ENERGY USE, HUMAN

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I. Patterns and Scale of Human Energy Use
II. Implications of the Laws of Thermodynamics
III. Biodiversity Impacts of Industrial Energy
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GLOSSARY

energy The capacity to perform work. Potential energy is this capacity stored as position (e.g., in a gravitational or electromagnetic field) or as structure (e.g., chemical or nuclear bonds). Kinetic energy is this capacity as manifested by the motion of matter. The joule (J) is the common SI unit of energy, where 1 J equals the amount of energy required to increase by one Kelvin the temperature of one gram of water. Other units include kilocalories (kcal), kilowatt-hours (kWh), and British thermal units (BTU).

energy, industrial Forms of energy generally transformed in bulk at centralized facilities by means of complex technology. The major forms of industrial energy are oil, coal, natural gas, nuclear, and hydroelectric. In addition to hydroelectric, industrial energy also includes other technologically complex methods of harnessing renewable energy, including photovoltaics, electricity-generating wind turbines, and geothermal turbines.

energy, nonrenewable Forms of energy whose transformation consumes the energy source. The major forms include oil, coal, natural gas, and nuclear.

energy, renewable Forms of energy whose transformation does not consume the ultimate source of the energy, harnessing instead solar radiation, wind, the motion of water, or geologic heat. The major forms of renewable energy are solar, biomass, wind, hydropower, and geothermal. The forms of renewable energy that depend on complex technology are forms of industrial energy. The simpler renewable systems are forms of traditional energy.

energy, traditional Forms of energy generally dispersed in nature, renewable, utilized in small quantities by rural populations, and often not counted in government statistics. The principal forms of traditional energy are firewood, charcoal, crop residues, dung, and small wind and water mills.

energy efficiency A measure of the performance of an energy system. First law efficiency, the most commonly used measure, equals the ratio of desired energy output to the energy input. Second law efficiency equals the ratio of the heat or work usefully transferred by a system to the maximum possible heat or work usefully transferable by any system using the same energy input.

entropy A measure of disorder or randomness at the microscopic level. The entropy of a completely ordered system (e.g., a system at a temperature of absolute zero) is zero.

fossil fuels Forms of stored energy produced by the action of pressure and temperature on organic matter buried over geologic time. The major types of fossil fuels are oil, natural gas, and coal.

law of thermodynamics, first Physical principle that energy is neither created nor destroyed, only converted between different forms. Energy is therefore conserved. In thermodynamic terms, the change in energy of a system equals the difference of the heat absorbed by the system and the work performed by the system on its surroundings.

law of thermodynamics, second Physical principle that any system will tend to change toward a condition of increasing disorder and randomness. In thermodynamic terms, entropy must increase for spontaneous change to occur in an isolated system.

power The rate of energy transformation over time. The watt (W) is the common SI unit of power, where 1 W equals the power expended by the transformation of one joule in one second.

HUMAN ENERGY USE is the extraction, collection, harnessing, and conversion of energy into forms that available technologies can utilize. Our energy use directly alters patterns of biodiversity through changes in land use and through industrial pollution. Indirectly, human energy use is changing global biodiversity through the emission of greenhouse gases that cause global climate change and through other broad environmental effects of industrialization. Whereas the direct effects cause acute damage, the indirect effects generally induce chronic harm. Because human energy use is equivalent to the product of population, per capita economic production, and energy use per unit of economic production, each of these factors can exert an equivalent indirect impact on biodiversity. Several other chapters in the *Encyclopedia of Biodiversity* cover important topics closely related to human energy use. Consequently, this chapter focuses on issues most unique to human energy use. Related entries include Acid Rain and Depositions; Air Pollution; Economic Growth and the Environment; Greenhouse Effect; Pollution, Overview.

I. PATTERNS AND SCALE OF HUMAN ENERGY USE

We use energy both to meet our subsistence needs and to satisfy our wants. In a subsistence society, a farmer's wife will burn wood to cook the day's meals. In an industrial society, a couple will jump in the car on Saturday night to go to a movie. Yet the forms of energy involved in these activities—wood, gasoline, electricity—constitute just the means to desired end-uses—cooking, driving, operating a theater—that ultimately provide unique services—food, transportation, entertainment.

As used by humans, energy falls into two broad categories: industrial and traditional. Industrial energy includes those forms of energy generally transformed in bulk at centralized facilities by means of complex technology. In general, these forms fuel the technology developed in the two-and-a-half centuries that have passed since the Industrial Revolution. The major forms of industrial energy are oil, coal, natural gas, nuclear, and hydroelectric. Industrial energy also includes other technologically complex methods of harnessing solar radiation, wind, and heat, including photovoltaics, electricity-generating wind turbines, and geothermal turbines.

Traditional energy includes those forms generally dispersed in nature and utilized in small quantities by rural people. The principal forms are firewood, charcoal, crop residues, dung, and small wind and water mills. Humans most depended on these forms of energy in the early stages of the development of the species. Because traditional energy sources occur widely and because their transformation does not rely on complex technology, they constitute the most important sources today for rural people in the less industrialized parts of the world. In most cases, a rural household will harvest its own traditional energy sources for its own needs. Because no commercial transaction occurs in these situations, and because most governments do not regulate the use of traditional sources, official statistics do not closely track traditional energy use.

Traditional energy is one form of renewable energy, which includes those forms of energy whose transformation does not consume the ultimate source of the energy. Renewable energy harnesses solar radiation, wind, the motion of water, or geologic heat. The major forms of renewable energy are solar, biomass, wind, hydropower, and geothermal. Conversely, the nonrenewable energy systems consume the very source of the energy, most notably, oil, coal, natural gas, and nuclear fuel.

Besides traditional energy and industrial hydroelectric energy, renewables include a host of recently developed, sometimes technologically complex, methods of harnessing sunlight, wind, water, or heat. These other renewable energy forms include photovoltaics,

TABLE I

1997 Energy Use (TW) by Region and Energy Source. Data from FAO 1997, PCAST 1997, and BP 1998.

	Oil	Natural gas	Coal	Nuclear	Hydroelectric	Traditional	Total	Percent of total
Africa	0.2	0.1	0.1	<0.05	<0.05	0.4	0.8	5%
Asia and Oceania	1.6	0.5	1.5	0.2	0.2	0.8	4.8	33%
Europe	1.1	0.5	0.5	0.3	0.2	0.2	2.8	19%
Latin America	0.4	0.2	<0.05	<0.05	0.2	0.2	1.0	7%
United States and Canada	1.3	0.9	0.8	0.3	0.3	0.2	3.8	26%
Former Soviet Union	0.3	0.6	0.3	0.1	0.1	<0.05	1.4	9%
World	4.8	2.8	3.3	0.9	1.0	1.8	14.6	100%
Percent of total	33%	19%	22%	6%	7%	12%	100%	

electricity-generating wind turbines, geothermal turbines, and other technologies in development. These sources require some of the complex machinery associated with industrial energy, yet depend only upon nondestructive methods of harnessing natural energy sources.

In 1997, the world rate of industrial energy use totaled 12.8 TW (BP 1998). Estimates of the rate of traditional energy use fall in the range of 1.7–1.9 TW (Johansson *et al.* 1993, PCAST 1997, unpublished International Energy Agency data). Of this, firewood and charcoal account for 0.7 to 1.1 TW (FAO 1997, unpublished FAO data). Total world energy use amounted to approximately 14.6 TW, or 14.6 trillion W. As a comparison, this rate of energy use is equivalent to the power drawn continuously by 146 billion light bulbs rated at 100 W. To put this in another perspective, consider that utilities in the United States generally built nuclear plants at a standard rating of 1 GW. So world energy use in 1997 required the equivalent of the continuous output of 14,600 standard nuclear plants.

Table I shows global energy use in 1997 by region and by energy source. The world depends on industrial energy sources for almost 90% of its energy use. Industrial countries, including the United States, Canada, countries of Europe, countries of the former Soviet Union, Japan, China, and India, account for most industrial energy use. Most industrial energy sources are nonrenewable fossil fuels and nuclear. Over a third of industrial energy goes to electricity generation.

Traditional energy comprises only approximately one-tenth of world energy use. Mainly nonindustrial countries in Africa, Asia, and Latin America account for most of the world's traditional energy use. In these countries, firewood and charcoal constitute the primary sources of energy. Indeed, firewood and charcoal provide more than 70% of the energy used by more than 30 countries in these regions.

The world uses renewable energy sources for only one-fifth of its energy use. The main renewables and their approximate rates of use are firewood and charcoal (0.7–1.1 TW), large hydroelectric (1 TW), agricultural crop residues (50 GW), biomass electric (25 GW), small hydroelectric (20 GW), wind electric (8 GW), geothermal (7 GW), urban waste (1 GW), biomass methane (1 GW), energy crops (500 MW), and photovoltaics (400 MW).

Figure 1 shows the tremendous increase in world energy use over time. In the 20th century alone, energy use has increased by a factor of 12. While total biomass use has remained constant, the world has witnessed an explosion in the use of fossil fuels.

Figure 2 shows the share of the United States in world population, economic production, and industrial energy use in 1997. Although the United States hosts

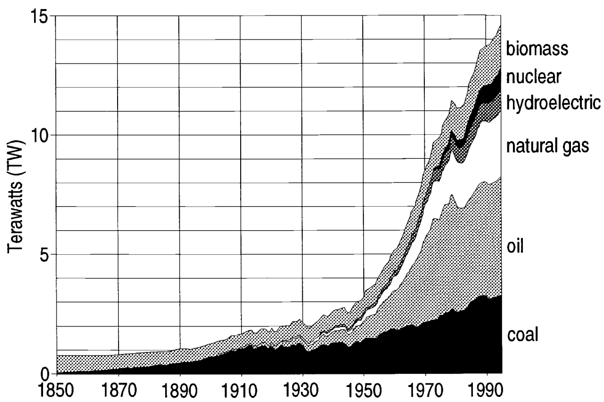

FIGURE 1 World energy use 1850–1995 (data from WEC and IIASA 1995).

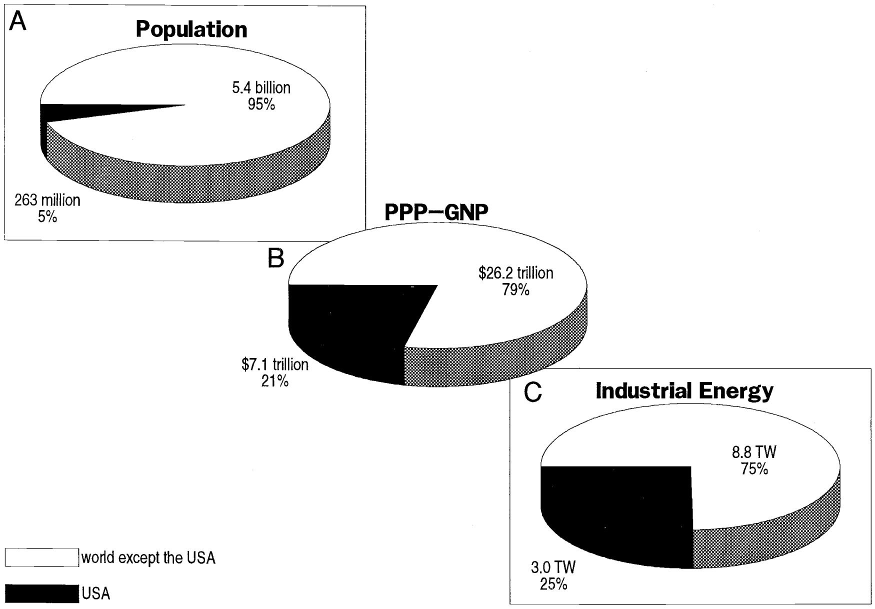

FIGURE 2 Share of the United States in world population, economic production, and industrial energy use in 1995 (data from the World Bank and IEA 1997a, 1997b).(a) Population. (b) Gross national product (GNP) adjusted for purchasing power parity (PPP). (c) Industrial energy use. (This total of 11.8 TW counts only the energy output of hydroelectric generators. Counting the equivalent input if the electricity were produced by nonrenewables, the method used in Table I, would increase the total to 12.2 TW.)

only 5% of the world's population, it generates 21% of the world's economic production and uses 25% of the world's energy. The average 1995 industrial energy use per person in the United States of 11,200 W cap^{-1} greatly exceeded the world average of 2000 W cap^{-1}, as well as the industrial energy use in other industrial countries, such as the United Kingdom at 5400 W cap^{-1}. On average, each American uses 10 times the amount of energy as each person in the People's Republic of China (1000 W cap^{-1}) and 30 times the amount of energy of each citizen of India (370 W cap^{-1}). Figures 3a and Figure 3b show the 10 countries with the highest and the 10 countries with the lowest industrial energy use per person.

One measure of energy efficiency is energy intensity, the amount of energy used per unit of economic production, generally per dollar of gross national product, adjusted for purchasing power parity. The 1995 industrial energy intensity of the United States, 0.42 W \$$^{-1}$, exceeded the world average of 0.35 W \$$^{-1}$. Figures 3c and Figures 3d show the 10 countries with the highest and 10 ten countries with the lowest industrial energy intensity.

Concerning energy end use, detailed data on a global scale are not gathered. In the United States, however, the Department of Energy does regularly survey energy end use. Americans use approximately 40% of total energy for industrial processes and agriculture. Approximately 35% of energy use goes to cooling, heating, lighting, and maintaining commercial and residential buildings. The remaining 25%, almost all from oil, goes to transportation. Passengers vehicles use half of all transportation energy. The high energy per unit volume and the flexibility of a liquid render petroleum products extremely convenient for powering vehicles.

Globally, a third of energy use goes to electricity generation, mainly from coal, hydroelectric, and nuclear. Power plants release two-thirds of that as waste heat (see the next section). The remaining third mainly goes into the end use of industrial processing with the balance going to cooling, heating, and lighting.

Households generally use the traditional energy sources of firewood and charcoal for the end uses of cooking and heating. Generally, cooking a joule of food requires 2 J of firewood wood or 8 J of wood converted to charcoal. Consequently, rural people use 1 to 2 kg wood cap^{-1} d^{-1} for a rate of energy use of 250 to 500 W cap^{-1}. Actually, a total of only 20 to 40 W cap^{-1} actually enters the cooked food and warmed people.

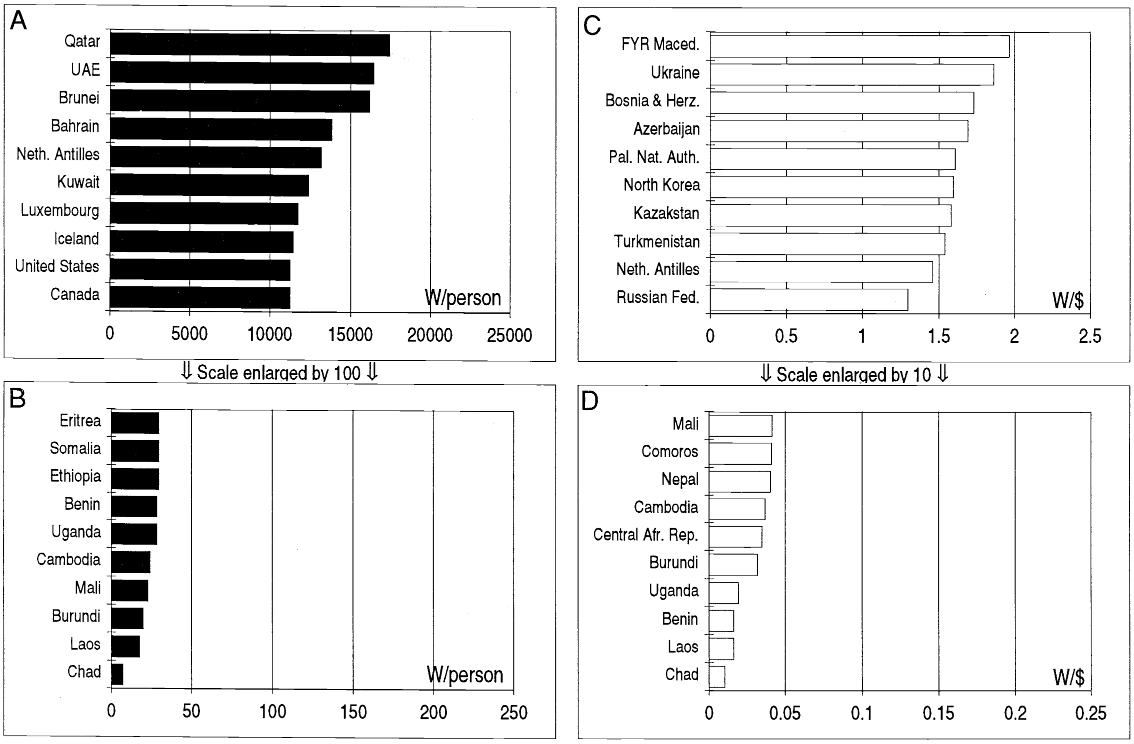

FIGURE 3 Per capita industrial energy use and energy intensity of economic production in 1995 (data from the World Bank and IEA 1997a, 1997b). (a) Ten countries with the highest per capita industrial energy use. (b) Ten countries with the lowest per capita industrial energy use. (c) Ten economies with the highest industrial energy use per dollar of economic output. (d) Ten economies with the lowest industrial energy use per dollar of economic output.

Open fires will diffuse the rest as waste heat (see the next section).

In urban areas of nonindustrial countries, people often rely on charcoal for energy. Even though the conversion of wood to charcoal releases waste heat, the end product has higher energy per unit mass than firewood. This makes charcoal easier to store and transport than firewood. Urban people use 100 to 150 kg charcoal cap^1 y^{-1}, requiring 800 to 1200 kg wood cap^1 y^{-1}. The ultimate end-use energy requirement is 30 to 45 W cap^{-1}.

II. IMPLICATIONS OF THE LAWS OF THERMODYNAMICS

The first law of thermodynamics states that energy is neither created nor destroyed, only converted between different forms. This is the principle of conservation of energy. The first law means whatever energy a process does not convert into useful forms must still go somewhere. The nonuseful energy does not just disappear. Humans use the environment as the sink for this waste energy.

The second law of thermodynamics states that any system will tend to change toward a condition of increasing disorder and randomness. This is the principle of increasing entropy. The second law means that no energy transformation can convert 100% of one energy form completely into a useful form. The process will always release amounts of energy wasted in forms that are unrecoverable due to the disorderliness or randomness of the waste energy forms. The fewer energy transformations that a system contains, the fewer chances for random second law energy losses.

For example, the objective of an automobile's internal combustion engine is the conversion of chemical energy in the covalent bonds of hydrocarbons in gasoline to heat energy of an expanding fuel-air mixture in the piston, to kinetic energy of the drive shaft, to kinetic energy of the main axle. No matter how efficient the engine and automobile technology is, the conversion process will always waste energy as heat in the friction of engine parts, sound in the banging of vehicle components, heat in the friction of tires on the road, kinetic energy of the wind displaced by the vehicle, and countless other unrecoverable losses.

As another example, the objective of a coal-fired electric power plant is the transformation of the chemical energy in the coal to heat energy in the boiler, to heat energy in steam, to kinetic energy of a turbine fan, to electromagnetic energy in the generator coil. Along the way, the conversion processes lose energy as the light and sound of the boiler fire, the vibration of turbine parts, the heat of power plant components, and, most significantly, the waste heat carried by the power plant cooling water.

Theoretically, the maximum efficiency across a heat gradient is the Carnot efficiency:

$$\eta = 1 - \frac{\text{Temperature of heat sink}}{\text{Temperature of transformation}}$$

with temperatures in Kelvin.

For a coal-fired power plant, materials limit boiler temperatures to 1000 to 1200 K. At an ambient environmental temperature of 293 K, the maximum efficiency will be 70 to 75%. Typically, coal plants only achieve 30 to 35%, releasing two-thirds of the total as waste heat.

Table II gives various formulations of the first and second laws of thermodynamics. The inevitability of entropy losses makes the colloquial interpretation of the second law "You can't even break even."

III. BIODIVERSITY IMPACTS OF INDUSTRIAL ENERGY

A. Oil

The major impacts of oil on biodiversity derive from a fuel and use cycle that ranges over vast areas of terrestrial and marine habitat. Exploration, drilling, crude oil transport, refining, and utilization in vehicles change land use and introduce industrial pollution to land and sea.

Petroleum, or oil, consists of a complex mixture of hydrocarbons formed over geologic time from organic matter compressed under anoxic conditions. The most important chemical constituents are alkanes such as octane and methane and aromatics such as benzene and toluene.

The majority of oil deposits derive from aquatic plants and bacteria deposited in inland seas and coastal basins during the Cretaceous Period 100 million years ago. In the early stages of formation, bacteria initiated the anoxic reduction of the organic matter. Over time, pressure and temperature replaced microbial activity as the main agent of transformation. Eventually, these forces drove off most of the water, oxygen, and nitrogen from the condensate, leaving carbon and hydrogen compounds. Dispersed between sediment granules, the oil eventually migrated to low pressure geologic traps at depths of 1 to 7 km. Today, oil fields occur at an average depth of 1.5 km. On average, the stoichiometric composition of crude oil is $CH_{1.5}$, with a very small amount of sulfur.

Petroleum exploration entails geologic surveys over extensive areas often with low human populations and relatively undisturbed natural communities. Exploratory surveys generate vehicle traffic and temporary dwellings that bring localized disturbances, but the most serious impacts occur with seismic detection. This method involves controlled detonations along lines or at points so that seismometers can extrapolate the layout of subsurface formations. These activities destroy areas of vegetation, disturb certain animals, especially ground-nesting birds, and fragment habitat. If such activities disturb animal behavior during breeding times, the impact can last over many growth periods.

Edwin L. Drake drilled the world's first commercial oil well in Titusville, Pennsylvania, in 1859. All oil wells require access roads, and high-volume wells require buildings and electric and water lines. This infrastructure destroys vegetation and takes land away from animal habitat. The more extensive an exploited oil field, the wider the habitat impacts extend. Infrastructure at the Prudhoe Bay field, opened for drilling in 1968, now extends over 1700 km^2 of Arctic tundra. This has noticeably displaced calving of *Rangifer tarandus* (caribou) from the field. Likewise, proposed exploitation of Area 1002 in the Arctic National Wildlife Refuge would disrupt the migration routes of the porcupine caribou herd to its calving grounds.

TABLE II

Formulations of the First and Second Laws of Thermodynamics

	First law	Second law
Universal	The total energy in the universe is constant.	All physical processes proceed such that the entropy of the universe increases.
Concise	Energy is conserved.	Entropy increases.
Colloquial	You can't get something for nothing.	You can't even break even.

Drilling operations produce water and air pollution. Serious water pollution comes from the vast amount of used drilling muds, which are lubricating substances pumped down to the drilling bit to carry away rock cuttings, to keep the bit from overheating, and to protect the drilling shaft from surrounding rock. Drilling muds consist of water mixed with light molecular weight oils. Used muds contain bits of metal from drilling components and any trace metals mobilized out of the drilled rock.

All stages of the oil production system from drilling operations to end use spill oil into surface and ground waters. Globally, oil spills into surface waters total more than 3 million tons each year. Half of these spills come from oil production, 40% come from nonpoint urban runoff, and the remaining come from natural seeps. At the start, spills occur at well blowouts when equipment fails to contain naturally high fluid pressures in oil-bearing strata. Spills also occur along the significant lengths of pipeline from the wellhead to tank farms to supertanker ports to refineries to gas stations. Pipes, valves, and tanks leak from fatigue and from human error.

These and other problems roused concern when oil companies first proposed construction of the Trans-Alaska pipeline to carry crude oil 1300 km from the North Slope to the Gulf of Alaska. When it eventually started operations on June 20, 1977, the Trans-Alaska pipeline integrated a set of environmental protection features. To prevent thawing of permafrost areas, brackets elevate 700 km of pipeline to heights of 3 m. Heat pipes at the bracket legs dissipate heat generated by the friction of oil passing through the pipe.

The elevated sections serve as underpasses for caribou. Over buried sections in certain permafrost areas, construction engineers designed refrigerated overpasses for caribou. Bridges carry the pipeline over 800 streams. Zigzags along the pipeline translate longitudinal movement of pipes expanding under heat to lateral movement, reducing the risk of leakage. Oil companies revegetated areas denuded by construction activities.

An access road now open to the public parallels the entire length of the pipeline. This road has opened up a strip of habitat to human contact, possibly changing behaviors among caribou and other mammals.

On March 24, 1989, the supertanker *Exxon Valdez* ran aground on Bligh Reef in Prince William Sound in the Gulf of Alaska, ruptured, and poured out 41 million liters of crude oil, the largest oil spill ever in U.S. waters. The spill caused acute damage to birds, marine mammals, and intertidal communities. The spill also caused chronic damage to fish species and intertidal and subtidal communities. The progression of the spill demonstrates a pattern repeated in smaller spills that occur frequently in the world's shipping lanes.

Oil floats on top of water. Gravity and wind will spread a floating slick out to a thickness of 0.5 to 10 μm. Patches 0.1 to 5 mm thick can cover just 10% of the total slick area yet contain 90% of the total slick volume. Some oil dissolves and emulsifies into the water column, forming emulsions containing 80% H_2O. Oil generally will not sink to depths below 20 m. In the *Exxon Valdez* spill, recovery teams deployed an array of countermeasures that included booms, skimmers, sorbents, pumps, burning, and surfactants for chemical dispersion.

Exposure to sunlight initiates photolysis of hydrocarbons into lighter molecular weight compounds. Heterotrophic bacteria will also oxidize hydrocarbons to smaller compounds, CO_2, and water. The lightest hydrocarbons, as well as aromatic compounds such as benzene, volatilize. Loss of the lighter fraction leaves the remaining slick more viscous over time. This thick oil forms tar balls and pancake-like forms. Oil from the *Exxon Valdez* eventually spread across hundreds of kilometers of beaches, penetrating deeply into cobbled stretches and mussel beds. Today, oil still persists beneath the surface layer of rocks in many areas.

Three years after the *Exxon Valdez* spill, photolysis degraded 70% of the original oil. Bacteria then eliminated photolysis products amounting to 50% of the original crude oil; the other 20% evaporated. Work crews recovered 14% of the spill. Thirteen percent of the original oil sank into subtidal sediments. Beaches absorbed 2%, leaving 1% still suspended in the water column.

The spill occurred in early spring, just before the young of many species emerged to rejuvenate marine animal populations. *Clupea pallasi* (Pacific herring) were spawning inshore. Millions of *Oncorhynchus gorbuscha* (pink salmon) fry were soon to be washed from gravel spawning beds into the spring plankton bloom offshore. *Phoca vitulina* (harbor seal) and *Enhydra lutris* (sea otter) pups were testing the frigid waters. Seabirds were beginning to converge on breeding colonies in the gulf. Consequently, the oil devastated populations of birds, marine mammals, and fish.

Thousands of birds can die in even moderate spills, but the *Exxon Valdez* spill eventually killed more than a quarter of a million birds of more than 90 species, the greatest demonstrated mortality of birds from any oil spill. Workers physically recovered 36,000 carcasses. Of these, 8000 were *Brachyramphus marmoratus* (marbled murrelets) and 150 were *Haliaeetus leucocephalus* (bald eagles). The spill killed individuals of two *Fratercula* spp. (puffins) and four *Gavla* spp. (loons). For the following three years, fewer breeding *Uria aalge* (common murres) showed up at spring colonies.

Oil coats feathers, matting and waterlogging them. The water repellency, buoyancy, and insulating properties of plumage derive from a precise, orderly arrangement of feather barbules and barbicelles. Contact with oil disrupts these arrangements. Soaked birds can die of hypothermia and drowning. Those that survive risk chronic exposure to toxic organic compounds through ingestion, inhalation of fumes, or absorption. Moreover, eggs are highly sensitive to contact with oil.

Many of the aromatics in petroleum, including benzene, toluene, xylene, and phenols, are lethal to animals on contact and carcinogenic under chronic exposure. Moreover, polycyclic aromatic hydrocarbons bond to lipophilic sites, an affinity that magnifies these compounds up the food chain. Even when not deadly, sublethal disruption of physiology or behavior activities can reduce resistance to infection and cause generalized stress.

In the wake of the *Exxon Valdez* spill, 300 of the 2200 harbor seals in Prince William Sound died, as well as 3500 to 5500 out of 10,000 sea otters. Like birds, oil obliterates the insulating properties of marine mammal pelage, leaving them to die of hypothermia. In addition, oil can clog the nostrils of seals, causing them to suffocate. Whales, insulated not by hair, but by layers of oily blubber, resist the effects of oil, although a well blowout off Santa Barbara, California, in 1969 led to the death of gray whales. In Prince William Sound, harbor seals may experience chronic problems because oil is accumulating in their bile and fatty tissues. Since the spill, sea otters have continued to experience elevated mortality.

An unfortunate coincidence has resulted in the geographic juxtaposition of important commercial fisheries and high yield offshore oil fields on the continental shelves. Not only do oil spills invariably cause fish kills, but chronic effects also reduce fish fitness years after initial exposures.

Oil at the air-water interface acts as a physical barrier interfering with gas exchange. In fact, oil has been a traditional line of defense used for mosquito larvae control. Under a thick slick, fish larvae can suffocate.

Fish eggs, which often float at the sea surface, and fish larvae, which are often distributed in the upper water column, both occur in the areas of highest oil concentration. Hydrocarbons and aromatics damage eggs on contact. Oil concentrations will quickly exceed the LC_{50} of 1 to 10 ppm for fish larvae. The early life stages of intertidally spawning fish are especially susceptible.

Exposure to toxics from the *Exxon Valdez* spill has caused chronic problems in *Clupea pallasi* (Pacific herring), *Oncorhynchus clarki* (cutthroat trout), *Oncorhynchus gorbuscha* (pink salmon), and *Salvelinus malma* (Dolly Varden). Fish species have shown elevated egg, larvae, and adult mortality, larval deformities, and poor adult growth rates, even in situations of constant food supply. Fish tissues in some species contain elevated concentrations of toxics.

Over time, tidal action spreads and coats the shore of the intertidal zone in a band of oil. This oil ring smothers intertidal invertebrates, crustaceans, mussels, barnacles, limpets, and algae. Oil coatings will asphyxiate filter feeders. Recovery crews use hot water washes to clean oil coated shores, an effective method, yet destructive to intertidal organisms.

Oil spills also damage phytoplankton and other marine plants. Oil absorbs photosynthetically active radiation, so direct coating hinders plant growth and increases plant tissue temperatures. Aromatics may disrupt the orderly arrangement of grana in chloroplasts. An increase in ruderals characterizes the changes in plant species diversity. Blue-green algae blooms will increase eutrophic conditions.

Oil refining focuses on the catalytic cracking of carbon-carbon bonds of long-chain alkanes for the production of lower molecular weight hydrocarbons. Refineries try to recover every possibly useful organic compound, from the light products methane, benzene, toluene, and kerosene, to medium-weight products like gasoline and diesel fuel, to heavy tars and asphalt. These processes, as well as sulfur recovery, inevitably generate water pollution.

Most constituents of petroleum and refined oil products volatilize easily. Consequently, each step of the petroleum fuel cycle generates air pollution. Methane, ethane, benzene, toluene, and other compounds will evaporate from crude oil exposed to air. The major emissions from oil refineries include CH_4, CO, CO_2, H_2S, NO_x, and SO_2.

This section has concentrated on the impacts from the core stages of the petroleum fuel cycle: exploration, extraction, transport, and refining. Nevertheless, manufacture of the infrastructure and materials needed for these end uses generates industrial pollution and requires land. Moreover, armed conflicts caused, in part, by efforts to control access to oil fields and refineries take human life and directly disrupt ecosystems.

The combustion of refined oil products for transportation, heating, and other end uses generates perhaps the gravest by-product of the entire fuel cycle—carbon dioxide, the principal greenhouse gas (see Greenhouse Effect).

B. Natural Gas

Natural gas is a mixture of light hydrocarbons that exists at a gaseous state at standard temperature and pressure. Methane (CH_4) is the main constituent, but the presence of higher molecular weight alkanes, including ethane, propane, and butane, changes the average stoichiometric composition for natural gas with the water vapor removed to 0.79 $CH_{3.62}$. Formed by the same processes that formed oil, natural gas is often found at the top of oil deposits. The most voluminous natural gas reservoirs occur in Cretaceous strata. The land use changes brought by the exploration and extraction of natural gas produce the same biodiversity impacts as described for oil.

In the nineteenth century, companies had not yet erected natural gas pipelines or processing facilities. Moreover, industry had not yet developed much technology for using natural gas. Because companies found natural gas uneconomical to exploit, they just burned it off to reduce the risk of fire and explosion. The entire history of natural gas production has flared the equivalent of 8 years worth of U.S. energy use. Today, U.S. companies generally flare only small amounts at refineries, but companies from other countries flare enough that the total amount flared amounts to 5% of global natural gas production.

Gas companies generally pump natural gas straight from the well to a processing plant, eliminating the need for storage facilities at the wellhead and thus reducing the potential for leakage. Gas companies generally divide natural gas into three fractions: natural gas liquids (NGL), liquefied petroleum gas (LPG), and liquefied natural gas (LNG). NGL consists of the higher molecular weight fraction of natural gas that often settles out by gravity. Processing of natural gas from oil wells produces liquefied petroleum gas (LPG). Finally, pressurization of natural gas produces liquefied natural gas (LNG), a product that is expensive because of the special containers required for transport.

The major end-uses of natural gas, cooking and heating, burn the fuel directly with no further transformation. Electricity generation from natural gas uses a gas turbine, which directly uses the hot gas products of combustion to turn the turbine fan, eliminating the intermediate step of steam generation used in oil and coal-fired plants. Cogeneration plants increase the energy efficiency of gas turbine systems by utilizing the waste heat of gas turbines for space heating or industrial processes.

The extraction and combustion of natural gas pollute much less than the extraction and combustion of oil. Because it exists in the gaseous state for much of the fuel cycle, natural gas exploitation does not produce significant amounts of water pollution. However, methane itself is a greenhouse gas, and its combustion produces the main greenhouse gas, CO_2.

C. Coal

Coal consists of hard carbonaceous material formed by the compression and transformation of terrestrial plant matter rich in cellulose buried at the bottom of ancient freshwater swamps and bogs. The richest coal-bearing strata date from the Cretaceous period 100 to 200 million years ago and from the Permian period 250 million years ago. Similar to the process of petroleum formation, the deposited plant matter undergoes incomplete decay in anoxic conditions.

In geologic time, the pressure of overlying rock and the temperatures generated therein drive off oxygen and hydrogen, leaving thick seams of reduced carbonaceous rock containing much more organic than mineral matter. The average stoichiometric equation of coal is $0.75CH_{0.8}$, but elemental sulfur also contaminates most coal deposits. The four major types of coal, in order of decreasing carbon content and increasing sulfur, are anthracite, bituminous, subbituminous, and lignite. Bituminous coal is the most physically abundant type worldwide. Peat, the partially oxidized, moist, organic soil that forms in marshes and bogs, is the very early precursor to coal. In certain areas, people burn peat for heating, cooking, and light.

The coal fuel cycle extends from extraction at the mine to conversion at a power plant to distribution across the electric grid to end uses in lighting, heating, and all the uses of electricity.

Coal mines generally fall into three types: deep, open pit, and strip. Deep mines extend down to a depth of around 1 km. Open pit mines reach down to 300 m. Strip mining generally removes the upper 30 m of land surface. Coal mines consume land, not just for areas actually excavated and areas used to dump unwanted extracted rock, but also for the support infrastructure of buildings, roads, and rail lines.

Deep and open pit mines remove huge amounts of rock, termed overburden, lying over the coal. The land over deep mines will sink, a process termed subsidence, drastically changing the topography, hydrology, and microclimatic profile of a landscape. This can destroy vegetation and alter important animal habitat characteristics. Underground coal fires in abandoned mines and refuse banks will not only exacerbate subsidence, but they will also release CO_2 and other air pollutants.

Miners dump the huge amounts of unwanted extracted rock, termed mine tailings, in abandoned parts of active mines or on the surface. Pyrite (FeS_2) usually comprises a signicant fraction of the tailings. The reaction of water and pyrite produces sulfuric acid (H_2SO_4). In addition to being poisonous to plant and animal life, sulfuric acid mobilizes other toxic substances. The leaching of acids, trace metals, dissolved solids, and toxic organics produces a brew known as acid mine drainage that can devastate surface waters. Selenium and cadmium often occur in high concentrations in tailings, so acid mine drainage can initiate the bioaccumulation and bioconcentration of these trace metals in the surviving sections of the food chain.

Surface mining consumes vast tracts of land. Heavy machinery remove the upper layer of a landscape to expose relatively shallow coal seams, completely destroying the mined area. Although coal companies generally fill back the overburden into the mined area and replant it, strip-mined land never recovers its original characteristics. Replanting even creates opportunities for ruderals to expand where perennial plant species may have dominated. Rodents and other animals that adapt readily to human disturbance also take advantage of reclaimed areas.

Coal mines often need to impound surface streams to satisfy the significant water needs of mine operations. These needs include water cannon drilling, transport by slurry, fugitive dust spraying, coal washing, and size sorting.

Mines crush and screen coal for uniform sizing, then wash and dry the coal for open air storage. The fugitive emissions from these processes consist of particulates that coat any exposed surface, blocking photosynthetically active radiation from plants, contaminating food and water sources for animals, and acidifying affected soil. Leaching of toxic substances from coal storage piles can also add to the pollution of surface waters. Rail transport provides the most cost-effective means of moving the bulky commodity of coal. Fugitive emissions from unit trains increase the particulate load in rail corridors. To save money on rail transport, many utilities will site electric power plants next to the mine then wire out the electricity. In certain regions, this shifts the pollutant load from urban areas to less polluted rural areas.

Most coal worldwide goes to electricity generation. A conventional power plant burns coal in a boiler to boil water that circulates through a closed loop system of pipes. The steam from the boiler enters a steam turbine to turn huge fans that power an electric generator that converts kinetic energy to electric energy. As a principal of physics, the movement of a conductor across a magnetic field creates electric current in the conductor. In the coal-fired power plant electric generator, the conductor consists of stationary coils of wire surrounding a magnet on a shaft rotated by the turbine fan. Much of the steam that moves through the fan transfers its heat energy to the kinetic energy of the fan, causing the steam to condense back to water. A condenser will then allow heat to transfer from any steam that continues past the turbine to an external supply of cold water. The water in the internal loop from the condenser returns back to the boiler to enter the steam cycle again.

Coal combustion releases CO, CO_2, SO_2, NO_x, particulates, fly ash, arsenic, cadmium, chromium, mercury, and selenium. Nearly 40% of anthropogenic CO_2 emissions come from burning coal, whereas coal burning produces 80% of human SO_2 emissions. Consequently, greenhouse gases and acid precipitation may constitute the agents of coal's most extensive environmental effects.

The slag remaining from coal burned in the boiler contains high amounts of trace metals, especially cadmium and mercury. In addition, the sludge from flue gas desulfurization units, the pollution control devices known as scrubbers, contains trace metals and toxic organics. The disposal of this sludge presents problems for land use and water quality.

Internal steam turbine water is the working fluid circulating from the boiler to the turbine to the condenser and back to the boiler. Cooling water is the medium that draws heat from the internal steam turbine water. In most conventional coal-fired power plants, the internal steam turbine water remains separate from power plant cooling water. A typical condenser consists of copper coils, carrying cooling water, that pass through larger structures carrying the internal steam turbine water. As a physical principle, heat passes from the steam turbine water through the walls of the copper coils into the cooling water.

A 1 GW coal-fired power plant typically requires 4 million m^3 per day for all operations, mostly for cooling. These water needs dictate the necessity to locate a plant next to a natural water body. Power plants mainly use fresh water because of the corrosive effects of salt water. Water withdrawals change the hydrology of a watershed, changing water levels, surface area of mudflats, surface area of wetlands, and other important habitat characteristics that can strand hydrophilic plant species such as *Salix* spp. (willows) and harm fish and shorebird populations. Impingement on intake screens kills significant numbers of fish and other aquatic species. Organisms that get through the screens undergo entrainment through the condenser, causing even greater mortality. The stress that any surviving organisms undergo reduces their fitness considerably.

All power plants, including coal, oil, and nuclear, generate three-quarters of the waste heat dumped into U.S. surface waters and into the atmosphere above the United States. Once-through systems dump the waste heat directly into local waters. Cooling towers dump waste heat into the atmosphere, condensing steam from the air. Cooling ponds provide a buffer for releasing some of the heat from cooling water into the atmosphere, reducing the temperature of the cooling water before it enters surface waters.

Thermal discharges into freshwater and coastal zones cause a host of negative effects on aquatic species:

1. Direct lethality to fish and crustaceans at water temperatures $\geq 35°C$.
2. Decrease in dissolved oxygen.
3. Increase in metabolic rates and nutrition needs for fish and changes in nutrition requirements for other taxa.
4. Displacement of diatoms by green and blue-green algae.
5. Inhibition of vertical migratory behavior by zooplankton.
6. Thermal plume blockage of migratory fish movement.
7. Avoidance of warm areas by migratory waterfowl.
8. Early emergence of aquatic insect adult life stages into inhospitable environmental conditions.
9. Copper contamination from condenser coils.

Long-range transmission of electricity occurs across high-voltage lines strung on metal towers up to 30 m tall. The 115 kV network in the United States stretches across 200,000 km and occupies 2 million ha. The clear cutting of corridors 30 to 60 m wide for transmission easements directly changes the vegetation and plant life in cut areas. Periodic clearing maintains and intensifies the original changes. The areas that remain favor ruderals and animal species that adapt readily to human disturbance, such as *Odocoileus virginianus* (white tailed deer). Herbicides used for periodic clearing can hurt insect and bird species. Transmission line corridors fragment habitat and increase the area of habitat susceptible to edge effects. The cleared areas can also block migrating land animals.

Short-range electricity transmission occurs across low-voltage lines strung on wood, metal, or concrete poles generally 5 m tall. Harvesting wood poles can produce all the potential biodiversity impacts of commercial logging, monospecic plantations, and milling. In many countries, utilities treat the wood with creosote to guard against the action of insects and weather. Creosote, a by-product of crude oil refining, contains significant amounts of toxic organics that can leach and contaminate surface waters.

The material and energy needs for building the massive infrastructure of the coal fuel cycle produce wide-ranging environmental effects. Because most coal goes to electricity generation, the end uses of coal produce the environmental effects associated with climate control, lighting, commercial production machinery, residential appliances, and other electric devices.

D. Nuclear Fission

Nuclear fission is the splitting of high molecular weight elements to release energy held among protons and neutrons in the nucleus of the atom. Uranium and plutonium are the elements that provide the most effective yield from fission at current levels of technology. A fission reaction produces energy in the form of light, heat, motion of the split pieces, and radiation. Radiation consists of kinetic energy of small molecules and atomic particles and electromagnetic energy of photons traveling at certain frequencies. When radiation passes through living tissue, the particles or photons impart their energy to atoms and molecules in the tissue, disrupting molecular and atomic structures.

The fission products themselves will continue to emit radiation until they reach a stable atomic state. Strontium-90 and Cesium-137 have half-lives of decades, but Plutonium-239 decays with a half-life of 25,000 y and Iodine-129 will halve in mass only after 17 million years.

Nuclear fission plants require highly processed uranium fuel. A 1 GW fission plant requires 150,000 Mt U_3O_8-containing ore to fabricate enough fuel for one year. Milling this removes 150 Mt U_3O_8. In order to concentrate Uranium-235, a conversion plant converts U_3O_8 to 188 Mt of UF_6 gas. Differential diffusion of the UF_6 separates 31 Mt UF_6 enriched in Uranium-235. A fuel fabrication plant then produces 30 Mt of UO_2 pellets.

The mining and milling of uranium ore creates most of the same environmental problems already described for deep mining for coal and for coal processing. Conversion, enrichment, and fuel fabrication require fluorine gas, which is lethal on contact to animals, damages vegetation, and reacts to form toxic by-products.

According to the International Atomic Energy Agency (IAEA), at the end of 1998, 434 nuclear fission plants were operating in 33 countries around the world; 104 nuclear fission plants were operational in the United States. These plants possessed a combined rated capacity of 349 GW and generated 2300 TWy of electricity, 16% of the world total. Plant operating experience reached 9000 plant years.

Nuclear plants generate electricity in a steam cycle very close to that employed in coal plants, except that nuclear fission provides heat to the boiler. The higher operating temperatures require more cooling water than a coal-fired plant of the same electric generation capacity. A 1 GW nuclear fusion plant requires 6 million m^3 of cooling water each day, so the effects of water intake and thermal discharge described in the previous coal section are all more serious for nuclear plants.

Because nuclear plants involve combustion only in construction and in support vehicles for operations, they produce few air emissions. Nuclear plants do, however, produce long-lived radioactive wastes. Low-level wastes include reactor containment water, worker clothing, exposed tools, and plant fixtures irradiated for limited periods of time. High-level wastes consist of the spent fuel and the fuel rods in which they are encased.

Permanent disposal of these wastes in a manner that isolates their radiation from the living world has proven an intractable task. In 1999 the U.S. Department of Energy finally opened the Waste Isolation Pilot Plant for low level wastes in the Carlsbad Cavern system of New Mexico. The department has also been working on a repository for high-level wastes deep under Yucca Mountain, Nevada.

The greatest single release of nuclear radiation came from the Chernobyl Unit 4 accident on April 26, 1986, in the Republic of Ukraine in the then–Soviet Union. Operator error combined with design drawbacks of the RBMK graphite moderated reactor resulted in a virtually instantaneous catastrophic increase of thermal power and in a steam explosion. The explosion destroyed the reactor, releasing over 3% of the reactor fuel and up to 60% of the volatile products in the reactor core, mainly Iodine-131, Cesium-134, and Cesium-137. The accident deposited radioactive fallout over the entire northern hemisphere.

Twenty-eight people died from acute radiation doses, while more than 6500 may contract fatal cancers through the year 2080. The Soviet government evacuated all people from a zone of 30 km radius and constructed a cement sarcophagus to contain the remains of the reactor core.

Lethal radiation killed many conifers and small mammals within 10 km of the accident in the first few weeks, but populations have since mostly recovered. By 1996, radioactive decay had diminished the amount of radioactive materials in the immediate area to 1% of their original amount, mainly as Cesium-137 in topsoil. Trees have accumulated Cesium-137 in growth rings. Grass, mushrooms, and berries also continue to incorporate the isotope, perpetuating a source of exposure for species that feed on contaminated plants. Aquatic ecosystems have generally tolerated the radioactivity concentrating in sediments, although fish may be accumulating radionuclides.

Ecologists have still not determined the long-term genetic effects of the fallout from Chernobyl. Apparently, the accident did not eliminate any plant or animal species, except where cleanup activities involved soil removal. Indeed, as a result of the evacuation, some plant and animal populations have thrived.

From 1961 to 1976, ecologists, led by George M. Woodwell, examined the chronic effects of irradiating a forest at Brookhaven, New York. Gamma radiation from Cesium-137 caused sensitive species to die, allowing resistant species and ruderals to invade. Species richness in 2 m square plots fell by half.

E. Hydroelectric

Hydroelectric systems harness the potential energy represented by an elevated mass. The potential energy of water at elevation will convert to increased kinetic energy of the water when the water runs to a lower elevation. A dam concentrates the difference in elevation, termed hydraulic head, in a spillway equipped with a turbine and electric generator. The electricity produced immediately enters the electric grid. In this manner, a hydroelectric plant will generate electricity with few direct air emissions and little thermal discharge. The principal effects of hydroelectric plants come from the total physical and hydrologic alteration and partial inundation of a watershed. Besides the forced removal of people and inundation of homes, hydroelectric plants also cause significant ecological changes.

More than 40,000 large dams now straddle rivers around the world, creating reservoirs that inundate more than 400,000 km^2. The Akasambo Dam on the Volta River in Ghana created the largest impoundment in the world, covering 8500 km^2. The Three Gorges

Dam under construction in the People's Republic of China will be the hydroelectric plant with the highest generation capacity in the world, 18.2 GW. The project, under construction in the period 1993–2009, will flood 1100 km^2 along 600 km of the world's third longest river, the Yangtze, and displace 1.2 million people. The dam will require 26 million m^3 of concrete.

The inundation of formerly dry land submerges vegetation and immediately decreases the area of animal habitat. Lost forests represent ecosystem services and biomass wasted to decomposition. In Brazil, a country that depends on hydroelectric for 20% of its industrial energy, the land requirement for hydroelectric reservoirs averages 450 $km^2\ GW^{-1}$ with a range of 17 to 10,000 $km^2\ GW^{-1}$.

A dam blocks nutrient-rich sediment that a river system otherwise would have deposited in floodplains, wetlands, and at the outlet delta. Not only does the sediment buildup fill in a reservoir and eventually impair electricity generation, but the blocked sediment also represents a source of organic carbon and other nutrients wasted at the bottom of the reservoir. At the delta, bay and estuary topography changes, mudflat areas decrease, and nutrient-rich upwellings can decline. The Aswan High Dam blocks 98% of the 120 million tons of sediment that the Nile had carried to the sea each year, formerly depositing 10 million tons on the floodplain and delta. Consequently, soil depth has thinned and agricultural production has declined in the Nile Valley. Blockage of sediment and fresh water by the Akasombo Dam in Ghana has caused the decline of clam populations in the Volta estuary, and populations of *Sphyraena barracuda* (barracuda) offshore in the Gulf of Guinea. In addition, coasts become more susceptible to erosion.

Utilities start and stop the flow of water based on electricity and operational requirements. One operational objective is to smooth out natural extremes in the flood regime. This will usually change the meandering response and other channeling processes of a river. Ever since the Glen Canyon Dam removed spring floods in the near downstream section of the Colorado River, sandbar erosion has increased because the river does not flow fast or deep enough to move the amount of silt required for extensive sandbar formation. The resulting disappearance of some riparian tree species has led to the decline of *Empidonax traillii* (Southwestern willow flycatcher) and other birds. To mitigate the problem, the U.S. Department of the Interior staged a controlled flood in 1996.

For some dammed rivers, the flow of water unburdened by silt can deepen the riverbed. This lowers the water table of surrounding land. Also, the depletion of riverbed gravel can harm any species of fish, insect, mollusk, or crustacean that requires gravel bottoms to spawn. Many insect, amphibian, and fish species also use gravel areas for habitat or for protection.

The depth of a reservoir will often keep water at a temperature lower than that in the native river. For example, the Glen Canyon Dam changed the water temperature in the near downstream section of the Colorado River from a range of 0 to 27°C to a relatively constant 8°C. This has been a major factor in the extinction of *Ptychocheitus lucius* (Colorado squawfish), *Gila robusta* (roundtail chub), and *Gila elegans* (bonytail chub) and in the endangerment of five other fish species. Whereas the release water is clear, reservoir water often becomes slightly eutrophic and turbid. This degraded water quality can harm certain species.

The impacts of dams on anadromous fish relate to the migratory behavior and timing of the life cycles of these unique species. Dams render hazardous the downstream migration of young fish and block the upstream migration of adults. Moreover, salinity and temperature adaptations occur on a precise schedule, making long delays lethal. Disoriented and fatigued fish more easily fall prey to predation. Despite the deployment of extraordinary means in contemporary times to facilitate fish migration, including fish ladders, elevators, and trap and haul trucking, dams have eliminated anadromous species from many rivers. Runs of *Salmo salar* (Atlantic Salmon) and *Alosa sapidissima* (American shad) have disappeared from many rivers in the Northeast United States. In the Columbia River Basin in the Northwest United States, overfishing, pesticide runoff, and hydroelectric plants have endangered populations of *Oncorhynchus nerka* (Snake River sockeye salmon) and *Oncorhynchus tshawytscha* (Snake River chinook salmon). The physical barrier formed by a dam can even divide populations of aquatic species, altering patterns of gene flow and genetic variation.

Exotic fish species adapted to human disturbance and introduced into reservoirs for sport fishing will often outcompete native species. In the 1350 km^2 reservoir straddling the Brazil-Paraguay border behind the Itaipu Dam—with a generation capacity of 12.6 GW that currently ranks it the highest in the world—a non-native species, *Plagioscyon squamosissimus* (curvina) has become the second most numerous species.

PCBs released from circuit breakers and oil leaking from machinery constitute the worst direct industrial pollution from dams. These and toxic organics build up in sediments and magnify up through the food chain. Impingement of aquatic organisms on intake screens and entrainment through turbines kills many individuals and causes stress and injury in survivors.

The material and energy needs for building the massive infrastructure of the hydroelectric energy cycle produces wide-ranging environmental effects. The end uses of hydroelectricity will produce the environmental effects associated with climate control, lighting, commercial production machinery, residential appliances, and other electric devices. Because smelting aluminum from bauxite ore requires a large amount of electricity, aluminum smelting comprises an end use closely tied to the hydroelectric option. The air emissions from smelters include CO, CO_2, particulates, NO_X, and trace metals. Major water emissions include trace metals and sulfates.

F. Renewable Energy Technologies

Renewable energy includes those forms of energy whose transformation does not necessarily consume the ultimate source of the energy, harnessing instead solar radiation, wind, the motion of water, or geologic heat. This section covers renewable energy technologies, including solar heating, solar thermal electric, solar photovoltaics, electric wind turbines, biomass-to-electricity conversion, biomass-to-alcohol fuels, and geothermal electric. These are renewable energy systems that depend on complex technology, so they are forms of industrial energy. The following section on traditional energy covers the simpler forms of renewable energy—firewood and charcoal.

Renewable energy forms share the physical characteristics of site specificity, variable availability, diffuse flow, and low or no fuel costs. Except for biomass-to-electricity conversion, renewable energy technologies do not involve combustion, so they do not directly produce much air pollution. The major environmental impacts derive from the fabrication, installation, and maintenance of renewable energy devices.

Solar energy systems fall into the categories of passive and active. Passive solar technologies consist of architectural forms that more effectively follow the diurnal and seasonal patterns of sunlight for the efficient heating and cooling of a building. Passive systems use the natural phenomena of radiation and convection. On the other hand, active systems use moving devices to achieve heat transfer. The simplest active systems use pipes or other collectors to heat water for residential or commercial use. For the most part, solar heating is environmentally benign.

Solar thermal uses arrays of reflective collectors to focus sunlight on a water boiler for the turbine production of electricity. These systems require significant amounts of land for the parabolic or trough collectors. Because solar is generally economically feasible only in hot sunny areas, sites are generally arid and water is scarce. Water withdrawals for the turbine and for washing the collectors can damage aquatic ecosystems. The bright arrays can also harm birds.

Photovoltaics are solid-state devices in which photons stimulate the emission of electrons and semiconductor materials channel the electrons for collection. In this way, photovoltaics directly convert sunlight to electricity with no moving parts, except for devices that move photovoltaics to track the sun, and no water, except for water to occasionally wash photovoltaic surfaces.

The fabrication of photovoltaic (PV) cells produces noxious environmental impacts. The first step is mining the quartz that constitutes the base material of a PV cell, so this produces many of the impacts on aquatic and terrestrial biodiversity described for coal mining. Then the production of metallurgical grade silicon requires the refining of quartz to 99% purity at 3000°C in an electric arc furnace. The production of semiconductor grade silicon occurs through a fluidized bed reaction of the silicon with hydrochloric acid. Then the production of semiconductor grade polycrystalline silicon occurs by electrically heating at 1000°C the semiconductor-grade silicon for vapor deposition on a silicone substrate. Remelting the polycrystalline silicon produces a form that can grow into crystals. These crystals are sawed into wafers 0.5 mm thick, wired, and encapsulated in glass 3 mm thick.

Trace metals are used to dope the semiconductor for the principal types of photovoltaic cells, including gallium arsenide, copper indium diselenide, cadmium telluride, indium phosphide, and cadmium sulfide. The trace metals, together with chlorinated organic solvents and phosgene gas, produce hazardous air, water, and solid wastes that can be lethal on contact or carcinogenic in small doses.

The conversion of biomass into electricity involves burning specially grown wood or crops in low pressure boilers to power steam turbines or the gasification of organic matter into methane to power gas turbines. The United States currently possesses a biomass electricity-generating capacity of 7.6 GW. Biomass-for-energy plants in the United States often employ cogeneration to provide process heat for an adjacent industrial facility. The principal species used include short rotation trees *Populus* spp. (poplars, aspen, cottonwoods), *Platanus* spp. (sycamore), and *Acer saccharinum* (silver maple) grown at densities of 1600 to 5000 trees ha^{-1}. Herbaceous energy crops include *Panicum virgatum* (switchgrass) and *Andropogon gerardii* (big bluestem). Brazil generates electricity and cogenerates heat from the organic wastes, or bagasse, left from the processing of sugarcane and orange juice.

The environmental impact of an energy crop depends on the previous land use as well as the cultivation techniques of both the new crop and any previous old crops. An energy crop can generate negative effects on biodiversity if it is grown in monoculture, if it is grown using pesticides, and if vegetation is clear-cut to prepare for the energy crop. Still, if previous land-uses were less environmentally sound than the energy crop, then the energy crop constitutes a mitigating practice. Previous sections detail the negative biodiversity effects of electric turbines and condensers.

The conversion of biomass into alcohol fuels also requires the dedicated growing of energy crops. Fermentation of cellulose and other complex carbohydrates produces ethanol, which certain engines can burn straight or mixed with gasoline. The United States now produces 4 billion liters of ethanol annually, mainly from corn. Brazil produces enough ethanol from sugarcane to provide for 10% of the country's energy use.

Otto Cycle engines burn neat ethanol, a mixture of 96% ethanol and 4% water. Modified conventional automobile engines can burn gasohol, a mixture of 78% gasoline and 22% ethanol. At one time, half of the automobiles in Brazil ran on gasohol, the other half on ethanol. Because the combustion of ethanol mainly produces CO_2 and water, with much smaller amounts of hydrocarbons and NO_x than gasoline combustion, ethanol used for transportation mitigates the most harmful direct effects of petroleum.

For centuries, society has captured wind for moving sailing ships, pumping water, and milling grain. Contemporary wind turbines also power electric generators. Rated at 100 to 300 kW per wind turbine, the steel machines reach heights of 10 m with pinwheel diameters up to 7 m. Arranged in arrays of up to hundreds of turbines, wind "farms" occupy considerable land areas. The greatest arrays cover unique areas in the Altamont Pass in the San Francisco Bay Area in California, the Tehachapi Pass in Southern California, in the Netherlands, and Denmark. Wind farms fragment terrestrial habitats and access road networks cause soil erosion. Spinning turbines can also kill birds.

Geothermal energy captures the heat of hot geologic formations, generating more than 7 GW of electricity worldwide. Geothermal plants sink pipes down to either capture deep hot water or to inject water for it to boil on contact with hot rocks. This process mobilizes trace metals contained in certain geologic strata and releases H_2S gas associated with geothermal deposits.

IV. BIODIVERSITY IMPACTS OF TRADITIONAL ENERGY

The most important sources of traditional energy are firewood and charcoal, which is produced from firewood. Local people harvest firewood either by coppicing, or cutting at the base, moderately sized shrubs, by lopping branches off mature trees, or only rarely by felling whole trees and splitting the logs.

In semiarid areas of Africa, women prefer the straight, moderately sized branches that only coppiced shrubs produce. Each year, women and, sometimes, their husbands or fathers go out in the dry season and cut at the base shrubs mainly in the family *Combretaceae,* carry the branches back to the village, and let them dry out. Just before the first rains, men and women cut a store of firewood for the rainy season. This serves, first, to avoid cutting wood that is wet and difficult to burn and, second, to get a time-consuming and strenuous chore out of the way before the exhausting and rushed rainy season. Coppiced shrubs will resprout in the rainy season and, in a year, regrow a full set of branches. When shrubs become scarce, women begin to pull down branches from adult trees, sometimes using long-handled hooks. This harms the growth potential of a tree by removing shoot apical meristem tissues and only provides difficult, thorny branches. When branches are exhausted, women fall back on noxious, dead stalks of spurges, family *Euphorbiaciae*. The last resort is animal dung. Only rarely will people cut down an adult tree for their own firewood needs. Men cut down trees for firewood for community events, large baptisms, weddings, or funerals, but even then, men prefer trees that have already died because these yield dry, more combustible wood.

Although women carry firewood for rural use, rural people load beasts of burden and carts to transport wood for sale in urban areas. So a town or city can produce land use changes far beyond its borders.

The low energy density of wood makes its transport onerous relative to the energy gained. Conversion of firewood to charcoal creates a product with double the energy per unit mass, but emits as waste heat up to two-thirds of the energy contained in the original wood. Charcoal makers cut down live and dead trees, particularly prizing sturdy tree trunks. In the field, they pile the wood, cover it with soil to form a kiln 1 to 3 m in height and 1 to 3 m in diameter, and ignite a slow burn. Over 3 to 6 days, the wood converts to charcoal by partially anaerobic pyrolysis.

Firewood harvesting can superimpose locally severe changes in biological diversity over wider alterations caused by long-term climate change. Global warming, the El Niño Southern Oscillation, and desertification all lead to systemic ecological changes at a regional scale. Embedded within these regions, firewood harvesting can reduce vegetative cover in less extensive areas where people depend on wood for their energy use.

The impacts of desertification in the West African Sahel clearly illustrate this complex situation. In Senegal, anthropogenic and climate factors caused a decline in forest species richness of one-third in the last half of the twentieth century (Gonzalez 1997).

Rainfall in the Sahel has shown a persistent downward trend in the past four decades, with the rainfall average of all years since 1919 falling at Louga, Senegal (15″37′ N, 16″14′ W) from 470 mm in 1953 to 400 mm in 1993. Serious droughts have hit in the periods 1910–1914, 1942–1949, and 1968–1973. An increase in human population has coincided with the decline in rainfall. The population of Senegal doubled in the period 1945–1988, growing at a rate of 0.025 y^{-1}.

In Northwest Senegal, the average forest species richness of areas of 400 ha fell from 64 ± 2 species ca. 1945 to 43 ± 2 species in 1993. Moreover, densities of trees of height ≥3 m declined from 10 ± 0.3 trees ha^{-1} in 1954 to 7.8 ± 0.3 trees ha^{-1} in 1989. Both the fall in species richness of 33 ± 5% and the decrease in tree densities of 23 ± 5% translate to a rate of −0.8% per year.

In West Africa, rainfall increases and evapotranspiration decreases toward the equator, creating a gradient that differentiates species into three broad bands of increasingly mesic vegetation: the vegetation zones of the Sahel, the Sudan, and Guinea. In Senegal, arid Sahel species (e.g., Family *Mimosaceae*) expanded in the north, tracking a concomitant retraction of mesic Sudan (e.g., Family *Caesalpiniaceae*) and Guinean species (e.g., Family *Bombacaciae*) to the south. Vegetation zones shifted southwest 25 to 30 km in the period ca. 1945–1993 (Fig. 4), a rate of 500 to 600 m y^{-1}, foreshadowing the magnitude of projected shifts driven by CO_2-induced climate change. The historical change acted through a higher mortality among mesic species, leaving drought-resistant species to dominate the remaining tree cover. The most notable species that have experienced local extinctions include *Dalbergia melanoyxlon* (Senegal ebony), *Prosopis africana* (ironwood), *Sterculia setigera* (mbep), and *Tamarindus indica* (tamarind).

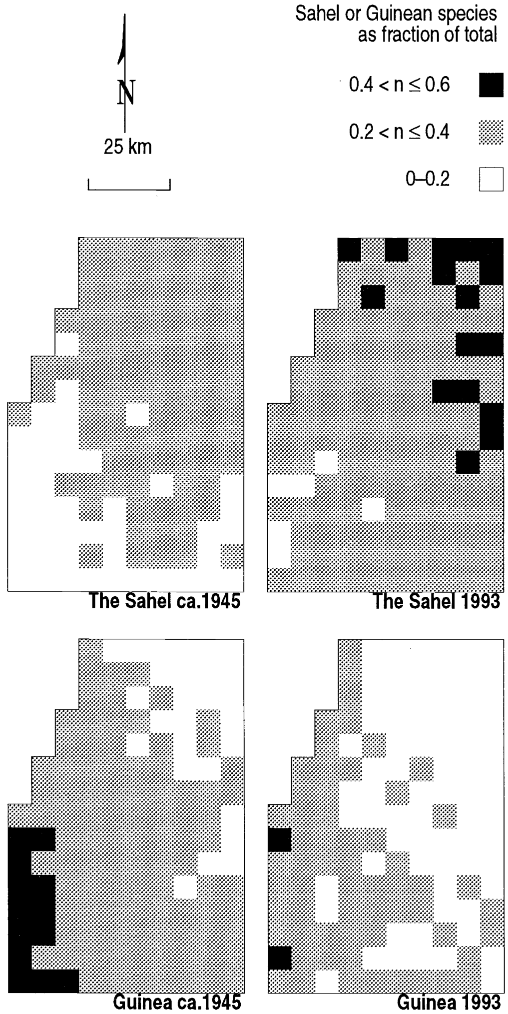

FIGURE 4 Shift of the Sahel and Guinean vegetation zones in Northwest Senegal from ca. 1945 to 1993 (Gonzalez 1997).

Out of 215 ecological and socioeconomic variables, multivariate statistical analyses identifies rainfall and temperature as the most significant factors explaining the distribution and densities of trees and shrubs in Northwest Senegal. Rainfall and temperature override local anthropogenic factors.

Examination of dead trees along the coast supports a predominance of climatic over local anthropogenic factors. The sparsely populated coast offers a view of the state of the countryside before cultivation. Natural stands of *Euphorbia balsamifera* still occur there. In contrast, elsewhere in the Senegal Sahel, farmers have cut all natural stands of this species and replanted it along field boundaries. In the collective memory of local people, vast areas along the coast have not been cultivated. Dead trees still stand along the coast, but they show no ax marks or any sign that humans directly caused their death.

On a subcontinental scale, however, human activities may have caused the decline in rainfall. Deforestation of tropical rain forests in the Congo vegetation zone from the Republic of Guinea to Côte d'Ivoire may have reduced the evapotranspiration inputs essential to the maintenance of the Southwest Monsoon. Reduced rainfall over an extended period would reduce the vegetation cover in the Guinea zone. This in turn would decrease rainfall and vegetation in the Sudan, eventually reducing rainfall and vegetation in the Sahel. Thus, human activities in the distant rain forests may initiate a concatenation of climatic links that ultimately touch the Sahel.

Nevertheless, population growth has undoubtedly placed increasingly inordinate pressures on the area's vegetative cover. In Northwest Senegal, rural firewood use exceeds firewood production from shrubs over 90% of the land area, affecting 95% of the rural population. The rural population density of 45 people km^2 exceeded the 1993 carrying capacity of firewood from shrubs of 13 people km^2 (range 1–21 people km^2). The rural population density has exceeded carrying capacity since 1956.

The standing biomass of trees across the research area decreased from 14 t ha^{-1} in 1956 to 12 t ha^{-1} in 1993, matching a cumulative firewood deficit in the same period of 2 t ha^{-1}. The reduction in standing biomass released carbon into the atmosphere at a rate of 60 kg C cap^{-1} y^{-1}, somewhat less than the 100 kg C cap^{-1} y^{1} released from the burning of fossil fuels, mainly by the urban industrial and transport sectors.

Not only do the quantitative uses of firewood and charcoal exceed the area's wood production, but the fall in species richness has also reduced people's options qualitatively. For example, rural women depend on two particular shrub species for firewood because of the size of the branches, high wood density, and ease of collection. Beyond that, few fallback species remain. The fraction of women that reported shrub species as most prevalent in firewood use fell from 87% ca. 1945 to 50% in 1993. With respect to traditional medicine, 25 useful species have diminished significantly. Furthermore, eight species that provided fruit, leaves, and gum in past droughts have disappeared from as much as 53% of their range. If a grave famine hit the area in its current condition, people would not be able to find the emergency foods that saved others in past episodes.

In the Sahel, the natural regeneration of local species could halt the declines in biodiversity and forest biomass. Natural regeneration is a traditional practice in which farmers and herders protect and promote the growth of young native trees. Traditionally, local people protect small trees that have germinated naturally or resprouted from roots, prune them to promote growth of the apical meristem, and, if necessary, set a stake to straighten the small tree.

Natural regeneration has expanded *Acacia albida* from an original restricted range along rivers in Southern Africa over thousands of km^2 up through the Sahel and the Sudan. In Senegal, the Sereer have protected dense parks of *Acacia albida* and *Adansonia digitata* in wide areas south of the research area. On the Mossi Plateau in Burkina Faso, farmers have similarly protected expanses of *Butyrospermum parkii* for the valuable oil from the tree's seeds. Across the Sahel, leather workers protect *Acacia nilotica adansonii* for the tannin enriched bark.

Natural regeneration requires no external inputs. It concerns species well known and appreciated by villagers. It focuses on young trees that have demonstrated their hardiness by surviving with no human caretaker, no watering, and no special treatment. Furthermore, natural regeneration not only augments the supply of wood, poles, fruit, medicine, and other products, it puts trees where farmers and herders really need them: in fields to maintain soil fertility and in pastures to provide forage.

Although photosynthetic activity in semiarid lands is an inefficient conversion of the total available solar radiation, the inefficiency of human tools renders end uses even more inefficient in the final conversion into heat and light. Table III shows this energy chain from sunshine to wood end use in the West African Sahel.

TABLE III

Energy Chain from Sunshine to Wood End Use in the West African Sahel (W ha^{-1})

Insolation at ground	2,400,000
NPP	1,720
Total wood production	118
Human wood energy use	213
Imported fossil fuels	93
Food consumption	53
Human wood energy end-use	13

Gonzalez 1997.

Therefore, another practice that can serve to conserve vegetative cover in rural areas dependent on firewood is the use of improved efficiency cook stoves. In many areas, women customarily cook with a kettle over an open fire. International development agencies have worked to develop and introduce stoves such as the *ban ak suuf* in Senegal, a horseshoe-shaped hearth constructed from clay and cow dung that provides a more enclosed combustion space to more effectively channel heat to the cooking vessel. The *lorena* in Guatemala is another earthen stove. The *jiko* in Kenya and *sakkanal* in Senegal are enclosed metal or ceramic charcoal stoves that more effectively contain heat than do traditional open charcoal burners.

V. FUTURE ENERGY PATHS

Human energy use directly alters patterns of biodiversity through changes in land use and through industrial pollution. Indirectly, human energy use is changing global biodiversity through the emission of greenhouse gases that cause global climate change and through other broad environmental effects of industrialization. Not only does the direct processing of energy generate environmental impacts, but the end uses that convenient energy forms make possible produce impacts locally and globally.

Table IV summarizes the major environmental impacts of human energy use on biodiversity. Almost every source requires land (Table V), a requirement that leads to habitat fragmentation and destruction. Globally, the climate change caused by CO_2 emissions constitutes the major impact of fossil fuels, but nonfossil fuel sources also produce air and water pollution. No energy transformation system operates without negative environmental effects, yet renewable sources generally restrict harmful effects to the capital formation stage and do not produce much ongoing pollution.

Holdren and Ehrlich (1974) proposed that environmental impact is equivalent to the multiplicative effect

TABLE IV

Major Sources of Biodiversity Impacts from Human Energy Use

	Oil	Natural gas	Coal	Nuclear fission	Hydroelectric	Renewable technologies	Wood
Habitat destruction and fragmentation	Exploration, access roads, pipelines	Exploration	Mining, electricity transmission lines	Mining, electricity transmission lines	Flooding vast areas, changes to hydrology of rivers	Land requirement for collectors	Unsustainable harvesting can eliminate or fragment habitat
Water pollution	Oil spills, drilling muds		Acid leachate from tailings, water removal for processing and cooling water	Acid leachate from tailings, water removal for processing	Thermal changes	Toxics from photovoltaic production	
Effects on aquatic organisms	Oil spills		Entrainment, impingement, thermal pollution	Entrainment, impingement, thermal pollution	Complete alteration of habitat, barriers to migration, entrainment, impingement		
Air pollution	CO_2, toxic organic compounds from refining	CO_2, flaring, volatilization of CH_4	CO_2, SO_2	Radiation, toxic halogenated compounds in fuel processing			CO_2
Soil	Oil spills		Tailings	Radioactive waste		Toxic solid wastes from photovoltaic production	Erosion possible with unsustainable harvesting
Major end-uses	Automobiles	Cooking, heating	Electricity	Electricity	Electricity, smelters	Electricity	Cooking, heating

TABLE V

Land Requirements and Major Air Emissions for Electric Generation

	Land req. (ha MW^{-1})	($t\ GW^{-1}\ h^{-1}$)		
		CO_2	NO_x	SO_2
Geothermal	0.1–0.3	57		
Natural gas turbine	0.3–0.8	500		
Wind electric	0.4–1.7	7		
Nuclear	0.8–1.0	8	0.03	0.03
Coal	0.8–8.0	1000	3	3
Solar thermal electric	1–4	3.6		
Hydroelectric	2–1000	3		
Photovoltaics	3–7	5	0.008	0.02
Biomass	150–300		0.6	0.2

OTA 1995.

TABLE VI

Estimates of World Energy Resources at Current Technologies

Nonrenewable stocks	**TWy**
Petroleum	600
Natural gas (conventional)	400
Coal	5000
Heavy oils, tar sands, unconventional gas	1000
Uranium	3000
Renewable flows	**TW**
Solar electric	52
Biomass	26
Hydroelectric	1.2
Wind electric	1.5

Holdren 1991.

of population, affluence, and technology:

$$\text{Environmental Impact} = \text{Population} \times \frac{\text{Resource use}}{\text{Person}} \times \frac{\text{Environmental impact}}{\text{Resource use}}$$

People now call this identity the IPAT equation (impact = population × affluence × technology). Because the environmental impact of human energy use is proportional to the rate of energy use, and energy use is proportional to economic production, then the IPAT equation for energy becomes

$$\text{Environmental impact } \alpha \text{ energy use} = \text{Population} \times \frac{\text{GNP}}{\text{Person}} \times \frac{\text{Energy use}}{\text{GNP}}$$

Here, economic production per person indicates the level of material affluence, while energy use per unit of economic production indicates the level of technological efficiency. This highlights the great leverage that both energy conservation and efficiency wield to reduce the environmental impact of energy use. Indeed, improvements in energy efficiency reduced the energy intensity of economic activity in the United States by nearly one-third between 1975 and 1995.

For a 2100 AD global population of 10 million people to stay within the environmental limits of the earth, Holdren (1991) suggests that industrial countries improve their energy efficiency to allow for an increase in economic activity in the nonindustrial countries so that everyone converges on an average use of 3 kW per person. This would increase total world energy use to 30 TW, more than double today's total. Imagine a world with twice as many nuclear power plants, coal mines, automobiles, and other energy infrastructure as today. Because many environmental impacts increase exponentially, the total impact will be much more than double.

Yet, the historical path of industrialization has left the world with only costly and environmentally disruptive energy alternatives. The earliest exploitation of fossil fuels depleted the most convenient oil and gas deposits. This is why fossil fuel production over time follows the bell-shaped Hubbert Curve. Not only has this left the current generation with deposits that are farther in polar and desert regions, deeper underground, and dispersed, but the low-cost energy has also shaped the expectations of people around the world for inexpensive on-demand energy services. Societies even subsidize the provision of convenient energy through infrastructure support to energy industries, tax breaks to oil drillers, preferential treatment to automobile companies, and other schemes.

The depletion of nonrenewable resources (Table VI) and other serious environmental and social constraints hobble most energy options for the future: recoverable oil and gas reserves will last only another 50 years; coal burning releases the principal agent of global warming, CO_2; biomass energy requires vast amounts of land; the small number of exploitable sites limits the potential for hydroelectric and wind power; and health and safety concerns prevent expansion of nuclear energy.

As a response to these constraints, governments, industry, and academia have placed enormous effort into the development of technologies such as electric vehicles, hydrogen cars, fuel cells, and nuclear fusion. Still, the future of human energy use may not lie with exotic devices. Instead, renewable energy sources, conservation, and efficiency of end use could form the future energy path of the world. Amory Lovins (1977) called this the "soft path." This would occur if societies set as their goal the provision of services, not just the acquisition of energy stocks and devices. In effect, people don't require light bulbs, they need illumination.

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See Also the Following Articles

DEFORESTATION • DESERTIFICATION • ECOLOGICAL FOOTPRINT, CONCEPT OF • ENERGY FLOW AND ECOSYSTEMS • GREENHOUSE EFFECT • HUMAN EFFECTS ON ECOSYSTEMS, OVERVIEW

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