# 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
IV. Biodiversity Impacts of Traditional Energy
V. Future Energy Paths

## 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 1 K the temperature of 1 g of water. Other units include kilocalories (kcal), kilowatt-hours (kWh), and British Thermal Units (BTU).

**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.

**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.

**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 0) is 0.

**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 1 J in 1 s.

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***HUMAN ENERGY USE*** is the extraction, collection, and conversion of energy into forms that available technologies can utilize. Our energy use directly alters biodiversity through changes in land use and through industrial pollution. Indirectly, human energy use is changing biodiversity through the emission of greenhouse gases that cause global climate change and through other broad impacts on the natural function of ecosystems. While the direct effects cause acute damage, the indirect effects generally induce chronic harm. Both direct and indirect impacts of human energy use alter biodiversity at all scales: the globe, continents, ecoregions, landscapes, local sites, and individual species. 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. Consequently, future energy paths need to reduce the magnitude of each of these factors to most effectively reduce the impacts of human energy use on ecosystems.

## I. PATTERNS AND SCALE OF HUMAN ENERGY USE

We use energy both to meet subsistence needs and to fulfill nonessential wishes. In a subsistence society, a farmer burns wood to cook the day's meals. In an industrial society, people drive a car to go see 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 movie 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. Innovative technologies, including cogeneration systems, which produce electricity and industrial heat from natural gas, and hybrid gasoline–electric vehicles, have also emerged that combine two forms of energy transformation to increase overall efficiency.

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 mostly 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 regions 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, renewable energy sources include a host of recently developed, sometimes technologically complex, methods of harnessing sunlight, wind, water, or heat. These other renewable energy forms include photovoltaics, electricity-generating wind turbines, and geothermal turbines. These sources require some of the complex machinery associated with industrial energy, yet they depend only upon nondestructive methods of harnessing natural energy sources.

TABLE I

**Energy use (TW) in 2003 by region and energy source**

| | Coal | Hydroelectric | Natural gas | Nuclear | Oil | Renewable technologies | Wood, charcoal, biomass | TW | Fraction |
|---|---|---|---|---|---|---|---|---|---|
| Africa | 0.1 | 0.01 | 0.1 | <0.01 | 0.2 | 0.01 | 0.35 | 0.7 | 0.05 |
| Asia | 1.7 | 0.1 | 0.7 | 0.2 | 1.7 | 0.01 | 0.96 | 5.4 | 0.38 |
| Australia and New Zealand | 0.1 | <0.01 | 0.04 | 0 | 0.1 | <0.01 | 0.01 | 0.2 | 0.01 |
| Europe | 0.5 | 0.1 | 0.7 | 0.4 | 1.0 | 0.04 | 0.05 | 2.7 | 0.19 |
| Latin America | 0.03 | 0.1 | 0.2 | 0.01 | 0.4 | <0.01 | 0.13 | 0.8 | 0.06 |
| Russia | 0.1 | 0.02 | 0.5 | 0.1 | 0.2 | <0.01 | <0.01 | 0.8 | 0.06 |
| USA and Canada | 0.8 | 0.1 | 0.8 | 0.3 | 1.3 | 0.01 | 0.02 | 3.4 | 0.24 |
| World | 3.4 | 0.3 | 3.0 | 0.9 | 4.8 | 0.1 | 1.5 | 14.0 | 1.00 |
| Fraction | 0.24 | 0.02 | 0.21 | 0.07 | 0.34 | 0.01 | 0.11 | 1.00 | |

Data from BP (2004), IEA (2005), and REN21 (2005).

TABLE II

**Renewable energy rates of use in 2003**

| | |
|---|---|
| Firewood, charcoal, and other biomass | 1.5 TW |
| Large hydroelectric | 0.3 TW |
| Solar thermal heat | 77 GW |
| Small hydroelectric | 60 GW |
| Wind electric | 48 GW |
| Biomass-to-energy electric | 40 GW |
| Geothermal heat | 28 GW |
| Geothermal electric | 9 GW |
| Photovoltaics | 4 GW |

Data from IEA (2005) and REN21 (2005).

In 2003, the world rate of energy use totaled 14 trillion watts (terawatts (TW)) (Table I). As a comparison, this rate of energy use is equivalent to the power drawn continuously by 140 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 gigawatt (GW). So, world energy use in 2003 required the equivalent of the continuous output of 14,000 standard nuclear plants. The world uses renewable energy sources for only 14% of its energy (Table II).

The world rate of energy use includes the energy content of all industrial and traditional energy sources, except for hydroelectric, for which the world rate includes only the electricity output. Because hydroelectric does not consume fuel, it does not emit much waste heat (see Section II). If an equivalent amount of fossil fuel were used to generate the 0.3 TW generated by hydroelectric plants, then the world rate of energy use would total 14.6 TW. Thus, hydroelectric displaces 0.6 TW of fuel use and the associated impacts of that amount of industrial energy transformation.

The world depends on industrial energy sources for 89% of its energy use. The United States, Canada, People's Republic of China, European Union, India, Japan, and Russia account for 70% of world energy use. Fossil fuels and nuclear are the primary industrial energy sources. A third of industrial energy goes to electricity generation.

Traditional energy comprises approximately one-tenth of world energy use. Countries in Africa, Asia, and Latin America that are primarily nonindustrial account for the majority of world traditional energy use. In these countries, firewood and charcoal constitute the primary sources of energy. The International Energy Agency estimated that 2.4 billion people depended on firewood and charcoal in 2000, 40% of the world's population of 6.1 billion in 2000. The Food and Agriculture Organization of the United Nations estimated a global fuelwood use in 2002 of 1.8 billion $m^3$.

World energy use has increased significantly in just the past 150 years (Fig. 1). In the twentieth century alone, energy use increased by a factor of 12. While traditional energy use has remained nearly constant, the world has witnessed an explosion in the use of fossil fuels.

The United States uses a disproportionate share of the world's energy (Fig. 2). Although the United States hosts only 5% of the world's population, it generates 21% of the world's economic production, and uses 22% of the world's energy. The average 2003 energy use per person in the United States of 10,400 W/person greatly exceeded the world average of 2200 W/person, as well as energy use per person in most other industrial countries, such as France (5900 W/person). On average, each American uses seven times the amount of energy as each person in Brazil (1500 W/person) and 15 times the amount of energy of each citizen of India (690 W/person) (Fig. 3).

One measure of energy efficiency is energy intensity, the amount of energy used per unit of economic production. In 2003, United States energy intensity per

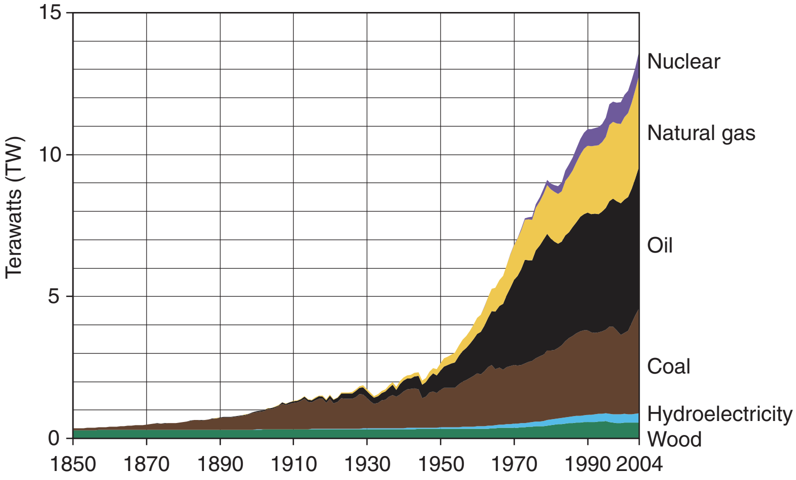

FIGURE 1 World energy use 1850–2004. Data from BP (2006), FAO (2005), and WEC and IIASA (1995).

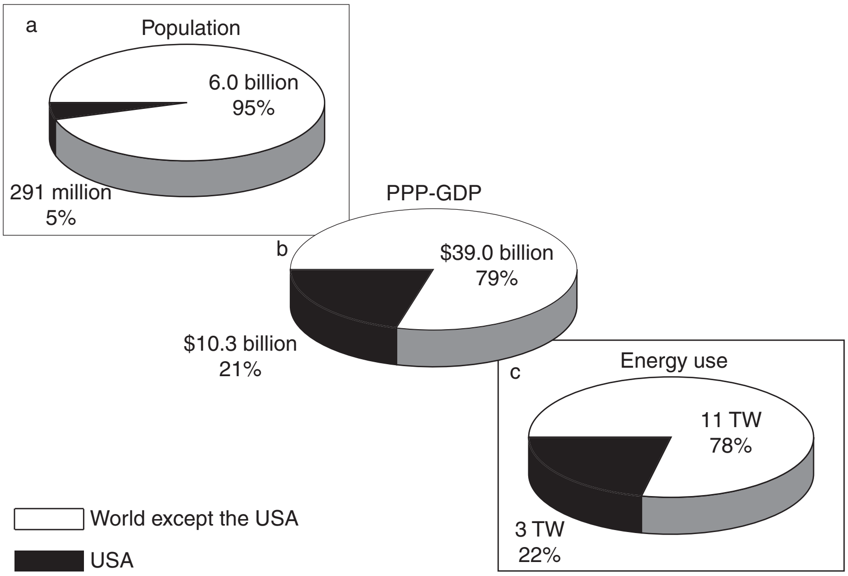

FIGURE 2 Share of the United States in world population, economic production, and industrial energy use in 2003. (a) Population, (b) GDP, adjusted for PPP, and (c) energy use. Data from IEA (2005).

unit of gross domestic product (GDP), adjusted for purchasing power parity (PPP), was 0.29 W/$. This slightly exceeded the world average energy intensity of 0.28 W/$, although the United States is more energy efficient than many oil producing countries (Fig. 4).

Countries at different stages of industrialization exhibit different patterns of end-use. In 2003, industrial countries used 40% of total energy use for industrial processes, 10% for commercial offices, 16% for residential buildings, and 33% for transportation, almost all of the latter in the form of oil (United States Department of Energy, 2006). This compares to global average end-uses of 49% industrial, 8% commercial, 16% residential, and 27% transportation.

In the United States, passenger 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 Section II).

| Highest energy use | (W/person) |
|---|---|
| Qatar | 32,500 |
| Equatorial Guinea | 31,100 |
| Iceland | 15,500 |
| Bahrain | 13,500 |
| United Arab Emirates | 12,900 |
| Kuwait | 12,700 |
| Luxembourg | 12,600 |
| Trinidad and Tobago | 11,200 |
| Canada | 10,900 |
| USA | 10,400 |

| Lowest energy use | (W/person) |
|---|---|
| Niger | 13 |
| Madagascar | 11 |
| Central African Republic | 7 |
| Burundi | 7 |
| Mauritania | 5 |
| Rwanda | 4 |
| Guyana | 4 |
| Burkina Faso | 3 |
| Cambodia | 1 |
| Comoros | 1 |

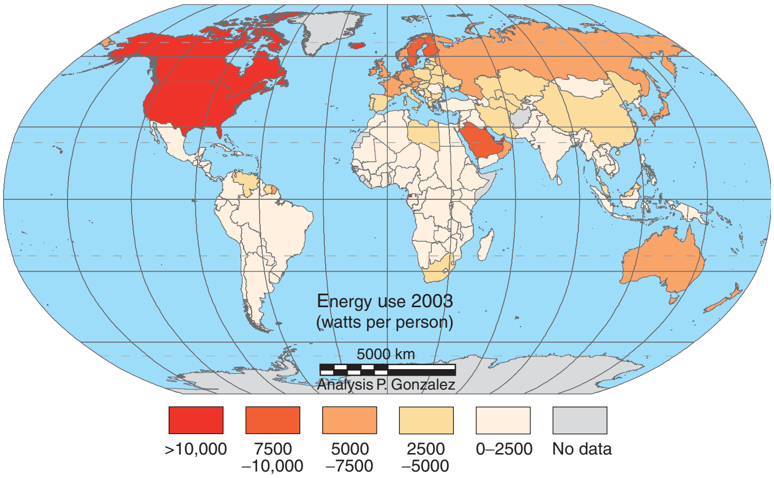

FIGURE 3 Energy use per person in 2003 and the 10 countries with the highest and 10 countries with the lowest energy use. Data from IEA (2005) and World Bank (2005).

| Lowest Efficiency | (W/$ PPP-GDP) |
|---|---|
| Equatorial Guinea | 6.40 |
| Brunei | 4.26 |
| Uzbekistan | 1.64 |
| Iraq | 1.55 |
| Suriname | 1.29 |
| Bhutan | 1.26 |
| Trinidad and Tobago | 1.10 |
| Tanzania | 1.08 |
| Serbia and Montenegro | 1.06 |
| Zambia | 1.03 |

| Highest Efficiency | (W/$ PPP-GDP) |
|---|---|
| Burundi | 0.010 |
| Guinea | 0.009 |
| Central African Republic | 0.007 |
| Rwanda | 0.003 |
| Burkina Faso | 0.003 |
| Mauritius | 0.003 |
| Mauritania | 0.003 |
| Guyana | 0.001 |
| Cambodia | 0.001 |
| Comoros | 0.001 |

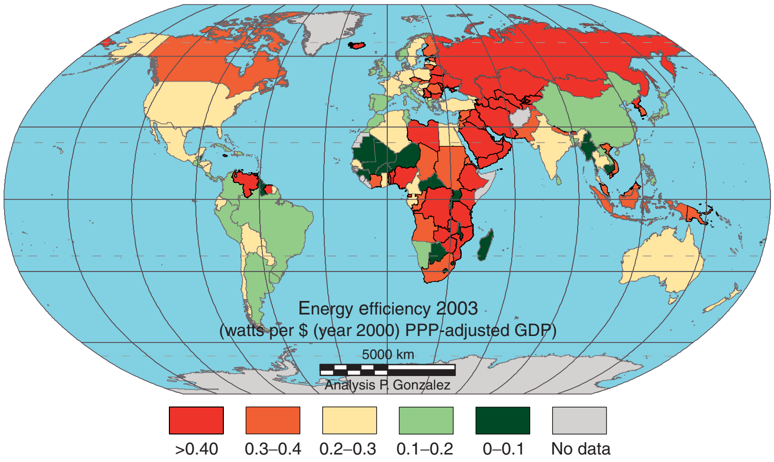

FIGURE 4 Energy efficiency of economic production in 2003 (watts per dollar (year 2000) of PPP-adjusted GDP) and the 10 most and 10 least energy efficient countries. Data from IEA (2005) and World Bank (2005).

The traditional energy sources of firewood and charcoal principally serve the end-uses of cooking and heating. Generally, cooking 1 J of food requires 2 J of firewood or 8 J of wood converted to charcoal. Consequently, rural people use 1–2 kg wood/person/day for a rate of energy use of 250–500 W/person. Actually, a total of only 20–40 W/person enters the cooked food and warmed people. Open fires will diffuse the rest as waste heat.

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 contains higher energy per unit mass than firewood. This makes charcoal easier to store and transport than firewood. Urban people use 100–150 kg charcoal/person/year, requiring 800–1200 kg wood/person/year. The ultimate end-use energy requirement is 30–45 W/person.

## 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 that the energy that 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. Therefore, the fewer energy transformations that a system performs, the fewer chances it creates for random second law energy losses.

For example, the objective of an automobile's internal combustion engine is to convert the chemical energy in the covalent bonds of hydrocarbons in gasoline to heat energy in an expanding fuel–air mixture in the piston to kinetic energy in the drive shaft to kinetic energy in 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 to transform the chemical energy in the covalent bonds of hydrocarbons in coal to heat energy in the boiler to heat energy in steam to kinetic energy in the 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:

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

with temperatures in kelvin (K).

For a coal-fired power plant, materials limit boiler temperatures to 1000–1200 K. At an ambient environmental temperature of 293 K (20°C), the maximum efficiency will be 70–75%. Typically, coal plants only achieve 30–35%, releasing two-thirds of the total as waste heat.

Table III 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."

TABLE III

**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 cannot get something for nothing | You cannot 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 combustion 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 aromatic hydrocarbons, 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 Ma. 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 primary agent of transformation. Eventually, these forces drove off most of the water, oxygen, and nitrogen in the condensate, leaving carbon and hydrogen compounds. Dispersed between sediment granules, the oil eventually migrated to low-pressure geologic traps at depths of 1–7 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 small amount of sulfur.

Petroleum exploration entails geologic surveys over extensive areas that often host low human populations and relatively undisturbed natural communities.

Exploration surveys bring vehicle traffic and temporary construction that generate local 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 vegetation, disturb animals, especially ground-nesting birds, and fragment habitat. If such activities disturb animal behavior during breeding periods, the impact can last over many growth periods.

Edwin L. Drake drilled the world's first commercial oil well in Titusville, Pennsylvania in 1859. Since then, oil fields have grown to cover millions of hectares of land around the world, but particularly in the Middle East, North America, Russia, Mexico, Venezuela, and Nigeria. The construction of oil well pads, access roads, buildings, electricity, and water lines, and other infrastructure destroys vegetation and withdraws land from natural habitat. Roads and other linear infrastructure fragment a landscape that extends far outside core areas of operation. For example, while the core infrastructure at the Prudhoe Bay field, Alaska, opened for drilling in 1968, covers 70 $km^2$, the 2000 km network of roads, short-distance pipelines, and electric lines extend across 2600 $km^2$ of Arctic tundra. Proposed exploitation of Area 1002 in the Arctic National Wildlife Refuge would further fragment and alter the North Slope Arctic ecosystem.

Globally, the length of pipelines for oil and refined products totals 660,000 km, according to the US Central Intelligence Agency. In addition to leaking and fragmenting natural ecosystems, pipelines create avenues for immigrants to settle and clear forest and other natural vegetation. For example, the 1000 km pipeline for the Chad-Cameroon Petroleum Development and Pipeline Project, a World Bank project completed in 2003, has sliced across some intact forest ecosystems and attracted new migrants who have cleared land for agriculture.

To mitigate environmental impacts of the 1300 km trans-Alaska pipeline and adjacent access road, which entered into operation on June 20, 1977, the oil companies integrated a unique set of environmental protection features. To prevent thawing of permafrost areas, brackets elevate 700 km of pipeline to heights of 3 m. Pipes at the bracket legs dissipate heat generated by the friction of oil passing through the pipe. The elevated sections serve as underpasses for *Rangifer tarandus* (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.

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 low-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. The National Academy of Sciences of the USA estimates that oil spills into oceans and freshwater bodies average 1.3 million t each year. Approximately 15% of the spills come directly from oil wells, pipelines, and supertankers, 40% come from nonpoint urban runoff, and the remaining come from natural seeps. During oil production, 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. The most catastrophic potential for oil spills dwells at the seaport terminal and in the supertankers that carry the oil over the oceans between terminals (Table IV).

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

Exposure to sunlight initiates photolysis of hydrocarbons into lower 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. Some oil will sink into sediments; other oil will coat beaches; a fraction of oil will remain suspended in the water column for years.

TABLE IV

**Ten most voluminous oil spills since 1960**

| Rank | Incident location | Volume (million l) | Date |
|---|---|---|---|
| 1 | Persian Gulf War | 900 | January 26, 1991 |
| 2 | Ixtoc I well, Gulf of Mexico | 530 | June 3, 1979 |
| 3 | Production well, Uzbekistan | 330 | March 2, 1992 |
| 4 | *Atlantic Empress*, off Trinidad and Tobago | 320 | July 19, 1979 |
| 5 | Nowruz platform no. 3, Persian Gulf | 300 | February 4, 1983 |
| 6 | *Castillo de Bellver*, off coast of South Africa | 300 | August 6, 1983 |
| 7 | *ABT Summer*, off coast of Angola | 290 | May 28, 1991 |
| 8 | *Amoco Cadiz*, off coast of France | 260 | March 16, 1978 |
| 9 | *Odyssey*, off coast of Canada | 160 | November 10, 1988 |
| 10 | *Haven*, Genoa, Italy | 160 | April 11, 1991 |

Data from Oil Spill Intelligence Report, International Tanker Owners Pollution Federation.

Oil will kill birds by coating, matting, and waterlogging their feathers. 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 aromatic hydrocarbons in petroleum, including benzene, toluene, xylene, and phenols, are lethal to animals on contact and carcinogenic under chronic exposure. Moreover, polycyclic aromatic hydrocarbons bind to lipophilic sites, an affinity that magnifies these compounds up the food chain. Even when not deadly, sublethal disruption of physiology or behavior reduces resistance to infection and causes general stress.

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. Marine mammals may experience chronic problems after a spill because oil can accumulate in their bile and fatty tissues.

An unfortunate coincidence juxtaposes important commercial fisheries and high-yield offshore oil fields on the continental shelves. Not only do oil spills kill fish directly, but chronic effects also reduce fish fitness years after initial exposures.

Oil at the air–water interface acts as a physical barrier that impedes gas exchange. In fact, oil has served as a traditional medium to control mosquito larvae. 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 occupy the areas of highest oil concentration. Hydrocarbons damage eggs on contact. Oil concentrations will quickly exceed the $LC_{50}$ for fish larvae of 1–10 ppm. The early life stages of intertidal-spawning fish are especially susceptible.

Over time, tidal action 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 will asphyxiate filter feeders.

Oil spills also damage phytoplankton and other marine plants. Because oil absorbs photosynthetically active radiation, a coat of oil will hinder plant growth and increase plant tissue temperature. Aromatic hydrocarbons 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 produce eutrophic conditions.

The largest oil spill in continental US waters occurred on March 24, 1989, when the supertanker *Exxon Valdez* ran aground in Prince William Sound, Alaska, and poured out 42 million l of crude oil. The spill caused acute damage to birds, marine mammals, and intertidal communities and caused chronic damage to fish species and intertidal and subtidal communities.

The spill occurred in early spring, just before the young of many species emerge 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 over 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 species of the genus *Frattercula* (puffins) and four species of the genus *Gavla* (loons). For the following 3 years, fewer breeding *Uria aalge* (common murres) showed up at spring colonies.

Exposure to toxics from the *Exxon Valdez* spill has caused chronic problems in *C. pallasi* (Pacific herring), *Oncorhynchus clarki* (cutthroat trout), *O. gorbuscha* (pink salmon), and *Salvelinus malma* (Dolly Varden). Fish 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.

Oil refining can also generate water pollution. Refining employs catalytic cracking of carbon–carbon bonds of long-chain alkanes to produce lower molecular weight hydrocarbons. Refineries try to recover every possibly useful organic compound, from light products, such as methane, benzene, and kerosene, to medium-weight products, such as gasoline and diesel fuel, to heavy tars and asphalt. Unless treated, wastewater from these processes, as well as sulfur recovery, will pollute surface waters.

Most constituents of petroleum and refined oil products volatilize easily. Consequently, each step of the petroleum fuel cycle generates air pollution. Methane, 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 water and air pollution and requires land. The combustion of refined oil products for automobiles, 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). Moreover, armed conflicts caused, in part, by efforts to control access to oil fields and refineries, directly harm human well-being and ecosystem health.

## 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 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 particular, exploration grids, roads, and other linear infrastructure fragment a landscape that extends far outside core areas of operation. Accelerated natural gas leasing in Rocky Mountain and adjacent grassland regions by the US Government since 2001 has created networks so dense that no undisturbed ecosystems remain in some areas.

In the nineteenth century, companies had not yet erected natural gas pipelines or processing facilities. Moreover, industry had not yet developed extensive technology that burned natural gas. Because companies found natural gas uneconomical to exploit, they just burned it off to reduce the risk of fire and explosion. Consequently, the entire history of natural gas production has flared the equivalent of more than 8 years worth of US annual energy use. Today, North American and European companies generally flare only small amounts at refineries, but companies in other countries flare 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 will generally divide natural gas into three fractions: natural gas liquids (NGL), liquified petroleum gas (LPG), and liquified 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 LPG. Finally, pressurization of natural gas produces LNG, a product that is expensive because of the special containers required for transport.

Globally, the length of natural gas pipelines totals 1.3 million km, according to the US Central Intelligence Agency. As with oil pipelines, natural gas pipelines destroy and fragment natural ecosystems and create avenues for immigrants to settle and clear forest and other natural vegetation. The construction of specialized natural gas terminals often destroys or modifies coastal sites.

The major end-uses of natural gas, cooking and heating, burn the fuel directly with no further transformation. Electricity generation from natural gas employs 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 a 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 with a global warming potential of 21, indicating an impact on global warming 21 times more intense than carbon dioxide. The combustion of methane also produces carbon dioxide and contributes to climate change.

## 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 100–200 Ma and from the Permian period 250 Ma. 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 heat 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 regions, people burn peat for heating, cooking, and light.

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

Coal mines generally fall into three types: deep, open pit, and strip. Deep mines extend down to a depth of ~1 km. Open pit mines reach down to 300 m. Strip mining generally removes the upper 30 m of a land surface and the underlying deposits. 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 microclimate profile of a landscape. Subsidence 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 significant 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 liquid 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 removes 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 invasive species to expand where perennial native 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 size, 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 of the coal mined worldwide powers electricity generation plants. A conventional power plant burns coal in a boiler to boil water that circulates through a closed loop of pipes. The steam from the boiler enters a 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 a coal-fired 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, while 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 impacts.

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. 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 $m^3$ water per day for all operations, mostly for cooling. This need dictates the necessity to locate a plant next to a natural water body. Power plants mainly use freshwater because of the corrosive effects of saltwater. Water withdrawals alter 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 US 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 $\geqslant 35^{\circ}C$.
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 migration 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 60 m tall. The network of high-voltage electricity lines (230, 345, 500, and 765 kV) in the United States stretches across 250,000 km, according to the US Department of Energy, and occupies more than 13,000 $km^2$ of land. Clear-cutting of forest to create corridors 30–60 m wide for transmission easements directly removes vegetation. Periodic clearing maintains and intensifies the original changes. The areas that remain favor ruderals and animal species that adapt readily to human disturbance. 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 while providing avenues for the dispersal of invasive weeds. 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, monospecific plantations, and milling (see Deforestation and Land Clearing). In many countries, utilities treat the wood with creosote to guard against 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 materials and energy needed to build the massive infrastructure of the coal fuel cycle produce wide-ranging environmental impacts. Because most coal goes to electricity generation, the end-uses of coal produce the environmental impacts associated with air conditioning, commercial 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. While the half-life of strontium-90 is 29 years and the half-life of cesium-137 is 30 years, plutonium-239 decays with a half-life of 25,000 years, and a quantity of iodine-129 will decay to half of its mass only after 17 My. The similarity of the atomic structure of strontium to calcium increases its uptake in animals and incorporation into bones.

Nuclear fission plants require highly processed uranium fuel. Uranium rests in geologic strata in the minerals uraninite and pitchblende. The isotope uranium-238 accounts for over 99% of the uranium in nature, but nuclear fission fuel requires the uranium-235 isotope. A standard 1 GW nuclear fission plant requires 150,000 Mt uranium-containing ore to fabricate enough fuel for 1 year. Milling, roasting, and acid leaching of the ore produces 150 Mt uranium oxide ($U_3O_8$) in a granular form called yellowcake, as well as significant amounts of ore tailings and chemical effluents. Fluorination of the yellowcake produces 188 Mt of uranium hexafluoride ($UF_6$).

Processors use one of three methods—gaseous diffusion, gas centrifuge separation, or liquid thermal diffusion—to divide the $UF_6$ into separate fractions, one of which is enriched in a higher concentration of uranium-235 than that found in nature. Nuclear fission for electricity generation requires enrichment to 2–3% uranium-235. Continuation of the process produces material enriched to 97–99% uranium for use in nuclear bombs.

The original ore for the standard 1 GW nuclear fission plant has now yielded 31 Mt $UF_6$ enriched in uranium-235. Fuel fabrication then produces 30 Mt of uranium dioxide ($UO_2$) pellets for use in the nuclear reactor core.

The mining and milling of uranium ore creates most of the same environmental problems already described for deep coal mines and coal processing. Uranium conversion, enrichment, and fuel fabrication requires many toxic chemicals, including fluorine gas, which is lethal on contact to animals, damages vegetation, and forms toxic by-products.

According to the International Atomic Energy Agency (IAEA), 443 nuclear fission plants with a combined rated capacity of 370 GW were operating in 32 countries in April 2006. Among these, the United States operates 104 nuclear fission plants with a combined rated capacity of 99 GW.

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

Because nuclear plants involve combustion only in construction and in support vehicles, 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 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 US Department of Energy opened the Waste Isolation Pilot Plant for low-level wastes in the Carlsbad Cavern system of New Mexico. The Department has also proposed a repository for high-level wastes deep under Yucca Mountain, Nevada.

The greatest single release of radiation from a nuclear fission power plant came from the Chernobyl Unit 4 accident on April 26, 1986 in an area of the Republic of Ukraine, which was then in the former Soviet Union. Operator error combined with design drawbacks of the RBMK graphite-moderated reactor generated a nearly instantaneous catastrophic increase of thermal power and 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 over 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.

## E. Hydroelectric

Hydroelectric systems harness the potential energy represented by an elevated mass. The potential energy of water at elevation will convert into increased kinetic energy of the water when it runs to a lower elevation. A dam concentrates the difference in elevation, termed hydraulic head, in a spillway equipped with a turbine and an 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 alteration of topography and stream flow and the partial inundation of the watershed. Besides the forced removal of people and inundation of homes, hydroelectric plants also cause significant ecological changes.

Over 45,000 large dams now block rivers around the world, creating reservoirs that inundate up to 1 million $km^2$, according to the World Commission on Dams. In 1965, the Akosombo Dam on the Volta River in Ghana created Lake Volta, at 8500 $km^2$ the largest impoundment in the world, according to the US Government. 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, scheduled for completion in 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 use 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 forfeited and biomass wasted.

A dam blocks nutrient-rich sediment that a river system otherwise would have deposited in floodplains, wetlands, and at the river's outlet delta. Not only does the sediment buildup fill in a reservoir and 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 outlet delta, dams alter bay and estuary topography, reduce the area of mudflats, and decrease nutrient-rich upwellings. The Aswan High Dam in Egypt blocks 98% of the 120 million t of sediment that the Nile River had carried each year, formerly depositing 10 million t on the floodplain and delta. Consequently, soil depth has thinned and agricultural production has declined in the Nile Valley. Blockage of sediment and freshwater by the Akosombo 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, the reduction of estuaries and mudflats at a dammed river's outlet delta renders the coast more susceptible to tidal 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 US Department of the Interior staged controlled floods in 1996 and 2004.

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 a gravel stream bottom to spawn. Many insect, amphibian, and fish species also use gravel areas for habitat or 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 0–27°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 $\text{km}^2$ reservoir straddling the Brazil–Paraguay border behind the Itaipu Dam, the hydroelectric plant with the highest generation capacity in the world, 12.6 GW, a nonnative species, *Plagioscyon squamosissimus* (curvina) has become the second most numerous species.

Polychlorinated biphenyls (PCBs) released from circuit-breakers and oil leaking from machinery constitute the worst direct industrial pollution from dams. These 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 materials and energy needed to construct the massive infrastructure of the hydroelectric energy cycle produces wide-ranging environmental impacts. The end-uses of hydroelectricity will produce the environmental impacts associated with air conditioning, 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 polluntants 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.

Forms of renewable energy generally 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 principal environmental impacts emerge 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. In contrast, 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. Solar heating is almost completely 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 parabolic or trough collectors. Because solar is generally economically feasible only in hot sunny areas, sites are generally arid and water is scare. 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 cells produces toxic environmental impacts. The process starts with mining of the quartz that constitutes the base material of a photovoltaic 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 takes place in a fluidized bed reaction of the silicon with hydrochloric acid. Then the process produces semiconductor-grade polycrystalline silicon by electrical heating of semiconductor-grade silicon at 1000°C and vapor deposition on a silicone substrate. Remelting the polycrystalline silicon produces a form that can grow into crystals. Precision saws cut these crystals into wafers 0.5 mm thick. Then robotic devices wire and encapsulate the cells in glass 3 mm thick.

Trace metals are used to dope the semiconductor material for the principal types of photovoltaic cells, including cadmium telluride, copper indium diselenide, gallium arsenide, and gallium indium phosphide. The trace metals in these compounds, 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.

Biomass-to-energy plants are facilities that convert waste wood from lumber mills, specially grown wood, agricultural organic waste, or municipal waste to electricity either through direct combustion of biomass in low-pressure boilers to power electric steam turbines or through the gasification of organic matter into methane to power natural gas electric turbines. Biomass-to-energy plants often employ cogeneration to provide process heat for an adjacent industrial facility.

Utilities in Brazil generate electricity and cogenerate heat from the organic wastes, or bagasse, left from the processing of sugarcane and orange juice. Many landfills around the world use networks of collection pipes to capture methane released by decomposing municipal waste and send the methane to natural gas electric turbines on-site.

Most biomass-to-energy production uses waste wood and organic matter that would otherwise oxidize and release its energy as waste heat. The productive reuse of waste products in biomass-to-energy production therefore reduces the environmental impact of the disposal of biomass waste. Experimental schemes, however, that grow wood or agricultural crops specifically to burn for electricity generation, can produce negative environmental impacts if the schemes use conventional fossil-fuel-powered machinery and energy-intense fertilizers. Indeed, energy-intensive methods could expend more energy in the cultivation and processing of energy crops than the amount of energy generated by burning the biomass to generate electricity.

The principal species used by such experimental schemes include short-rotation trees such as *Populus* spp. (poplars, aspen, and cottonwoods) grown at densities of 1600–5000 trees/ha and *Panicum virgatum* (switchgrass). Moreover, an energy crop can generate negative effects on natural ecosystems if it is grown in monoculture or 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.

The section on coal details the negative effects of electric turbines and condensers that are also components of biomass-to-energy systems.

The conversion of biomass into alcohol fuels, known as biofuels, 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. 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. In 2005, the United States produced 350 million l of ethanol, mainly from corn. Brazil produces enough ethanol from sugarcane to provide for 10% of the country's energy use. Other countries produce smaller amounts of biofuel from seeds of the plant *Jatropha curcas* and from oil of the palm *Elaeis guineensis*.

Biofuel production that uses conventional fossil-fuel-powered machinery and energy-intense fertilizers can expend more energy in the cultivation and processing of energy crops than the amount of energy contained in the final biofuel product. Moreover, combustion of fossil fuels and energy use for inorganic fertilizer production generates the negative impacts identified in previous sections. Because the combustion of ethanol mainly produces $CO_2$ and water and much smaller amounts of hydrocarbons and $NO_x$ than gasoline combustion, ethanol produced by nonfossil fuel-intense processes can mitigate the most harmful direct effects of oil production and use.

For centuries, society has captured wind for moving sailing ships, pumping water, and milling grain. Contemporary wind turbines also power electric generators. Rated at 100–300 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, California, the Tehachapi Pass in Southern California, in the Netherlands, and Denmark. Wind farms fragment terrestrial habitats and access road networks cause soil erosion. Wind turbines can also kill significant numbers of birds.

Geothermal electric plants captured the heat of hot geologic formations, generating 28 GW of electricity worldwide in 2003. Geothermal plants sink pipes down to hot strata to either capture deep hot water or to inject hot water to boil it on contact with hot rocks. These processes mobilize trace metals contained in certain strata and release $H_2S$ 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 by coppicing, or cutting at the base, moderate size shrubs, and by lopping branches off mature trees. Only rarely do rural people in Africa, Asia, and Latin America fell whole trees and split logs for domestic firewood because of the time and labor required for such work.

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, will go out in the dry season and cut at the base shrubs of species that are mainly in the family *Combretaceae*. Then they carry the branches back to the village and let the wood dry. 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 often provides thorny branches that are difficult to handle. When branches are depleted, women in semiarid areas of Africa 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 will 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.

While 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 generate impacts far beyond its borders.

Wood contains energy at a density of ~15 GJ/t, one-third the energy density of oil. The relatively low-energy density of wood renders 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 1–4 m in height and 1–3 m in diameter, and ignite a slow burn. Over 3–6 days, the wood converts to charcoal by partially anaerobic pyrolysis.

If wood harvesting for firewood or charcoal exceeds the natural regeneration of shrubs and trees in an area, then wood harvesting will reduce vegetative cover. The reduction of vegetative cover and the conversion of forested or wooded land to savanna or grassland comprise the principal potential impacts of traditional energy on natural ecosystems. Yet, deforestation to expand subsistence agriculture reduces vegetative cover primarily to extend cultivatable land areas. This creates situations that make it nearly impossible to quantitatively attribute the fraction of land use change due to agricultural expansion or due to human energy use. Another potential impact arises with people's preferences of certain species for firewood. These preferences create a risk that people will harvest the preferred species to the point of local disappearance.

In some areas of Africa, Asia, and Latin America, international development agencies have funded the massive plantation of exotic species, such as *Eucalyptus camaldulensis*, for firewood production. Plantations that replace native forest or woodland eliminate natural ecosystems. Single-species, even-aged plantations offer greatly reduced spatial structure compared with natural forests with multiple species, age classes, and canopies. In general, the diversity of natural forests offers an area more resilience in the face of fire, wind, and insect disturbances.

Natural regeneration of local species can restore native forest cover in ecosystems changed by overharvesting for wood. 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. In Africa, natural regeneration has expanded *Acacia albida* from an original restricted range along rivers in Southern Africa to an extensive range that reaches across the continent north to the Sahel.

TABLE V

**Energy chain from sunshine to wood end-use in the West African Sahel (W/ha)**

| | |
|---|---|
| Insolation at ground | 2,400,000 |
| Net primary productivity | 1,700 |
| Total wood production | 120 |
| Human wood energy use | 210 |
| Imported fossil fuels | 93 |
| Food consumption | 53 |
| Human wood energy end-use | 13 |

Gonzalez (2001).

Natural regeneration requires no external inputs. It concerns species that are well known and appreciated by rural people. 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.

Photosynthetic activity only converts a fraction of total available solar radiation to wood. Nevertheless, the inefficiency of human tools for the conversion of wood to heat and light renders human end-uses even more wasteful. Table V shows this energy chain from sunshine to wood end-use in the West African Sahel.

Therefore, improved efficiency cook stoves can conserve vegetative cover in rural areas that depend on firewood. 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, in Senegal, the *ban ak suuf*, a horseshoe-shaped hearth constructed from local clay that provides an enclosed combustion space that more effectively channels heat to the cooking vessel. The *lorena* in Guatemala is another improved efficiency earthen stove. The *jiko* in Kenya and *sakkanal* in Senegal are enclosed metal or ceramic charcoal stoves that more effectively contain heat than traditional open charcoal burners.

## V. FUTURE ENERGY PATHS

Human energy use directly alters biodiversity through changes in land use and through industrial pollution.

TABLE VI

**Major sources of biodiversity impacts from human energy use**

| Impact | Oil | Natural gas | Coal | Nuclear fission | Hydroelectric | Renewable technologies | Wood |
|---|---|---|---|---|---|---|---|
| Habitat destruction and landscape 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 mine tailings, water removal for processing and cooling water | Acid leachate from mine tailings, water removal for processing and cooling water | 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 | | Mine 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 |

Indirectly, human energy use is changing biodiversity through the emission of greenhouse gases that cause global climate change and through other broad impacts on the natural function of ecosystems. Not only does the direct processing of energy generate environmental impacts, but the end-uses that convenient energy forms make possible produce impacts at all scales: the globe, continents, ecoregions, landscapes, local sites, and individual species.

Table VI summarizes the major environmental impacts of human energy use on biodiversity. Table VII summarizes the significant land requirements of energy sources. Land use change for energy use destroys and fragments natural ecosystems. Globally, climate change caused by emissions of $CO_2$ and other greenhouse gases constitutes the most significant impact of fossil fuels, but nonfossil fuel sources also produce air and water pollution. No energy transformation system operates without negative environmental impacts, yet renewable sources generally restrict harmful effects to the capital formation stage, and do not produce much ongoing pollution.

Scientists Holdren and Ehrlich (1974) proposed that environmental impact is equivalent to the multiplicative effect 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 refer to this identity as 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, the IPAT equation for energy becomes

$$\begin{aligned}\text{Environmental impact} &\propto \text{Human energy use}\\ &= \text{Population} \times \frac{\text{Economic production}}{\text{Person}}\\ &\quad \times \frac{\text{Energy use}}{\text{Economic production}}\end{aligned}$$

TABLE VII

Land requirements and major air emissions for electric generation

| | Land req. (ha/MW) | $CO_2$ (t/GWh) | $NO_x$ (t/GWh) | $SO_2$ (t/GWh) |
|---|---|---|---|---|
| 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 | 4 | | |
| Hydroelectric | 2–1000 | 3 | | |
| Photovoltaics | 3–7 | 5 | 0.008 | 0.02 |
| Biomass | 150–300 | | 0.6 | 0.2 |

US OTA (1995).

Economic production per person, often expressed as dollar of PPP-adjusted GDP per person, indicates a society's level of material affluence, although GDP does not price ecosystem services such as clean water and natural habitat at their full value and values activities with negative impacts, such as military spending, as positive. Energy use per unit of economic production, expressed as watts per dollar of purchasing power parity-adjusted GDP, indicates a society's level of technological efficiency. This relationship highlights the 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 an AD 2100 global population of 10 million people to stay within the environmental limits of the Earth, Holdren (1991) has suggested 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/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 would more than double, if such a world were even possible.

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 phenomenon explains why fossil fuel production over time follows the bell-shaped Hubbert Curve. Not only has this path left the current generation with deposits that are farther in Arctic and desert regions, deeper underground, and dispersed, but 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.

TABLE VIII

**Remaining world energy resources in 2000**

| Nonrenewable energy | Stock (TWy) | Time remaining at 2003 rates (y) | Carbon release to atmosphere (Gt) |
|---|---|---|---|
| Coal | 6000 | 2000 | 5200 |
| Heavy oil, tar sands, natural gas (unconventional) | 2000 | 350 | 900 |
| Natural gas (conventional) | 500 | 200 | 250 |
| Oil | 400 | 80 | 250 |
| Uranium | 50 | 50 | Unknown |
| **Renewable power flows** | **TW** | **Time remaining** | **Carbon release to atmosphere (Gt)** |
| Biomass | 8.8 | Lifetime of Sun | Negligible |
| Geothermal | 16 | Lifetime of Sun | Negligible |
| Hydroelectric | 1.6 | Lifetime of Sun | Negligible |
| Solar electric | 50–1600 | Lifetime of Sun | Negligible |
| Wind electric | 20 | Lifetime of Sun | Negligible |

Data from UNDP (2000).

The depletion of nonrenewable resources (Table VIII) 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 problems prevent expansion of nuclear energy.

As a response to these constraints, scientists and engineers have placed enormous effort into the development of technologies such as electric vehicles, hydrogen cars, fuel cells, and nuclear fusion. Still, exotic devices will not resolve our energy problems if they depend on nonrenewable fuels. Instead, energy efficiency, conservation, and renewable energy sources form the only sustainable future energy path for the world. This path asks us to set as our goal not the acquisition of energy stocks and devices, but the provision of the services that we get from energy. In effect, we do not require light bulbs, we need illumination.

## See Also the Following Articles

ACID RAIN AND DEPOSITION • AIR POLLUTION • DEFORESTATION AND LAND CLEARING • ECONOMIC GROWTH AND THE ENVIRONMENT • GREENHOUSE EFFECT • POLLUTION, OVERVIEW

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