents a net energy loss of 3.6 million kcal per 1000 L of ethanol produced. Put another way, about 70% more energy is required to produce ethanol than the energy that ethanol contains (Pimentel, 2001).

Methanol can be produced from a gasifier–pyrolysis reactor using biomass as a feedstock (Hos and Groenveld, 1987; Jenkins, 1999). The yield from 1 t of dry wood is about 370 L of methanol (Ellington et al., 1993; Osburn and Osburn, 2001). For a plant with economies of scale to operate efficiently, more than 1.5 million ha of sustainable forest would be required to supply it (Pimentel, 2001). Biomass is generally not available in such enormous quantities, even from extensive forests, at acceptable prices. Most methanol today is produced from natural gas.

Processed vegetable oils from sunflower, soybean, rape, and other oil plants can be used as fuel in diesel engines. Unfortunately, producing vegetable oils for use in diesel engines is costly in terms of both time and energy (Pimentel, 2001).

TRANSITION TO RENEWABLE ENERGY ALTERNATIVES

Despite the environmental and economic benefits of renewable energy, the transition to large-scale use of this energy presents some difficulties. Renewable energy technologies, all of which require land for collection and production, must compete with agriculture, forestry, and urbanization for land in the United States and the world. The United States already devotes as much prime cropland per capita to food production as is possible, given the size of the U.S. population, and the world has only half the cropland per capita that it needs for a diverse diet and an adequate supply of essential nutrients (USBC, 2001; USDA, 2001). In fact, more than 3 billion people are already malnourished in the world (WHO, 1996, 2000). According to some sources, the U.S. and world population could double in the next 50 and 70 years, respectively; all the available cropland and forest land would be required to provide vital food and forest products (PRB, 2001).

As the growing U.S. and world populations demand increased electricity and liquid fuels, constraints like land availability and high investment costs will restrict the potential development of renewable energy technologies. Energy use is projected on the basis of current growth to increase from the current consumption of nearly 100 quads to approximately 145 quads by 2050 (USBC, 2001). Land availability is also a problem, with the U.S. population increasing by about 3.3 million people each year (USBC, 2001). Each person added requires about 0.4 ha (1 acre) of land for urbanization and highways and about 0.5 ha of cropland (Vesterby and Krupa, 2001).

Renewable energy systems require more labor than fossil energy systems. For example, wood-fired steam plants require several times more workers than coal-fired plants (Pimentel et al., 1988; Giampietro et al., 1998).

An additional complication in the transition to renewable energies is the relationship between the location of ideal production sites and large population centers. Ideal locations for renewable energy technologies are often remote, such as the deserts of the American Southwest or wind farms located kilometers offshore. Although these sites provide the most efficient generation of energy, delivering this energy to consumers presents a logistical problem. For instance, networks of distribution cables must be installed, costing about $179,000/km of 115-kV lines (DOE/EIA, 2002). A percentage of the power delivered is lost as a function of electrical resistance in the distribution cable. There are five complex alternating current electrical networks in North America, and four of these are tied together by DC lines (Casazz, 1996).

Based on these networks, it is estimated that electricity can be transmitted up to 1500 km.

A sixfold increase in installed technologies would provide the United States with approximately 13.1 × 1012 (thermal) kWh (45 quads) of energy, less than half of current U.S. consumption (Table 19.1). This level of energy production would require about 159 million ha of land (17% of U.S. land area). This percentage is an estimate and could increase or decrease, depending on how the technologies evolve and energy conservation is encouraged.

Worldwide, approximately 408 quads of all types of energy are used by the population of more than 6 billion people (Table 19.1). Using available renewable energy technologies, an estimated 200 quads of renewable energy could be produced worldwide on about 20% of the land area of the world. A self-sustaining renewable energy system producing 200 quads of energy per year for about 2 billion people would provide each person with about 5000 L of oil equivalents per year—approximately half of America's current consumption per year, but an increase for most people of the world (Pimentel et al., 1999).

The first priority of the U.S. energy program should be for individuals, communities, and industries to conserve fossil fuel resources by using renewable resources and by reducing consumption. Other developed countries have proved that high productivity and a high standard of living can be achieved with the use of half the energy expenditure of the United States (Pimentel et al., 1999). In the United States, fossil energy subsidies of approximately $40 billion/year should be withdrawn and the savings invested in renewable energy research and education to encourage the development and implementation of renewable technologies. If the United States became a leader in the development of renewable energy technologies, then it would likely capture the world market for this industry (Shute, 2001).

CONCLUSION

This assessment of renewable energy technologies confirms that these techniques have the potential to provide the nation with alternatives to meet approximately half of future U.S. energy needs. To develop this potential, the United States would have to commit to the development and implementation of nonfossil fuel technologies and energy conservation. The implementation of renewable energy technologies would reduce many of the current environmental problems associated with fossil fuel production and use.

The immediate priority of the United States should be to speed the transition from reliance on nonrenewable fossil energy resources to reliance on renewable energy technologies. Various combinations of renewable technologies should be developed, consistent with the characteristics of the different geographic regions in the United States. A combination of the renewable technologies listed in Table 19.3 should provide the United States with an estimated 45 quads of renewable energy by 2050. These technologies should be able to provide this much energy without interfering with required food and forest production.

If the United States does not commit itself to the transition from fossil to renewable energy during the next decade or two, the economy and national security will be at risk. It is of paramount importance that U.S. residents work together to conserve energy, land, water, and biological resources. To ensure a reasonable standard of living in the future, there must be a fair balance between human population density and use of energy, land, water, and biological resources.

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REFERENCES

Alfheim, I. and T. Ramdahl. 1986. *Mutagenic and Carcinogenic Compounds from Energy Generation*. Oslo (Norway): Senter for Industriforkning.

American Petroleum Institute (API). 1999. *Basic Petroleum Data Book*. Washington, D.C.: API.

American Wind Energy Association (AWEA). 2000a. Wind energy and climate change (20 October 2002; www.awea.org/pubs/factsheets/climate.pdf).

American Wind Energy Association (AWEA). 2000b. Wind energy: The fuel of the future is ready today (20 October 2002; www.awea.org/pubs/factsheets/wetoday.pdf).

Baechler, M.C. and A.D. Lee. 1991. Implications of environmental externalities assessments for solar thermal power plants. In T.T. Mancini, K. Watanabe, and D.E. Klett (eds.), *Solar Engineering 1991*, pp. 151–158. New York: American Society of Mechanical Engineers.

Balcomb, J.D. 1992. Introduction. In J.D. Balcomb (ed.), *Passive Solar Buildings*, pp. 1–37. Cambridge, MA: Massachusetts Institute of Technology Press.

Bilgen, E. 2000. Passive solar massive wall systems with fins attached on the heated wall and without glazing. *Journal of Solar Energy Engineering* 122: 30–34.

Birdsey, R.A. 1992. *Carbon Storage and Accumulation in United States Forest Ecosystems.* Washington, D.C.: USDA Forest Service.

Bockris, J.O.M. and J.C. Wass. 1988. About the real economics of massive hydrogen production at 2010 AD. In T.N. Veziroglu and A.N. Protsenko (eds.), *Hydrogen Energy Progress,* pp. 101–151. VII. New York: Pergamon Press.

Bradley, R.L. 1997. *Renewable Energy: Not Cheap, Not "Green."* Washington, D.C.: Cato Institute.

British Petroleum (BP). 2001. *British Petroleum Statistical Review of World Energy.* London: British Petroleum Corporate Communications Services.

Brown, L.R. and P.B. Moyle. 1993. Distribution, ecology, and status of the fishes of the San Joaquin River drainage, California. *California Fish and Game* 79: 96–114.

Casazz, J.A. 1996. Transmission access and retail wheeling: The key questions. In M. Einhorn and R. Siddiqui (eds.), *Electricity Transmission Pricing and Technology*, pp. 77–102. Boston, MA: Kluwer Academic.

Cassedy, E.S. 2000. *Prospects for Sustainable Energy*. New York: Cambridge University Press.

Chambers, A. 2000. Wind power spins into contention. *Power Engineering* 104: 14–18.

Clarke, A. 1991. Wind energy progress and potential. *Energy Policy* 19: 742–755.

Dickson, Y.L. and B.C. Yates. 1983. *Examination of the Environmental Effects of Salt-Gradient Solar Ponds in the Red River Basin of Texas*. Denton, TX: North Texas State University.

DP Energy. 2002. Got wind? (October 20, 2002; www.dpenergy.com/page7.htm).

Duncan, R.C. 2001. World energy production, population growth, and the road to the Olduvai Gorge. *Population and Environment* 22: 503–522.

Dutta, S., I.H. Rehman, P. Malhortra, and R.P. Venkata. 1997. *Biogas: The Indian NGO Experience*. Delhi, India: Tata Energy Research Institute.

Ecoglobe. 2001. Hydrogen energy (November 6, 2002; www.ecoglobe.org.nz/energy/hydrogen.htm).

Ellington, R.T., M. Meo, and D.A. El-Sayed. The net greenhouse warming forcing of methanol produced from biomass. *Biomass and Bioenergy* 4: 405–418.

Environmental Energy Technologies Division–Lawrence Berkeley National Laboratory (EETD). 2001. Home energy saver (October 20, 2002; http://hes.lbl.gov).

Federal Energy Regulatory Commission (FERC). 1984. *Hydroelectric Power Resources of the United States*. Washington, D.C.: FERC.

Ferguson, A.R.B. 2001. *Biomass and Energy*. Manchester, UK: Optimum Population Trust.

Gaudiosi, G. 1996. Offshore wind energy in the world context. *Renewable Energy* 9: 899–904.

Gawlik, K. and C. Kutscher. 2000. *Investigation of the Opportunity for Small-Scale Geothermal Power Plants in the Western United States*. Golden, CO: National Renewable Energy Laboratory.

Giampietro, M., A. Ulgiati, and D. Pimentel. 1998. Feasibility of large-scale biofuel production. *BioScience* 47: 587–600.

Gleick, P.H. and A.D. Adams. 2000. *Water: The Potential Consequences of Climate Variability and Change*. Oakland, CA: Pacific Institute for Studies in Development, Environment, and Security.

Godish, T. 1991. *Air Quality*. Chelsea, MI: Lewis Publishers.

Gregory, J., S. Silviera, A. Derrick, P. Cowley, C. Allinson, and O. Paish. 1997. *Financing Renewable Energy Projects: A Guide for Development Workers*. London: Intermediate Technology Publications.

Hall, D.O. 1992. *Biomass*. Washington, D.C.: World Bank.

Hartman, H., I. Angelidake, and B.K. Ahring. 2000. Increase of anaerobic degradation of particulate organic matter in full-scale biogas plants by mechanical maceration. *Water Science and Technology* 41: 145–153.

Hos, J.J. and M.J. Groenveld. 1987. Biomass gasification. In D.O. Hall and R.P. Overend (eds.), *Biomass*, pp. 237–255. Chichester, UK: John Wiley & Sons.

Hull, J.R. 1986. Solar ponds using ammonium salts. *Solar Energy* 36: 551–558.

International Commission on Large Dams (ICLD). 1988. *World Register of Dams*. Paris: ICLD.

International Energy Agency (IEA). 1987. *Renewable Sources of Energy*. Paris: IEA.

Jenkins, B.M. 1999. Pyrolysis gas. In O. Kitani, T. Jungbluth, R.M. Peart, A. Ramdani (eds.), *CIGAR Handbook of Agricultural Engineering*, pp. 222–248. St. Joseph, MI: American Society of Agricultural Engineering.

Jewell, W.J., S. Dell'orto, K.J. Fanfoli, T.D. Hates, A.P. Leuschner, D.F. Sherman. 1980. *Anaerobic Fermentation of Agricultural Residue: Potential for Improvement and Implementation*. Washington, D.C.: U.S. Department of Energy.

Kellet, J. 1990. The environmental impacts of wind energy developments. *Town Planning Review* 91: 139–154.

Kerlinger, P. 2000. *Avian Mortality and Communication Towers: A Review of Recent Literature, Research, and Methodology.* Washington, D.C.: U.S. Fish and Wildlife Service, Office of Migratory Bird Management.

Kishore, V.V.N. 1993. Economics of solar pond generation. In V.V.N. Kishore (ed.), *Renewable Energy Utilization: Scope, Economics, and Perspectives*, pp. 53–68. New Delhi, India: Tata Energy Research Institute.

Kitani, O. 1999. Biomass resources. In O. Kitani, T. Jungbluth, R.M. Peart, and A. Ramdami (eds.), *Energy and Biomass Engineering*, pp. 6–11. St. Joseph, MI: American Society of Agricultural Engineers.

Knapp, K.E. and T.L. Jester. 2000. An empirical perspective on the energy payback time for photovoltaic modules. American Solar Energy Society Solar 2000 Conference; June 16–21, 2000; Madison, WI (November 8, 2002; www.ecotopia.com/apollo2/knapp/pvepbtpaper.pdf).

Kreutz, T.G. and J.M Ogden. 2000. Assessment of hydrogen-fueled proton exchange membrane fuel cells for distributed generation and cogeneration. *Proceedings of the 2000 U.S. Department of Energy Hydrogen Program Review; Washington, D.C.* NREL/CP-570-28890.

Larminie, J. and A. Dicks. 2000. *Fuel Cell Systems Explained*. Chichester, UK: John Wiley & Sons.

Ligon, F.K., W.E. Dietrich, and W.J. Trush. 1995. Downstream ecological effects of dams: A geomorphic perspective. *BioScience* 45: 183–192.

MacKenzie, J.J. 1994. *The Keys to the Car: Electric and Hydrogen Vehicles for the 21st Century.* Washington, D.C.: World Resources Institute.

Natural Resources Canada (NRC). 2002. Technologies and applications (October 20, 2002; www.canren.gc.ca/tech_appl/index.asp?Cald=6&Pgld=232).

Nelson, V. 1996. *Wind Energy and Wind Turbines.* Canyon, TX: Alternative Energy Institute.

Nilsson, C. and K. Berggren. 2000. Alterations of riparian ecosystems caused by river regulation. *BioScience* 50: 783–792.

Ogden, J.M. and J. Nitsch. 1993. Solar hydrogen. In T.B. Johansson, H. Kelly, A.K.N. Reddy, and R.H. Williams (eds.), *Renewable Energy: Sources for Fuels and Electricity*, pp. 925–1010. Washington, D.C.: Island Press.

Organisation for Economic Co-operation and Development (OECD). 1998. *Environmental Impacts of Renewable Energy.* Paris: OECD.

Osburn, L. and J. Osburn. 2001. Biomass resources for energy and industry (October 20, 2002; www.ratical.com/renewables/biomass.html).

Peschka, W. 1987. The status of handling and storage techniques for liquid hydrogen in motor vehicles. *International Journal of Hydrogen Energy* 12: 753–764.

Peschka, W. 1992. *Liquid Hydrogen: Fuel of the Future*. New York: Springer Verlag.

Pimentel, D. 1991. Ethanol fuels: Energy security, economics, and the environment. *Journal of Agricultural and Environmental Ethics* 4: 1–13.

Pimentel, D. 2001. The limitations of biomass energy. In *Encyclopedia of Physical Sciences and Technology*, pp. 159–171. San Diego, CA: Academic Press.

Pimentel, D., A.F. Warneke, W.S. Teel, K.A. Schwab, N.J. Simcox, D.M. Evert, K.D. Baenisch, and M.R. Aaron. 1988. Food versus biomass fuel: Socioeconomic and environmental impacts in the United States, Brazil, India, and Kenya. *Advanced Food Research* 32: 185–238.

Pimentel, D. et al. 1994. Renewable energy: Economic and environmental issues. *BioScience* 44: 536–547.

Pimentel, D., O. Bailey, P. Kim, E. Mullaney, J. Calabrese, F. Walman, F. Nelson, and X. Yao. 1999. Will the limits of the Earth's resources control human populations? *Environment, Development and Sustainability* 1: 19–39.

Population Reference Bureau (PRB). 2001. *World Population Data Sheet*. Washington, D.C.: PRB.

Reddy, A.K.N., R.H. Williams, and T.B. Johansson. 1997. *Energy after Rio: Prospects and Challenges*. New York: United Nations Development Programme.

Repetto, R. 1992. Accounting for environmental assets. *Scientific American* 263: 94–100.

Roos, A. and B. Karlsson. 1994. Optical and thermal characterization of multiple glazed windows with low U-values. *Solar Energy* 52: 315–325.

Schneider, S.H., W.E. Easterling, and L.O. Mearms. 2000. Adaptation: Sensitivity to natural variability, agent assumptions, and dynamic climatic changes. *Climatic Change* 45: 203–221.

Schumer, C.E. 2001. New Analysis Shows America on Precipice of an Energy Crunch. Press Release of Senator Charles E. Schumer. April 26, 2001.

Shute, N. 2001. The weather: Global warming could cause droughts, disease, and political upheaval. *U.S. News & World Report*, November 11, 2001, pp. 44–52.

Simpson, J.R. and E.G. McPherson. 1998. Simulation of tree shade impacts on residential energy use for space conditioning in Sacramento. *Atmospheric Environment* 32: 69–74.

Smil, V. 1994. *Energy in World History*. Boulder, CO: Westview Press.

Smith, D.R. and M.A. Ilyin. 1991. Wind and solar energy: Costs and value. In D.E. Berg and P.S. Veers (eds.), *The American Society of Mechanical Engineers 10th Annual Wind Energy Symposium*, pp. 29–32. January 20–23, 1991; Houston, TX.

Sommer, S.G. and S. Husted. 1995. The chemical buffer system in raw and digested animal slurry. *Journal of Agricultural Science* 124: 45–53.

Sorensen, B. 2000. *Renewable Energy: Its Physics, Engineering, Use, Environmental Impact, Economics, and Planning Aspects*. San Diego, CA: Academic Press.

Tabor, H.Z. and B. Doran. 1990. The Beith Ha'arva 5MW (e) solar pond power plant (SPPP): Progress report. *Solar Energy* 45: 247–253.

Trainer, F.E. 1995. Can renewable energy sources sustain affluent society? *Energy Policy* 23: 1009–1026.

U.S. Bureau of the Census (USBC). 2001. *Statistical Abstract of the United States 1999*. Washington, D.C.: USBC.

U.S. Department of Agriculture (USDA). 2001. *Agricultural Statistics*. Washington, D.C.: USDA.

U.S. Department of Energy (DOE). 1999. *Fuel Cells for the 21st Century: Collaboration for a Leap in Efficiency and Cost Reduction*. Washington, D.C.: DOE.

U.S. Department of Energy (DOE). 2000. Consumer energy information: EREC fact sheets (October 20, 2002; www.eren.doe.gov/erec/factsheets/eewindows.html).

U.S. Department of Energy (DOE). 2001. Energy efficiency and renewable energy network (January 16, 2001; www.eren.doe.gov/state_energy/tech_solar.cfm?state=NY).

U.S. Department of Energy–Energy Information Administration (DOE/EIA). 1991. *Geothermal Energy in Western United States and Hawaii: Resources and Projected Electricity Generation Supplies*. Washington, D.C.: DOE/EIA.

U.S. Department of Energy–Energy Information Administration (DOE/EIA). 2001. *Annual Energy Outlook with Projections to 2020*. Washington, D.C.: DOE/EIA.

U.S. Department of Energy–Energy Information Administration (DOE/EIA). 2002. *Annual Energy Outlook with Projections to 2020*. Washington, D.C.: DOE/EIA.

U.S. Department of Energy–Energy Efficiency and Renewable Energy Network (DOE/EREN). 2001. Solar parabolic troughs: Concentrating solar power (February 28, 2001; www.eren.doe.gov/csp/faqs.html).

U.S. Environmental Protection Agency (EPA). 2000. *AgSTAR Digest*. Washington, D.C.: EPA.

U.S. Environmental Protection Agency (EPA). 2002. Wood smoke (October 20, 2002; http://216.239.51.100/search?q=cache:bnh0QlyPH20C:www.webcom.com/~bi/brochure.pdf+wood+smoke+pollution&hl=en&ie=UTF-8).

Vesterby, M. and S. Krupa. 2001. Major Uses of Land in the United States, 1997. Washington, D.C.: Resource Economics Division, Economic Research Service, USDA. Statistical Bulletin No. 973 (October 20, 2002; www.ers.usda.gov/publications/sb973/).

Voigt, C. 1984. Material and energy requirements of solar hydrogen plants. *International Journal of Hydrogen Energy* 9: 491–500.

Weisz, P.B. and J.F. Marshall. 1980. *Fuels from Biomass: A Critical Analysis of Technology and Economics*. New York: Marcel Dekker.

Winter, C.J. and J. Nitsch. 1988. *Hydrogen as an Energy Carrier: Technologies, Systems, and Economy*. Berlin: Springer-Verlag.

Winter, C.J., Meineke, W., and A. Neumann. 1991. Solar thermal power plants: No need for energy raw material—only conversion technologies pose environmental questions. In M.E. Arden, S.M.A. Burley, and M. Coleman (eds.), *1991 Solar World Congress*, pp. 1981–1986. Oxford, UK: Pergamon Press.

World Bank. 1992. *China: Long-Term Issues and Options in the Health Transition*. Washington, D.C.: World Bank.

World Health Organization (WHO). 1996. Micronutrient Malnutrition: Half of the World's Population Affected. Geneva, Switzerland: WHO. Press release.

World Health Organization (WHO). 2000. Malnutrition worldwide (October 20, 2002; www.who.int/nut/malnutrition_worldwide.htm).

World Health Organization–United Nations Environment Programme (WHO/UNEP). 1993. Urban Air Pollution in Megacities of the World. Geneva, Switzerland: WHO/UNEP.

Youngquist, W. 1997. *GeoDestinies: The Inevitable Control of Earth Resources over Nations and Individuals*. Portland, OR: National Book Company.