Energy Use, Human

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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 the temperature of 1 g of water by 1 K. 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 renewable energy systems, including solar photovoltaics, wind turbines, geothermal systems, and biofuels.

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, and subsurface water and geologic formations. The major forms of renewable energy are solar, wind, geothermal, hydropower, and biomass. Renewable energy systems 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, and utilized in small quantities by rural populations. The principal forms of traditional energy are firewood, charcoal, crop residues, dung, and small water and windmills.

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 s^{-1}.

Patterns and Scale of Human Energy Use

We use energy to meet subsistence needs and to fulfill nonessential wants. 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 – merely comprise the means to end-uses – cooking, driving, operating a movie theater – that ultimately provide desired 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 technologies developed 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 renewable energy systems, including solar photovoltaics, wind turbines, geothermal systems, and biofuels. Cogeneration systems that produce electricity and industrial heat from natural gas and hybrid gasoline-electric vehicles 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 water and windmills. Because traditional energy sources occur widely and because their transformation does not rely on complex technology, they comprise the most important sources for rural people in the less industrialized regions of the world. A rural household generally harvests traditional energy sources for its domestic 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 a form of renewable energy, which includes forms of energy whose transformation does not

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consume the ultimate source of the energy. Renewable energy harnesses solar radiation, wind, water movement, and cold and hot reservoirs in water and geologic strata. The major forms of renewable energy are solar, wind, geothermal, hydropower, and biomass. Conversely, nonrenewable energy systems consume the very source of the energy, primarily oil, coal, natural gas, and nuclear fuel.

In addition to traditional energy and industrial hydroelectric, renewable energy sources include technologically complex systems: solar photovoltaics, wind turbines, geothermal systems, and biofuels. These systems require complex machinery associated with industrial energy, yet depend only upon nondestructive methods of harnessing natural energy sources.

World energy use has increased substantially in the past 150 years (**Figure 1**). In the twentieth century, energy use increased by a factor of 12. During this time, the world witnessed an explosion in the use of fossil fuels, while renewable energy use increased slightly.

In 2008, the world used energy at a rate of 16.2 trillion watts (16.2 TW) (**Table 1**). As a comparison, this rate of energy use is equivalent to the power drawn continuously by 1.1 trillion compact fluorescent light bulbs rated at 15 W. As another comparison, world energy use in 2008 required the equivalent of the continuous output of 16,000 standard 1 GW nuclear plants.

The world uses renewable energy sources for 12% of its energy (**Table 2**). The rate of hydroelectric energy use (**Tables 1** and **2**) is equal to the hydroelectricity output. Unlike fossil fuel combustion systems, hydroelectric systems do not waste energy as heat. If an equivalent amount of fossil fuel were used to generate the 0.4 TW generated by hydroelectric plants, then the world rate of energy use would total 16.8 TW. Thus, hydroelectric displaces 0.6 TW of fuel use and the impacts from that amount of industrial energy transformation.

The world depends on industrial energy for 90% of its energy use. Fossil fuels and nuclear are the primary industrial energy sources. Traditional energy comprises approximately one-tenth of world energy use. Countries in Africa, Asia, and Latin America account for the majority of world traditional energy use, with firewood and charcoal as the main sources.

While the United States (U.S.) is home to 4.5% of the world's population, it uses 19% of the world's energy (IEA, 2010). The U.S. fraction of global energy use has decreased steadily in the twenty-first century because of large increases in other countries, especially the People's Republic (P.R.) of China, where energy use has grown to the amount used in the U.S. (IEA, 2010).

One measure of energy efficiency is energy use per person. In 2008, average world energy use was 2400 W person^{-1} (IEA, 2010). Average U.S. energy use (10,000 W person^{-1}) exceeds energy use per person in many other industrial countries, for example, France (5500 W person^{-1}). On average, each person in the U.S. uses six times the amount of energy as each person in Brazil (1700 W person^{-1}) and 15 times the amount of energy of each person in India (700 W person^{-1}) (**Figure 2a**).

Another measure of energy efficiency is energy intensity, the amount of energy used per unit of economic production. In 2008, average world energy intensity was 0.25 W \$$^{-1}$ of gross domestic product (GDP), adjusted for purchasing power parity (IEA, 2010). U.S. energy intensity matched the world average. The U.S. has steadily increased its energy efficiency for decades, although it still is less efficient than many other industrial countries, for example, the United Kingdom (0.15 W \$$^{-1}$) (**Figure 2b**).

In 2008, the world used 37% of energy for industry, 36% for the commercial and residential sectors, and 27% for transportation (IEA, 2010). In 2009, U.S. energy end-uses were: industry 30%, commercial 19%, residential 22%, and transportation 29% (U.S. Department of Energy, 2010). Globally, a third of energy goes to electricity generation, mainly from coal, hydroelectric, and nuclear. Power plants release two-thirds of that as waste heat (see the next section). In the U.S., personal cars use half of all transportation energy.

The traditional energy sources of firewood and charcoal mainly serve the end-uses of cooking and heating. Cooking 1 J

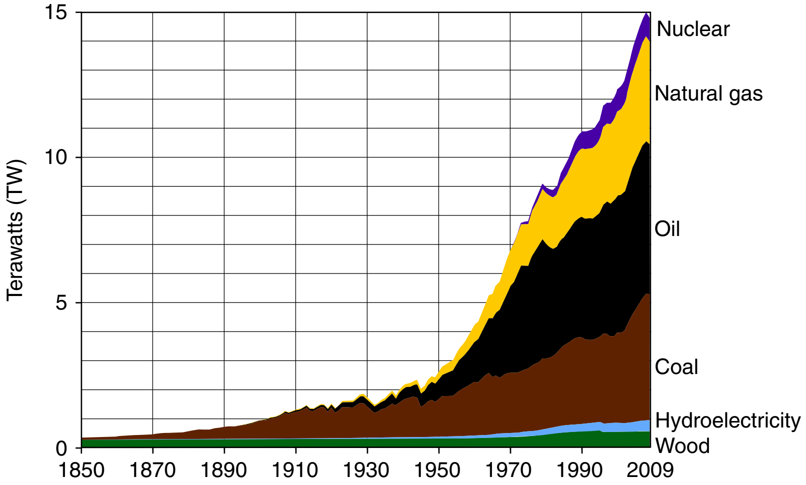

Figure 1 World energy use 1850–2009 (data from WEC and IIASA, 1995; BP, 2010; Food and Agriculture Organization (FAO) FAOSTAT <http://faostat.fao.org>; International Energy Agency (IEA) Statistics <http://www.iea.org/stats>). Because of a difference in FAO and IEA estimates of wood and biomass use, total 2008 energy use using FAO data is lower (15 TW) than total energy use using IEA data (16.2 TW).

Table 1 Energy use 2008

	Oil	*Natural gas*	*Coal*	*Nuclear*	*Hydroelectric*	*Renewable technologies*	*Wood and other biomass*	*Total*	*Fraction of total*
					(TW)				*(%)*
Africa	0.2	0.1	0.1	<0.1	<0.1	<0.01	0.5	1.0	6
Asia	2.0	1.1	2.7	0.2	0.1	0.01	0.6	6.8	42
Australia and New Zealand	0.1	<0.1	0.1	0	<0.1	<0.01	<0.1	0.2	1
Europe	1.0	0.7	0.5	0.4	0.1	0.02	0.1	2.8	17
Latin America	0.5	0.2	<0.1	<0.1	0.1	<0.01	0.2	1.1	7
Russia	0.2	0.5	0.1	0.1	<0.1	<0.01	<0.1	0.9	6
USA and Canada	1.3	0.9	0.8	0.3	0.1	0.01	<0.1	3.5	21
World	5.3	3.6	4.4	0.9	0.4	0.04	1.6	16.2	100
Fraction of total (%)	32	22	27	6	2	<1	10	100	

Source: Data from BP, 2010; IEA, 2010, Food and Agriculture Organization FAOSTAT http://faostat.fao.org; International Energy Agency Statistics http://www.iea.org/stats

Table 2 Renewable energy generation capacity 2009

Source	*GW*
Wood and other biomass	1600
Hydroelectric, large (>10 MW)	310
Biomass-to-energy (heat)	270
Solar thermal heat	180
Wind electric	160
Hydroelectric, small (<10 MW)	60
Geothermal heating and cooling	60
Biomass-to-energy (electricity)	54
Solar photovoltaics	21
Geothermal electricity	11

Source: Data from International Energy Agency (IEA) (2010) *Key World Energy Statistics* 2010. Paris: IEA and Renewable Energy Policy Network for the 21st Century (REN21) (2010) *Renewables 2010 Global Status Report*. Paris: REN21.

of food requires approximately 2 J of firewood or 8 J of wood converted to charcoal. Consequently, rural people use 1–2 kg wood person^{-1} day^{-1}, a rate of energy use of 250–500 W person^{-1} (FAO, 2009). Only 20–40 W person^{-1} enters the cooked food and warmed people because open fires diffuse the rest as waste heat (Gonzalez, 2001).

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 a higher energy density than firewood, making charcoal easier to store and transport. Urban people use 100–150 kg charcoal person^{-1} year^{-1}, requiring 800–1200 kg wood person^{-1} year^{-1}. The ultimate energy end-use is 30–45 W person^{-1}.

Implications of the Laws of Thermodynamics

The First Law of Thermodynamics states that energy is not created or destroyed, only converted between different forms. This is the principle of conservation of energy (**Table 3**). The First Law means that any energy that a process does not convert into useful forms will go into useless forms. Humans dump this waste energy into the environment.

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 (**Table 3**). The Second Law means that no energy transformation can convert 100% of one energy form completely into a useful form. The process will always waste energy 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 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 an engine and automobile can be, combustion processes 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 light and sound of the boiler fire, vibration of turbine parts, heat of power plant components, and, most of all, waste heat carried by the power plant cooling water.

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

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

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 efficiencies of 30–35%, releasing two-thirds of the total as waste heat.

Biodiversity Impacts of Industrial energy

Oil

The major impacts of oil on biodiversity come from a fuel cycle and end-uses that range over vast areas. Exploration, drilling, crude oil transport, refining, and combustion in vehicles alter terrestrial and marine habitat and pollute air, land, and water.

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 (e.g., octane and methane) and aromatic hydrocarbons (e.g., benzene and toluene).

Oil deposits originated in aquatic vegetation 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 primary agent of transformation. Eventually, these forces drove off most of the water, oxygen, and nitrogen in the condensate, leaving oil compounds enriched in carbon and hydrogen. Dispersed between sediment granules, the oil eventually migrated to low-pressure geologic traps at depths of 1–7 km. On average, the stoichiometric composition of crude oil is $CH_{1.5}$, with a small amount of sulfur.

Petroleum exploration involves geologic surveys over extensive areas, often with low human population densities and relatively undisturbed natural communities. Exploration brings vehicle traffic and construction activity, generating local disturbances, yet the most serious impacts occur with seismic detection. This involves controlled detonations along lines or at points so that seismometers can extrapolate the layout of subsurface formations. These activities destroy vegetation, disturb ground-nesting birds and other wildlife, and fragment habitat. If these activities disturb animal behavior during breeding periods, the impact can last over many growth cycles.

Highest energy use	W person^{-1}
Qatar	26 000
Iceland	21 900
Trinidad and Tobago	19 300
United Arab Emirates	17 300
Bahrain	16 000
Netherlands Antilles	14 800
Kuwait	12 800
Brunei Darussalam	12 100
Luxembourg	11 200
Canada	10 600

Lowest energy use	W person^{-1}
Comoros	76
Malawi	72
Uganda	47
Burkina Faso	46
Central African Republic	45
Niger	41
Rwanda	34
Mali	32
Burundi	27
Chad	12

Lowest efficiency	W \$$^{-1}$
Iraq	1.45
Trinidad and Tobago	1.22
Uzbekistan	1.09
Netherlands Antilles	0.96
Qatar	0.94
Nigeria	0.88
Tanzania	0.84
Zambia	0.77
Bahrain	0.72
Kazakhstan	0.72

Highest efficiency	W \$$^{-1}$
Central African Republic	0.04
Burundi	0.04
Lesotho	0.04
Niger	0.04
Uganda	0.03
Burkina Faso	0.03
Guinea	0.02
Rwanda	0.02
Mali	0.02
Chad	0.01

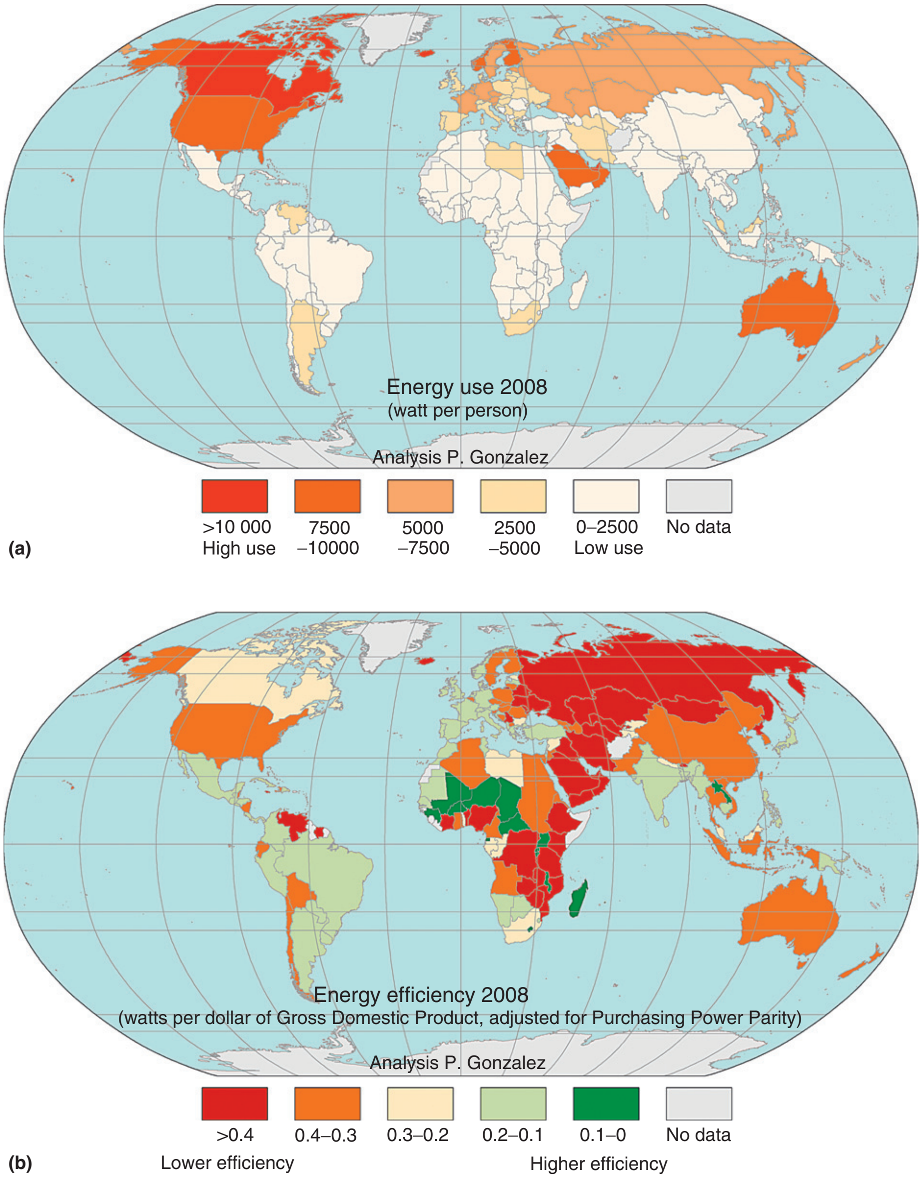

Figure 2 Energy efficiency by country (data from IEA, 2010; U.S. Department of Energy International Energy Statistics <http://www.eia.doe.gov>). (a) Energy use per person in 2008 and countries with the highest and lowest energy use per person. (b) Energy intensity in 2008 (watts per dollar (year 2000) of purchasing power parity (PPP)-adjusted gross domestic product (GDP)) and the most and least energy efficient countries.

Table 3 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

Based on original formulations by John P. Holdren.

Since the drilling of the world's first commercial oil well in Titusville, Pennsylvania in 1859, oil fields have grown to cover vast areas, especially in the Middle East, North America, Russia, Mexico, Venezuela, and Nigeria. Construction of oil well pads, buildings, roads, electricity and water lines, and other infrastructure destroys vegetation and natural habitat. Roads and other linear infrastructure fragment a landscape that extends 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 cover 2600 km^2 of Arctic tundra. Proposed oil exploitation in the

Arctic National Wildlife Refuge in Alaska would further fragment the Arctic ecosystem.

Hundreds of thousands of kilometers of pipelines carry oil and refined products around the world, fragmenting and polluting natural areas. For example, the 1000 km pipeline for the Chad–Cameroon petroleum project sliced through intact tropical forests and attracted new migrants who cleared land for agriculture. The 700-km Camisea natural gas pipeline in Peru cut across Amazon rainforest, fragmented habitat, spilled gas liquids, and eroded soil into rivers.

To mitigate environmental impacts of the 1300-km Trans-Alaska pipeline and adjacent access road (operations started in 1977), oil companies integrated a set of environmental protection features. To prevent thawing of permafrost, 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. Elevated sections provide passages for caribou (*Rangifer tarandus*). Bridges carry the pipeline over 800 streams. Zigzags along the pipeline translate the longitudinal movement of pipes expanding under heat to lateral movement, reducing the risk of leakage.

Routine drilling operations produce air and water pollution. Serious water pollution comes from drilling muds, a mixture of water and low-molecular-weight oil that drillers pump down to the drill bit to carry away rock cuttings, keep the bit from overheating, and protect the drill shaft from surrounding rock. Used muds contain bits of metal and trace metals mobilized from drilled rock.

All stages of oil production, from drilling to end-use, spill oil into surface and ground waters. Oil spills into oceans and freshwater bodies average 1.3 million tons year^{-1} (NRC, 2003). Approximately 15% of spilled oil comes directly from oil wells, pipelines, and supertankers, 40% comes from nonpoint urban runoff, and the remaining comes 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 long 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 accidental oil spills in history have occurred from offshore oil wells and supertankers (**Table 4**).

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, 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 below 20 m. Recovery teams can deploy an array of countermeasures that includes 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 and aromatic compounds (e.g., 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.

Oil kills birds by coating, matting, and waterlogging their feathers. The water repellency, buoyancy, and insulating properties of plumage derive from an orderly arrangement of feather barbules and barbicelles. Contact with oil disrupts these arrangements. Soaked birds can die of hypothermia and drowning. Survivors remain at risk for 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 bond to lipophilic sites, an affinity that concentrates these compounds in body tissues as they move up the food chain. Even when not deadly, sublethal disruption of physiology or behavior reduces resistance to infection and induces stress.

Oil obliterates the insulating properties of marine mammal pelage, leaving animals to die of hypothermia. In addition, oil can clog the nostrils of seals, causing them to suffocate. Whales, insulated by layers of oily blubber, not hair, resist the effects of oil. Marine mammals may experience chronic problems after a spill because oil can accumulate in bile and fatty tissues.

Important fisheries often lie over high-yield offshore oil fields on the continental shelves. Oil spills kill fish directly and chronic effects reduce fitness years after initial exposure. Oil at the air–water interface acts as a physical barrier that impedes gas exchange. Under a thick slick, fish larvae can suffocate.

Table 4 Most voluminous oil spills since 1960

Rank	*Incident*	*Volume (million liters)*	*Date*
1	Persian Gulf War	900	26 January 1991
2	Deepwater Horizon unit, Macondo well, Gulf of Mexico	700	20 April 2010
3	Ixtoc I well, Gulf of Mexico	530	3 June 1979
4	Fergana Valley well, Uzbekistan	330	2 March 1992
5	*Atlantic Empress* tanker, off Trinidad and Tobago	320	19 July 1979
6	Nowruz platform no. 3, Persian Gulf	300	4 February 1983
7	*Castillo de Bellver* tanker, off coast of South Africa	300	6 August 1983
8	*ABT Summer* tanker, off coast of Angola	290	28 May 1991
9	*Amoco Cadiz* tanker, off coast of France	260	16 March 1978
10	*Odyssey* tanker, off coast of Canada	160	10 November 1988

Source: Etkin, DS (1999) Historical overview of oil spills from all sources (1960–1998). *International Oil Spill Conference*, paper no. 169; Crone TJ and Tolstoy M (2010) Magnitude of the 2010 Gulf of Mexico oil leak. Science 330: 634, and International Tanker Owners Pollution Federation (ITOPF) (2010) *Oil Tanker Spill Statistics: 2009*. London: ITOPF.

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 high 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. Blue-green algae often bloom at oil spills, producing anoxic conditions.

The largest accidental oil spill in the world began with the 20 April 2010 blowout of the Deepwater Horizon mobile offshore drilling unit and the Macondo oil well in the Gulf of Mexico, off the coast of Louisiana, USA. A drilling pipe extended from the Deepwater Horizon on the ocean surface 1500 m to the Macondo wellhead on the ocean floor and 5600 m more to the oil reservoir. After the failure of a blowout preventer device at the wellhead, oil and natural gas shot up to the Deepwater Horizon and ignited in a massive explosion that killed 11 people and sunk the unit 2 days later. For 84 days, the well spilled 4.4 ± 0.9 million barrels of oil (700 ± 140 million liters) into the Gulf of Mexico (Crone and Tolstoy, 2010). Direct observations and modeling estimated the fate of the oil as: recovered 16–17%; burned 5–6%; skimmed 2–4%; chemically dispersed 10–29%; naturally dispersed 12–13%; evaporated or dissolved 20–25%; and washed up on coast, sunk due to sedimentation, exported from area in ocean currents 11–30% (Federal Interagency Solutions Group, 2010).

To reduce the amount of oil that could reach beaches, crews released 7 million liters of chemical dispersants, a record amount, at the wellhead and on the surface of the Gulf. As a consequence, much of the oil remained in the water column, increasing contact to and ingestion of oil by marine animals. U.S. Fish and Wildlife Service counts indicated that laughing gulls (*Larus atricilla*), northern gannets (*Morus bassanus*), brown pelicans (*Pelecanus occidentalis*), and royal terns (*Sterna maxima*) had the highest numbers of oiled birds, of over 100 species recorded. Also, leatherback sea turtles (*Dermochelys coriacea*), an endangered species, were oiled and biologists relocated nests of Kemp's ridley sea turtle (*Lepidochelys kempii*), another endangered species, to reduce the chance of exposure to spilled oil. The Gulf provides important marine habitat for sperm whales (*Physeter catodon*), an endangered species, bottlenose dolphins (*Tursiops truncatus*), and other marine mammals. Oil also coated areas of coastal wetlands, damaging marsh plants. Continued contact with oil could cause chronic harm to coastal plant and animal species for years. On the Mexican side of the Gulf of Mexico, oil spilled from the Ixtoc I remains under rocks in some areas decades after the spill. In France, local marine species and oyster farms needed a decade to recover from the Amoco Cadiz oil spill.

The largest oil spill in continental U.S. waters occurred on 24 March 1989, when the supertanker *Exxon Valdez* ran aground in Prince William Sound, Alaska, and poured out 42 million liters 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 wildlife species emerged to rejuvenate marine animal populations. Pacific herring (*Clupea pallasi*) were spawning inshore. Millions of pink salmon (*Oncorhynchus gorbuscha*) fry were soon to be washed from gravel spawning beds into the spring plankton bloom offshore. Harbor seal (*Phoca vitulina*) and sea otter (*Enhydra lutris*) pups were testing the frigid waters. Seabirds were beginning to converge on breeding colonies in the gulf. The *Exxon Valdez* spill killed more than a quarter of a million birds of over 90 species, including marbled murrelets (*Brachyramphus marmoratus*), bald eagles (*Haliaeetus leucocephalus*), puffins (*Frattercula* spp.), and loons (*Gavla* spp.). Exposure to toxics from the *Exxon Valdez* spill caused chronic problems in fish, with elevated egg, larvae, and adult mortality, larval deformities, and poor adult growth rates.

The high energy density and flexibility of liquid fuels refined from oil render them convenient for powering motor vehicles. Onshore refining of oil into other products generates liquid and solid waste that pollutes natural water bodies. Refining employs catalytic cracking of carbon–carbon bonds of long-chain alkanes to produce lower molecular-weight hydrocarbons. Refineries attempt to recover every possibly useful organic compound, from light products, such as methane, benzene, and kerosene, to medium weight products, like gasoline and diesel fuel, to heavy tars and asphalt. Unless treated, wastewater from these processes and from sulfur recovery will pollute surface waters.

Most constituents of petroleum and refined oil products volatilize easily, so each step of the petroleum fuel cycle generates air pollution. Methane, benzene, toluene, and other compounds evaporate from crude oil exposed to air. The major emissions from oil refineries are 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, transportation, and refining. Nevertheless, the entire life cycle, from manufacturing to disposal, of oil infrastructure generates air and water pollution and alters natural habitats. Combustion of refined oil products for automobiles, heating, and other end-uses generates the most serious emission of the fuel cycle, carbon dioxide, the principal greenhouse gas. Moreover, armed conflicts caused, in part, by efforts to control access to oil fields and refineries, directly harm human wellbeing and ecosystem health.

Natural Gas

Natural gas is a mixture of hydrocarbons that exists in 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.

Land use changes caused by exploration and extraction of natural gas produce the same biodiversity impacts described for oil. In particular, exploration grids, roads, and other linear infrastructure fragment landscapes that extend far outside core areas of operation. Accelerated natural gas leasing in the intermountain region of the western U.S. since 2001 has created networks so dense that no undisturbed ecosystems remain in some areas, threatening grassland habitats and species such as the greater sage-grouse (*Centrocercus urophasianus*) and the pronghorn (*Antilocapra americana*).

In the nineteenth century, companies had not yet erected natural gas pipelines or processing facilities. Moreover, industry had not yet developed extensive technology that used natural gas. Because companies found natural gas uneconomical to exploit, they burned it off to reduce the risk of fire and explosion. Consequently, the entire history of natural gas production has flared the equivalent of 8 years worth of U.S. energy use (Boden *et al.*, 2010). In 2008, natural gas flaring globally wasted an amount of energy equivalent to a quarter of U.S. natural gas use, or all of the natural gas use of Latin America, or twice the natural gas use of Africa (Elvidge *et al.*, 2009). Currently, Russia and Nigeria flare the most natural gas.

Gas companies generally pump natural gas straight from the well to a processing plant, avoiding the need for storage facilities at the wellhead and reducing the potential for leakage. Gas companies 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.

Hundreds of thousands of kilometers of natural gas pipelines destroy and fragment natural ecosystems and create avenues for people to settle and clear forests. Construction of specialized natural gas terminals can destroy or alter coastal ecosystems.

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.

Extraction and combustion of natural gas pollute much less than 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. Yet, methane 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.

Coal

Coal consists of hard carbonaceous material formed by 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 million years ago and the Permian period 250 million years ago. Similar to the process of petroleum formation, 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 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 abundant type worldwide. Peat, the partially oxidized, moist, organic soil that forms in marshes and bogs, is an early precursor of coal. In certain regions, people burn peat for heating, cooking, and lighting.

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 sprawl over vast land areas, including areas for excavation, dumps for extracted rock, and the support infrastructure of buildings, roads, and rail.

Deep and open pit mines remove huge amounts of rock, termed overburden, lying over the coal. Land over deep mines will sink, a process termed subsidence, physically changing a landscape. Underground coal fires in abandoned mines and refuse banks not only exacerbate subsidence, but they also release CO_2 and other air pollutants.

Miners dump large 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 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 the overburden back into the mined area and replant it, strip-mined land can never completely recover its original characteristics. In addition, disturbance 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 impound surface streams to satisfy the large 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. 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 adds to the pollution of surface waters. Rail transport provides the most cost-effective means of moving the bulky commodity of coal, but fugitive emissions from unit trains increase particulate concentrations in rail corridors. To save money on rail transport, many utilities build electric power plants next to the mine and transmit the electricity by wire. In certain regions, this shifts the pollutant load from urban to rural areas.

Most coal goes to generate electricity. 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. The generator exploits a physical principal in which 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. Approximately 40% of anthropogenic CO_2 emissions come from burning coal, while coal burning produces approximately 80% of human SO_2 emissions. Consequently, greenhouse gases and acid precipitation may be the agents of coal's most extensive environmental impacts.

Slag remaining from burned coal contains high amounts of trace metals, especially cadmium and mercury. In addition, sludge from flue gas desulfurization units, the pollution control devices known as scrubbers, contains trace metals and toxic organics. Disposal of sludge can pollute soil and water.

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 uses 4 million m^3 water per day for all operations, mostly for cooling. Consequently, electric utilities often build plants next to natural water bodies. Power plants use freshwater because of the corrosive effects of salt water. Water withdrawals alter the hydrology of a watershed and change water levels, surface area of mudflats, surface area of wetlands, and other important habitat characteristics that can strand hydrophilic plant species such as willows (*Salix* spp.) 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 can get entrained in the condenser, causing even greater mortality. The stress that any surviving organisms undergo reduces fitness considerably.

Industrial electric power plants (coal, oil, nuclear) generate three-quarters of the waste heat dumped into U.S. surface waters and into the atmosphere above the U.S. Once-through systems dump waste heat directly into local waters. Cooling towers systems 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 cooling water before it enters surface waters.

Thermal discharges into freshwater and coastal zones cause many negative impacts on aquatic species:

1. Direct lethality to fish and crustaceans at water temperatures $\geq 35\ ^\circ C$.
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 plumes 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, 765 kV) in the U.S. stretches across 250,000 km and occupies more than 13,000 km^2 of land (U.S. Department of Energy, 2010). Clear-cutting of forest to create transmission corridors 30–60 m wide destroys vegetation. Maintenance periodically disturbs the corridors, favoring ruderal plant species and animals that adapt readily to human disturbance. Herbicides used for periodic clearing can kill pollinating insects and birds. Transmission line corridors fragment habitat and increase the area of habitat susceptible to edge effects while providing avenues for the dispersion 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, timber plantations, and milling. 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 used 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. Owing to massive economic growth, P.R. China switched from a net exporter to a net importer of coal in 2009. Australia, Canada, Columbia, Indonesia, South Africa, and the U.S. export substantial amounts of coal to P.R. China. Environmental impacts of coal mining and processing occur in the exporting countries while environmental impacts of coal burning occur in P.R. China and around the entire world due to the emission of greenhouse gases.

Nuclear Fission

Nuclear fission is the splitting of high-molecular-weight elements to release energy held by protons and neutrons in the nucleus of the atom. Uranium and plutonium are the elements that provide the most effective yield from fission. A fission reaction produces energy in the form of light, heat, motion of the fission products, 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.

Fission products 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 million years. The similarity of the atomic structure of strontium to calcium increases the uptake of strontium by animals and its 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 substantial 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 UF_6 into separate fractions, one of which is enriched in a higher concentration of uranium-235 than 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 nuclear warheads.

The original 150,000 Mt of ore for a standard 1 GW nuclear fission plant has thus 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.

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

In December 2008, 438 nuclear fission plants with a combined rated capacity of 372 GW were operating in 31 countries (IAEA, 2009). Among these, the U.S. operates 104 nuclear fission plants with a combined rated capacity of 101 GW.

Nuclear plants generate electricity in a steam cycle similar to the system in coal plants, except that nuclear fission is the source of heat for 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 section on coal are all greater with nuclear plants.

Because nuclear plants involve fossil fuel combustion only in construction and in support vehicles, they produce few direct air emissions. Nuclear plants, however, produce wastes that can remain radioactive for millions of years. 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. The U.S. has not constructed a permanent repository for high-level wastes, which nuclear plants continue to store on site.

The greatest single release of radiation from a nuclear fission power plant came from the Chernobyl Unit 4 accident on 26 April 1986 in an area of the Republic of Ukraine that was in the former Soviet Union. Operator error combined with design aspects of the RBMK graphite-moderated reactor generated a nearly instantaneous catastrophic increase of thermal power and a steam explosion. The explosion destroyed the reactor and released 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 thyroid cancer has been found in at least 4000 people due to ingestion of iodine-131 (Chernobyl Forum, 2005). The Soviet government evacuated 116,000 people from a zone of 30 km radius and constructed a cement sarcophagus to contain the remains of the reactor. Increased risks of thyroid cancer and leukemia are possible for the 5 million people who lived in the contaminated parts of Belarus, Russia, and Ukraine.

Lethal radiation killed many conifers and small mammals within 10 km of the accident in the first few weeks. Radioactivity remains in trees and soil in the form of cesium-137. Grass, mushrooms, and berries continue to incorporate the isotope, perpetuating a source of exposure for people and wildlife that feed on contaminated plants. Atmospheric fallout from Chernobyl may also cause genetic abnormalities in the long term.

Hydroelectric

Hydroelectric systems harness the potential energy held by an elevated mass. The potential energy of water will convert to 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 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 considerable alteration of topography and flow of a watercourse and the partial inundation of its watershed.

Besides the forced removal of people and inundation of homes, hydroelectric plants also cause significant ecological changes.

Over 45,000 large dams block rivers around the world, creating reservoirs that inundate up to 1 million km^2 (World Commission on Dams, 2000). In 2010, P.R. China completed filling the reservoir of the Three Gorges Dam, the hydroelectric plant with the highest generation capacity in the world (18.2 GW). The project has inundated 630 km^2 along 600 km of the world's third longest river, the Yangtze, and displaced 1.2 million people. In 1965, the Akosombo Dam on the Volta River in Ghana created Lake Volta, at 8500 km^2 the largest impoundment in the world.

Inundation of formerly dry land destroys vegetation and decreases the area of terrestrial habitat. Inundated forests represent ecosystem services forfeited and biomass wasted. A dam blocks nutrient-rich sediment that a river system would have deposited in floodplains, wetlands, and the outlet delta. Sediment fills the reservoir, impairs electricity generation, and traps rich organic carbon and other nutrients at the bottom of the reservoir. At the outlet delta, dams alter bay and estuary topography, reduce the area of mudflats and wetlands, and decrease the upwelling of nutrient-rich water. The Aswan High Dam in Egypt blocks 98% of the 120 million tons of sediment that the Nile River had carried 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 freshwater by the Akosombo Dam in Ghana has caused the decline of clams in the Volta estuary and barracuda (*Sphyraena barracuda*) in the Gulf of Guinea. 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 use and operational objectives. One operational objective, smoothing out extremes caused by natural flood regimes, changes the meandering and other channeling processes of a river. After the Glen Canyon Dam ended spring floods in the near downstream section of the Colorado River, sandbar erosion increased because the river did 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 southwestern willow flycatcher (*Empidonax traillii*) and other birds. To mitigate the problem, the U.S. Department of the Interior began to stage controlled floods.

For some dammed rivers, the flow of water unburdened by silt can deepen the riverbed. 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 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 contributed to the extinction of Colorado squawfish (*Ptychocheitus lucius*), roundtail chub (*Gila robusta*), and bonytail chub (*Gila elegans*) and the endangerment of five other fish species. Whereas release water is clear, reservoir water often becomes slightly turbid and eutrophic.

Impacts of dams on anadromous fish relate to the migratory behavior and timing of the life cycles of these unique species. Dams erect a hazard for the downstream migration of young fish and block the upstream migration of adults. Moreover, salinity and temperature adaptations in anadromous fish occur on a precise schedule, making long delays lethal. Also, disoriented and fatigued fish more easily fall prey to predation. Despite the deployment of extraordinary means to facilitate fish migration, including fish ladders, elevators, and trap-and-haul trucking, dams have eliminated anadromous fish from many rivers. Runs of Atlantic salmon (*Salmo salar*) and American shad (*Alosa sapidissima*) have disappeared from many rivers in the northeastern U.S. In the Columbia River Basin in the northwestern U.S., overfishing, pesticide runoff, and hydroelectric plants have endangered populations of Snake River sockeye salmon (*Oncorhynchus nerka*) and Snake River chinook salmon (*Oncorhynchus tshawytscha*).

Exotic fish species introduced into reservoirs for sport fishing often outcompete native species. In the 1350 km^2 reservoir on the Brazil–Paraguay border behind the Itaipu Dam, the hydroelectric plant with the second highest generation capacity in the world (12.6 GW), a nonnative species, curvina (*Plagioscyon squamosissimus*), has become the second most numerous fish species.

Polychlorinated biphenyls (PCBs) from electric transformers and oil leaking from machinery comprise the worst direct industrial pollution from dams. These substances and toxic organic chemicals accumulate in sediments and magnify up the food chain. Impingement of aquatic organisms on intake screens and entrainment through turbines kills many individuals and causes stress and injury in survivors.

Materials and energy used to construct the massive infrastructure of the hydroelectric energy cycle produce wide-ranging environmental impacts. In addition, 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 large amounts of electricity, aluminum smelting comprises an end-use closely tied to the hydroelectric option. Air emissions from smelters include CO, CO_2, particulates, NO_x, and trace metals. Major water pollutants include trace metals and sulfates.

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, geothermal, biomass-to-energy (electricity and heat), and biofuels. These are renewable energy systems that depend on complex technology, so they are forms of industrial energy. The section on traditional energy covers the simpler forms of renewable energy – firewood, charcoal, and small water and windmills.

Forms of renewable energy generally require specific site characteristics, exhibit high temporal variability in availability, and capture diffuse flows. Except for biomass-to-energy (electricity and heat), renewable energy technologies do not involve combustion, so they do not directly produce much air pollution. The principal environmental impacts come from fabrication, installation, and maintenance of renewable energy devices.

Solar energy systems fall into two categories: passive and active. Passive systems 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. Active systems use moving devices to achieve heat transfer. Solar heating systems include passive solar building designs and simple active systems that use pipes or other collectors to heat water for residential or commercial use. Solar heating systems are nearly environmentally benign.

Complex active solar systems include solar thermal electric and photovoltaic systems. Solar thermal electric systems, also known as concentrating solar power systems, use arrays of reflective parabolic or trough collectors to focus sunlight on a water boiler to power a turbine to generate electricity. Photovoltaics are solid-state devices in which photons stimulate the emission of electrons and semiconductor materials channel the electrons for collection. They are flat rectangular chips placed into long flat arrays. Photovoltaics directly convert sunlight to electricity with no moving parts, except for motors that move the arrays to track the sun. These systems use water to wash photovoltaic surfaces.

The two types of complex active solar systems require vast areas of land for the solar collectors or the photovoltaic arrays. In 2010, the U.S. Government permitted 3.6 GW of solar thermal electric and photovoltaic plants in California and Nevada and advanced plans for large solar plants throughout the southwestern U.S. Many of these projects will occupy and possibly damage natural ecosystems and habitat for threatened species such as desert tortoise (*Gopherus agassizii*). Because solar is most economically feasible in sunny areas, solar sites are generally arid and water is scare. Water withdrawals for turbines and for washing collectors and arrays contribute to water flow reductions that can harm aquatic ecosystems.

Concentrating solar power systems are industrial scale plants that alter extensive areas of natural land far from energy users. In contrast, decentralized photovoltaic arrays above parking lots in urban areas have emerged in California as a more environmentally sound and economically feasible energy solution. Numerous colleges and schools, mainly in the San Francisco Bay Area, have erected solar arrays above parking lots. These projects use land that has already been urbanized and is close to the energy users, reducing transmission infrastructure and electricity losses. In some cases, solar arrays can provide for all school electricity uses. These systems demonstrate the solar potential of urban areas, especially parking lots and building roofs.

Fabrication of photovoltaic cells produces toxic environmental impacts. Mining the quartz base material of a photovoltaic cell produces many of the same impacts on aquatic and terrestrial biodiversity described for coal mining. Production of metallurgical grade silicon requires the refining of the quartz to 99% purity at 3000 °C in an electric arc furnace. Production of semiconductor-grade silicon takes place in a fluidized bed reaction of the silicon with hydrochloric acid. The process produces semiconductor-grade polycrystalline silicon by electrical heating of the semiconductor-grade silicon at 1000 °C and vapor deposition onto 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. 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: cadmium telluride, copper indium diselenide, gallium arsenide, and gallium indium phosphide. Trace metals in these compounds, chlorinated organic solvents, and phosgene gas all 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, wood from dedicated plantations, agricultural waste, or municipal waste to electricity either through direct combustion of biomass in low-pressure boilers to power electric steam turbines or through 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. The section on coal details the negative effects of electric turbines and condensers that are also components of biomass-to-energy systems.

Utilities in Brazil generate electricity and cogenerate heat from the organic wastes (bagasse) from sugar cane and orange juice processing. 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. Most biomass-to-energy plants use material that otherwise would be wasted and discarded in landfills. The biomass 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 schemes include short rotation trees such as poplars and aspen (*Populus* spp.), grown at densities of 1600–5000 trees ha^{-1}, and switchgrass (*Panicum virgatum*). An energy crop can damage natural ecosystems if it is grown in monoculture or if vegetation is clear-cut to prepare for the crop. If previous land uses were less environmentally sound than the energy crop, then the crop could mitigate the impacts of the previous land use.

Conversion of biomass into alcohol fuels, known as biofuels, also requires the dedicated growing of energy crops, primarily corn, palm trees (for palm oil), soybeans, and sugar cane. Fermentation of cellulose and other complex carbohydrates produces ethanol, which certain engines 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. The U.S. produces ethanol mainly from corn. Brazil produces enough ethanol from sugar cane to provide for 10% of the country's energy use.

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 product. Moreover, combustion of fossil fuels and energy use for inorganic fertilizer production generate 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.

Conversion of the principal areas of rainforest, peatlands, and grasslands to produce biofuels in Brazil, Southeast Asia, and the U.S. could potentially release 20–400 times more CO_2 than the displaced fossil fuels in the next half-century (Fargione *et al.*, 2008). In contrast, biofuel from waste biomass or biomass grown on abandoned agricultural lands planted with perennials can produce less CO_2 than displaced fossil fuels.

Since the 1980s, electric utilities have used wind turbines to power electric generators. Early electric wind turbines were typically 10 m tall with rotors diameters of 5–10 m and electricity generation ratings of 100–300 kW per turbine. Wind turbines are now typically 50–100 m tall with rotor diameters of 30–100 m and electricity generation ratings up to 2.5 MW per turbine. Offshore wind turbines are generally larger, to take advantage of steady winds and economies of scale.

Wind farms of hundreds of turbines occupy considerable land and offshore areas. The first large-scale wind farms operated in the Altamont Pass in the San Francisco Bay Area, California, the Tehachapi Pass in Southern California, in the Netherlands, and Denmark. They have now become widespread throughout the world.

Wind farms fragment terrestrial habitats and access road networks cause soil erosion. Wind turbines kill substantial numbers of birds and bats. Rotors produce substantial noise. Offshore wind turbines can act as artificial reefs, potentially changing local marine food webs. Electromagnetic fields from turbines and underwater cables can disrupt marine mammal navigation abilities.

Wind turbines could potentially produce all of the world's electricity. Wind turbines operating at only 20% of their rated capacity (due to diurnal and seasonal wind cycles, some turbines only turn 20% of the time) on available nonforest, ice-free, and nonurban areas could potentially generate electricity at a rate of 100 TW for the world and 8 TW for the contiguous U.S. (Lu *et al.*, 2009).

Geothermal devices capture heat or cold stored underground and directly use the heat or cold for different purposes on the surface or process the heat through turbines to produce electricity. The U.S., P.R. China, and Sweden led the world in installed capacity of geothermal direct use systems in 2010 while the U.S., Philippines, and Indonesia led in installed capacity of geothermal electric systems (REN21, 2010).

Geothermal direct heat systems pipe water from underground hot geologic formations to the surface to heat greenhouses, buildings, and fish farm ponds or to heat streets and sidewalks from below to melt snow and ice on the surface. Geothermal heating and cooling systems pump water or another working fluid through a closed loop of pipes and a heat exchanger in contact with shallow underground areas or water bodies that maintain a relatively constant range of temperatures. In temperate zone residential geothermal systems, underground soil and rock are cooler than the surface in summer and warmer than the surface in summer. The heat exchanger cools the house in summer and transfers heat from the ground to the house in winter.

In the largest geothermal cold storage system in the world, the 2 GW capacity Alderney 5 project in Halifax, Nova Scotia, pipes take cold harbor water for 7 months and stores it in a field of 200 m deep boreholes that cool bedrock under a ferry terminal parking lot. A heat exchanger uses the stored water to cool a commercial and industrial complex in summer.

Geothermal electric systems capture the heat of hot geologic formations from a system of pipes sunk down into hot strata. These systems capture deep hot water or inject water so that it boils on contact with hot rocks and process the heat through turbines to produce electricity. These systems mobilize trace metals contained in certain geologic formations and release H_2S gas from geothermal deposits.

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 shrubs and cutting branches from mature trees. Rural people in Africa, Asia, and Latin America generally avoid felling whole trees for domestic firewood because of the time and labor required to cut the tree and split the logs.

In semiarid areas of Africa, women prefer the straight, moderately sized branches that coppiced shrubs produce. Rural people go out in the dry season and coppice (cut at the base) small shrubs (family *Combretaceae*). Women carry branches back to the village and let them 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 complete a time-consuming and strenuous chore before the exhausting and rushed rainy season.

Coppiced shrubs resprout in the rainy season and regrow branches in a year. When shrubs become scarce, women pull branches from adult trees, sometimes using long-handled hooks. This harms the growth potential of a tree by removing shoot apical meristem tissues and can yield thorny branches that are difficult to handle. When branches are depleted, women in semiarid areas of Africa fall back on noxious, dead stalks of spurge (family *Euphorbiaciae*). The last resort is animal dung.

While women carry firewood for rural use, rural people also load beasts of burden and carts to transport wood for sale in urban areas. In this way, a town or city can generate impacts far beyond its borders.

Wood contains energy at a density of approximately 15 GJ t^{-1}, 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 up to two-thirds of the energy contained in the original wood as waste heat. Charcoal makers cut down live and dead trees, targeting sturdy tree trunks. 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, then wood harvesting will reduce vegetative cover. Reduction of vegetative cover and conversion of forested or wooded land to savanna or grassland comprise the principal potential impacts of traditional energy on natural ecosystems. People's preferences for certain species for firewood can also create a risk of overharvesting preferred species.

In some areas of Africa, Asia, and Latin America, international development agencies have funded the massive plantation of nonnative tree species for firewood production. Plantations that replace native forest or woodland eliminate natural ecosystems. In general, the biological and structural diversity of natural forests makes an area more resilient to fire, wind, and insect disturbances.

Natural regeneration of local species can restore native forest cover in ecosystems changed by overharvesting. 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. Natural regeneration requires no external inputs. It concerns species 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. Natural regeneration not only augments the supply of wood, poles, fruit, medicine, and other forest products, it puts trees where farmers and herders need them – in fields to maintain soil fertility and in pastures to provide forage.

Photosynthetic activity converts only 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 5** shows this energy chain from sunshine to wood end-use in the West African Sahel.

Table 5 Energy chain from sunshine to wood end-use in the West African Sahel

Stage	*W ha^{-1}*
Insolation at ground	2,400,000
Net primary productivity	1700
Total wood production	120
Human wood energy use	210
Imported fossil fuels	93
Food consumption	53
Human wood energy end-use	13

Source: Gonzalez P (2001) Desertification and a shift of forest species in the West African Sahel. *Climate Research* 17: 217–228.

Improved cook stoves with higher fuel efficiencies can help 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 helped to develop 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.

For centuries, society has channeled water to mill grain and captured wind to move sailing ships and pump water. Small water and windmills comprise a form of traditional energy that generally requires only local materials and expertise for building and maintenance. The simplest water mills are run-of-the-river systems in which a water wheel is placed in the current of a perennial stream or river. A water wheel typically turns a circular stone for the grinding of grain. More advanced systems use water channels, pipes, Pelton wheels, or other devices to increase rotation speeds enough to turn a turbine to produce electricity. Small hydropower is most common in mountainous countries like Perú. The simplest windmills have a fan with wood or metal blades erected on a tower 5–15 m tall. The fan axis rotates on a horizontal axis, lifting a vertical rod connected to a plunger in a pipe well dug down to the water table. The movement of the plunger lifts water to the surface. This type of windmill is most common in flat grassland regions. Windmills in the Netherlands pumped water from extensive inundated areas that the Dutch enclosed with dikes, dried, and used for agriculture.

Future Energy Paths

Human energy use directly alters biodiversity through changes in land use and through industrial pollution. Indirectly, human energy use is altering 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: individual species, local sites, landscapes, continents, and the world.

Table 6 summarizes the major environmental impacts of human energy use on biodiversity. **Table 7** summarizes the extensive land requirements and CO_2 production 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 severe 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

Table 6 Major sources of biodiversity impacts from human energy use

Impact	*Oil*	*Natural gas*	*Coal*	*Nuclear fission*	*Hydroelectric*	*Renewable technologies*	*Wood*
Terrestrial habitat destruction and fragmentation	Exploration, access roads, pipelines	Exploration, access roads, pipelines	Mining, electricity transmission lines	Mining, electricity transmission lines	Inundation of vast land areas, changes to river hydrology	Land requirement for solar collectors, wind turbines, crops for biofuels	Destruction or fragmentation of habitat from unsustainable harvesting
Water pollution and damage to aquatic species	Oil spills, drilling muds, soil eroded from pipeline corridors and roads	Natural gas liquids spills, soil runoff from pipeline corridors and roads	Acid mine drainage, water removal for mining and plant cooling, entrainment, impingement, thermal pollution	Acid mine drainage, water removal for mining and plant cooling, entrainment, impingement, thermal pollution	Complete alteration of habitat, barriers to migration, entrainment, impingement, thermal changes, PCBs from transformers	Toxics from photovoltaic production, water removal for cleaning solar collectors and irrigating biofuel crops, pesticide and fertilizer from production of biofuels	Soil runoff from overharvested areas and roads
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 emissions from biofuels farm machinery	CO_2 from burning
Solid waste	Oil spills, sludge	Natural gas liquids spills, sludge	Mine tailings, sludge	Radioactive waste	PCBs from transformers	Toxics from photovoltaic production	
Major end-uses	Automobiles	Cooking, heating	Electricity	Electricity	Electricity, smelters	Electricity	Cooking, heating

capital formation stage and do not produce much pollution from operations.

Environmental impact is equivalent to the multiplicative effect of population, affluence, and technology (Holdren and Ehlich, 1974):

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

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 (impact = population × affluence × technology) equation for energy becomes:

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

Economic production per person, often expressed as dollar of 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 GDP, indicates a society's level of technological efficiency.

Table 7 Land requirements and carbon dioxide emissions for electric generation

	Land required ($ha\ MW^{-1}$)	*CO_2 emissions ($t\ GW^{-1}\ h^{-1}$)*
Coal	0.8–8.0	900
Oil	0.3–0.8	850
Natural gas turbine	0.3–0.8	560
Solar photovoltaics	3–7	50
Wood and other biomass	150–300	40
Solar thermal electric	1–4	40
Nuclear	0.8–1.0	30
Hydroelectric	2–1000	20
Geothermal	0.1–0.3	14
Wind electric	0.4–1.7	11

Source: Data from US OTA, 1995; Cho A (2010) Energy's tricky tradeoffs. Science 239: 786–787.

This relationship highlights the leverage of energy conservation and efficiency in reducing the environmental impact of energy use. Improvements in energy efficiency reduced the energy intensity of economic activity in the U.S. by nearly one-third between 1975 and 1995 (U.S. Department of Energy, 2010). Energy conservation and currently available efficiency improvements could substantially reduce industrial energy use and greenhouse gas emissions. Energy efficient vehicles and appliances, installation of insulation and other residential weatherization features, and simple changes in driving behavior such as slower acceleration and reduced highway speeds could reduce U.S. greenhouse gas emissions 7% (Dietz *et al.*, 2009). In addition to those conservation and efficiency actions, walking or using public transit instead of cars, substitution of renewable energy sources for nonrenewable sources, and other currently available improvements could meet global energy uses and stabilize greenhouse gas emissions by the mid-twenty-first century (Pacala and Socolow, 2004).

If the world does not adopt such improvements, the historical path of industrialization has only left costly and environmentally disruptive energy sources. 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. Deposits are now more remote, deeper underground and underwater, and dispersed. Furthermore, low-cost energy has shaped the expectations of people around the world for inexpensive on-demand energy services. Societies 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.

Depletion of nonrenewable resources (**Table 8**) and other environmental and social constraints hobble most future energy options: oil and gas reserves will only last decades; coal burning releases the principal cause of global warming, CO_2;

Table 8 Remaining world energy reserves 2000

Nonrenewable energy stocks	*Reserve (TW year)*	*Time remaining at 2008 rates (years)*	*Carbon emissions (Gt)*
Uranium	80	80	20
Oil	220	40	1600
Natural gas	230	60	1100
Coal	1100	250	8600

Renewable power flows	*Potential (TW)*	*Time remaining*	*Carbon emissions ($Gt\ year^{-1}$)*
Hydroelectric	1.6	Lifetime of sun	0.3
Geothermal	4	Lifetime of sun	0.5
Wood and other biomass	9	Lifetime of sun	3
Wind electric	20	Lifetime of sun	2
Solar electric	50–1600	Lifetime of sun	20–600

Source: Data from Cho A (2010) Energy's tricky tradeoffs. Science 239: 786–787; UNDP, 2000.

biomass energy requires vast amounts of land; a small number of exploitable sites limits the potential for hydroelectric and wind power; and health and safety problems prevent expansion of nuclear energy.

Although engineers have placed enormous effort into the development of technologies such as hydrogen cars, fuel cells, and nuclear fusion, exotic devices will not resolve our energy problems if they depend on nonrenewable fuels. Instead, energy efficiency, conservation, and renewable energy offer a sustainable future energy path for the world. For this path, the goal is not the acquisition of energy stocks and devices, but the provision of services and end-uses. In effect, we don't require light bulbs, we need illumination.

See also: Air Pollution. Economic Growth and the Environment. Greenhouse Effect. Pollution, Overview

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