8

NUCLEAR AND HYDROPOWER

Oftentimes nuclear and hydro are linked together in energy statistics. Of course, they are quite different: nuclear power is generally viewed as dangerous while hydro is viewed as benign. This really is not quite true for either. Despite Three Mile Island and Chernobyl, the safety record for nuclear power speaks for itself: There have been over 13,000 reactor-years of safe commercial plant operation, coupled with an equivalent span of safe operation for nuclear-powered warships. The worst accident by far was Chernobyl, a case of an unsafe reactor design unsafely operated. Hydropower has its opponents, and dam failures are not unknown phenomena. This chapter covers the principal aspects of nuclear and hydropower as energy sources.

BACKGROUND

Nuclear power is the outgrowth of the nuclear weapons program to transform the world's most destructive weapon to peaceful uses. The 1953 launching of the Atoms for Peace program foretold a world where commercial nuclear energy would be clean, abundant, safe, and too cheap to even meter! Nuclear power is clean, because it does not generate emissions that contribute to global warming, but dirty because the spent fuel must somehow be disposed. Three Mile Island buried the myth that nuclear power was inherently safe, and Chernobyl showed how dangerous it could be. And cheap it is not, with cost overruns in the billions.

Despite predictions of a phase-out of nuclear power plants and general pessimism over the prospects for nuclear power as an energy source, 42 nuclear power plants are under construction (11 in China, 8 in Russia, 6 in India, 5 in South Korea, 2 each in Canada, Slovakia, and Japan, and 1 each in Argentina, Finland, France, Iran, Pakistan, and the United States).[1] There are some who believe that we may be at the dawn of a new age in nuclear power. One cannot cavalierly dismiss the fact that nuclear power is free of greenhouse gas emissions. Table 8.1 shows the EPA's estimates on the pounds of emissions to produce one megawatt-hour of electrical power; nuclear power leaves no carbon footprint. Emissions avoided by the U.S. nuclear industry in 2007 alone have been estimated to be 1 million tons of sulfur dioxide, 3 million tons of nitrogen oxides, and 693 million tons of carbon dioxide.[2]

Electricity rates are directly and significantly affected by fluctuations in energy costs of coal and natural gas, which are influenced by the cost of crude oil, but nuclear power is relatively insensitive to fuel costs. Though fuel assemblies have to be replaced over the life of a nuclear plant, fluctuations in the cost of uranium have a relatively minor impact on the price of electricity produced by a nuclear plant.

Nuclear power in the United States is criticized for being heavily subsidized. Table 8.2 shows

Table 8.1

Average Pounds of Emissions to Produce One Megawatt-Hour of Electricity

	Coal	Oil	Natural Gas	Nuclear
Carbon Dioxide	2,249	1,672	1,135	0
Sulfur Dioxide	13	12	0.1	0
Nitrogen Oxides	6	4	1.7	0

Table 8.2

Subsidies of Electricity Production

	Net Generation (million megawatt hours)	Subsidies (million $)	Subsidies $/ Megawatt-Hour
Natural Gas & Petroleum Liquids	919	$227	$0.25
Coal	1,946	$854	$0.44
Hydroelectric	258	$174	$0.67
Biomass	40	$36	$0.89
Geothermal	15	$14	$0.92
Nuclear	794	$1,267	$1.59
Wind	31	$724	$23.37
Solar	1	$174	$24.34
Clean coal	72	$2,156	$29.81

that all sources of electricity are subsidized and that nuclear power is far less subsidized than wind, solar, and clean coal.[3]

The promise of standardized "cookie-cutter" plants, built the way Ford manufactured Model Ts, would eliminate the enormous cost overruns associated with the one-of-a-kind nuclear plants that dominated past construction in the United States. Advancements in nuclear power technology, coupled with series production of a standard plant design, built as modules in a central manufacturing facility and shipped to a plant site, would make the cost of electricity from nuclear plants quite attractive compared to fossil fuel plants. The economics further favor nuclear power plants as fossil fuel prices continue to rise or a cap and trade program for carbon emissions or a tax on carbon are enacted. What has to be accomplished before any renaissance of nuclear power becomes possible is assuring the public that the human errors and circumstances responsible for the Three Mile Island incident and the Chernobyl catastrophe cannot happen again.

Human error played a major role in both the Three Mile Island incident and the Chernobyl catastrophe. Yet, nearly all of the radioactive release of the Three Mile Island incident was kept within its containment system, as it was designed to do. Soviet nuclear power plants do not have containment systems built to withstand the pressure generated from a ruptured reactor system, but are housed in buildings without an internal structure to withstand pressure. Nor did the Soviet Union select a safe plant design. Whereas most reactors shut down when the water moderator in the core boils away (an example of a negative feedback system), the same phenomenon with the Soviet graphite-moderated reactor led to a runaway power surge (an example of a positive feedback system).

In the United States where there is a higher per capita consumption of electricity, a typical large-sized nuclear power and coal-fired plants with an output of 1,000 megawatts, or 1gigawatt can supply the needs of 600,000 people depending on the degree of industrial activity. On a global scale where per capita consumption of electricity is considerably less as in Asia, a 1 gigawatt plant can serve the needs of 2 million people. For purposes of discussion, it is assumed that a 1 gigawatt plant can supply the electricity needs of one million people.

Base-load needs are most commonly handled by large nuclear and coal-fired plants. A 1-gigawatt coal-fired power plant releases about 6 million tons of carbon dioxide each year, plus potentially a large quantity of sulfur dioxides into the environment depending on the sulfur content of the coal and the effectiveness of the plant's scrubbers (if any). There is also pollution in the form of soot unless removed by precipitators, nitrous oxides, plus health-affecting emissions of mercury, cadmium, and arsenic. A nuclear plant of the same size consumes about 25 tons of enriched uranium (3.5–5 percent of the isotope U235) per year, which requires over 200 tons of uranium oxide concentrate produced by mining 25,000–100,000 tons of ore depending on the uranium concentration. The annual waste from a nuclear power plant is less than 30 tons of spent fuel, a highly radioactive and toxic waste. If reprocessed (chopped up and dissolved in acid to recover fissionable material for recycling), spent fuel can be reduced to about 1 ton of waste. Though even more dangerous and toxic than spent fuel, such relatively small quantities should be effectively managed for transport and permanent storage, or at least so it was thought.

Uranium is as common as tin and is mined both on the surface and underground. Half of the world's uranium ore production is in Canada and Australia, followed by Kazakhstan, Niger, Russia, Namibia, Uzbekistan, and the United States. The ore is first finely ground, then leached with sulfuric acid to remove uranium in the form of uranium oxide, called "yellow cake," which is then transformed to uranium fluoride gas. Both the gaseous diffusion and high-speed centrifuge processes take advantage of the fact that U235 is slightly lighter than U238. These processes create two streams of uranium fluoride gas: one enriched with U235 and the other depleted of U235. Starting with a concentration of 0.7 percent U235, the enriched stream has a concentration of about 3.5–5 percent, depending on the type of reactor, and the depleted stream is nearly pure U238. The depleted stream is 1.7 times denser than lead and can be used for reactor shielding and armor-piercing shells. Although most is stockpiled, some has been drawn down in recent years to mix with highly enriched uranium released from the Russian and U.S. weapons programs for transformation to reactor fuel.

Enriched uranium fluoride is converted to uranium oxide, pressed into small cylindrical ceramic pellets, and inserted into thin tubes of zirconium alloy or stainless steel to form fuel rods. These are then sealed and assembled into reactor fuel assemblies and placed in the core of the nuclear reactor. The core of a 1,000-megawatt or 1-gigawatt reactor contains about 75 tons of enriched uranium. The presence of a moderator such as water or graphite slows down the neutrons sufficiently for the U235 isotope to fission (or split) in a chain reaction that produces heat to transform water to steam. From that point on, the generation of electricity is the same as in a fossil-fueled plant.

Uranium reserves for conventional reactors can last over a century. Reserves can be extended by a factor of 100 or more by reprocessing spent fuel to reuse the plutonium generated by the fission process, by breeder reactors designed to create their own fuel, and by utilizing thorium, which becomes fissionable when transformed to U233 in a nuclear reactor. Taking into consideration uranium life extension through reprocessing, breeding, and transforming thorium to fissionable material, some view nuclear energy as a virtually inexhaustible source of energy.

PHYSICS OF A NUCLEAR REACTOR

U235 fissions or splits into fission byproducts such as barium and krypton, releasing about 2.5 prompt or fast neutrons and other products. The fission byproducts also decay, releasing delayed (or slow) neutrons. Both prompt and delayed neutrons are necessary to maintain criticality (a constant rate of fission). Slowing down fast neutrons in a moderator such as graphite or water is necessary for the neutrons to be absorbed by fissionable material in a conventional reactor. The exception is fast breeder reactors that depend only on prompt or fast neutrons to maintain criticality. The total mass of fission byproducts is less than the original U235 atom, and the heat released is equivalent to the loss of mass multiplied by the square of the speed of light (Einstein's famous $E = mc^2$).

From the perspective of converting matter to energy, a nuclear bomb and a nuclear reactor are similar. But a nuclear bomb is designed to have a runaway reaction, whereas a nuclear reactor is designed to prevent a runaway reaction. A nuclear bomb concentrates over 90 percent fissionable material for a single explosive event. A nuclear reactor disperses a low concentration (3.5–5 percent) of fissionable material within a fuel assembly, along with channels for coolant to pass through and to insert neutron-absorbing control rods. It is impossible for a nuclear reactor to sustain a nuclear explosion, but it is possible for the core to meltdown from a loss of coolant and release radioactivity.

A reactor is shut down when control rods are fully inserted. To operate a reactor, control rods are pulled out until a critical mass is formed where a self-sustaining chain reaction can occur (a constant number of fissions over time). The power output of the reactor is increased by pulling the control rods out further to increase the fission rate. A reactor control system scrams (or shuts down) the reactor by rapid insertion of control rods if system performance does not fit a tight set of specifications. Heat is generated within a reactor by the transfer of kinetic energy from fission byproducts to molecules in the fuel rod and then to molecules in the coolant and by slowing down of neutrons in the moderator. With exceptions, coolant is normally water flowing through channels within the assemblies of fuel rods and control rods. Nearly all fission products are locked in the fuel rod to ensure that the water coolant has a low degree of radioactivity. The water not only transfers heat from the reactor to the steam generators to drive the electricity generators, but, with exceptions, also serves as a moderator to slow down the neutrons.[4]

NUCLEAR INCIDENTS AND ACCIDENTS

A nuclear incident occurs when released radioactivity is contained; that is, prevented from escaping to the outside environment with no resulting loss of life and with minimal impact on the health of those exposed to radiation. Nuclear accidents involve radioactivity escaping to the outside environment with or without injuries or deaths. The history of nuclear accidents starts in 1952 with a partial meltdown of a reactor's core at Chalk River near Ottawa, Canada, when four control rods were accidentally removed. The resulting radioactive release was contained in millions of gallons of water and no injuries resulted. In 1957, Windscale Pile No. 1 north of Liverpool, England, sustained a fire in a graphite-moderated reactor and spewed radiation over a 200-square-mile area. In the same year, an explosion of radioactive wastes at a Soviet nuclear weapons factory in the South Ural Mountains forced the evacuation of over 10,000 people from the contaminated area. In 1976, a failure of safety systems during a fire nearly caused a reactor meltdown near Greifswald in former East Germany. Of all nuclear accidents, two stand out: Three Mile Island and Chernobyl.

Three Mile Island Incident

The Three Mile Island incident in March 28, 1979, was preceded by the release of the movie *China Syndrome* on March 16, 1979, a case of Hollywood prescience or fiction preceding fact. *China*

Syndrome was about a nuclear plant with internal problems that, if unattended, could have led to a core meltdown, which would then burrow its way toward China. The film dealt with management's decision to ignore and cover up the plant's problems.

The Three Mile Island incident proved that nuclear power plants were not immune to accidents, despite claims to the contrary. In this case a malfunction of the secondary cooling circuit caused the temperature in the primary coolant to rise, shutting down the reactor as expected. What was not expected was the failure of a relief valve to close and stop the primary coolant from draining away. The relief valve indicator on the instrumentation panel showed the valve as being closed, making it difficult for the operators to diagnose the true cause of the problem. As a result, the coolant continued to drain away until the core was uncovered. Without coolant, the residual decay heat in the reactor core raised the temperature within the core and led to a partial core meltdown.

Although the instrumentation panel failed to show that the relief valve was still open, the blame for the accident was eventually assigned to inadequate emergency-response training on the part of the operators. In other words, despite faulty indication of the relief valve, the operators should have identified the true cause of the problem and taken proper action before it was too late. The containment system performed as it was designed to do—nearly all the released radioactivity was prevented from escaping to the outside environment. Contrary to the *China Syndrome* plot, management did not hide the plant's problems from the public and the core did not melt through the earth.

There were minor health impacts and no injuries from the Three Mile Island incident. Even though the nuclear power industry took remedial steps to improve training and operations to make reactors even more safe and reliable, the Three Mile Island incident dealt a deathblow to the U.S. nuclear power industry. The incident halted all further orders of nuclear power plants in the United States and the cancellation of over forty orders for plants not yet started. Most plants under construction were completed, although a few were converted to fossil fuel plants. The public concern over nuclear safety generated by this incident was sufficient to prevent the Shoreham plant on Long Island from becoming operational when it was completed in 1984. A study showed that if a more serious incident than that of Three Mile Island were to occur at the Shoreham plant, the few bridges and tunnels connecting Long Island with the mainland would preclude any large-scale evacuation. For this reason, the plant was dismantled in 1992.

Chernobyl

In one respect, the two events were similar: Both involved human error. At Chernobyl, a runaway reactor occurred during a test, ironically one associated with reactor safety—how long could turbines supply power when cut off from reactor power? What made Chernobyl so much worse than Three Mile Island was the nature of its reactor design, actions taken by operators to defeat safety features, and the absence of a containment system (the reactor housing was not built to contain a pressure buildup from a rupture of the reactor or its piping). In conducting the test, the automatic reactor trip mechanisms were disabled and the emergency core cooling system was shut off. With its valves locked shut, none of the operators knew who had the keys! Having disabled the reactor's safety features, the two principal operators started "doing their own thing" without communicating to each other what they were doing.

The reactor design made a bad situation worse. The Soviet reactor used graphite as a moderator and water as a coolant. Graphite has several undesirable features as a moderator. At too high a temperature, graphite can burn or react violently with steam to generate hydrogen and carbon monoxide, both combustible gases. In a U.S. reactor, water, as both moderator and coolant, shuts down the reactor when water boils in the core. Void spaces in boiling water reduce the number of neutrons being slowed down to keep the reactor critical (negative feedback). In the Soviet reactor, the creation of void spaces in boiling water allowed a larger number of neutrons to reach the graphite moderator, increasing the fission rate (positive feedback). From a low power condition, the operators retracted more control rods than recommended and the reactor went supercritical, generating enough heat to turn the coolant to steam, which further increased the number of fissions. The resulting power surge ruptured the fuel elements and blew off the reactor cover plate. The graphite moderator burst into flames when air gained access to the core, and the resulting blast, along with the escaping steam, ruptured the roof of the building housing the reactor. Large chunks of the reactor core and graphite moderator were scattered outside the building, releasing far more radioactivity than the nuclear bombs dropped on Hiroshima and Nagasaki.

Death quickly followed for those in contact with the radioactive debris or caught in the radioactive cloud close by the plant. A group of people standing on a bridge not far away died from the exposure to radioactivity from gazing in wonderment at the strange lights given off by the reactor. About 200,000 people living within a thirty-kilometer radius of the plant had to be resettled, and increasing the exclusion zone a few years later required resettling another 200,000. Those caught in the radioactive cloud that reached to eastern Europe and Scandinavia now suffer from a higher incidence of cancer and birth defects. Although Russian inspectors monitor food for radioactivity from farms, they miss large quantities of contaminated berries and mushrooms gathered by individuals from forests that "all but glow in the dark." Many believe that the actual death toll far exceeds the official death count of a few hundred. Even so, this does not include the shortening of life from a higher incidence of cancer and the large number of babies born with serious birth defects.

Since the Chernobyl accident, Russian reactors have been retrofitted with modifications to overcome the deficiencies in the original design. Moreover, there has been significant collaboration between Russian and Western nuclear engineers to advance safety in nuclear reactor design and operation. The hurried Chernobyl reactor entombment is showing signs of deterioration, which will have to be revisited in order to ensure that the large amounts of radioactive material still entrapped in the building do not escape to the environment. Nevertheless, the legacy of these two events will live on. The Three Mile Island incident cast a pall over the U.S. nuclear power program and the Chernobyl nuclear catastrophe had far-ranging global implications.

The most recent nuclear incident occurred in 1999 in Tokaimura, Japan, in a uranium-reprocessing nuclear fuel plant. Workers inadvertently mixed spent uranium in solution in a container large enough to create a critical mass. Although there was no explosion, the liquid went critical, giving off large amounts of radioactivity. As the liquid solution boiled, void spaces stopped the chain reaction (lack of a moderator to slow down the neutrons). When cooled, the solution became critical again. This lasted for twenty hours before a neutron absorber could be added to the tank to keep its contents subcritical. Twenty-seven people were exposed to very high levels of radioactivity and two died, and more than 600 others were exposed to less dangerous levels of radiation.

Actually, Japan does relatively little fuel reprocessing; much of its spent fuel is shipped to the United Kingdom and France. Fissionable material from reprocessing is returned to Japan as a mixed oxide fuel for fabricating new fuel elements. Three years after this incident, in 2002, a scandal broke out when it was learned that Japanese utility management hid the fact that there were cracks in nuclear power plant piping (shades of *China Syndrome*). All nuclear power plants in Japan were shut down for inspection and repair, if necessary. No reactor incident came of this, but there was a justifiable loss of confidence in management, raising doubts about Japan's future reliance on nuclear power.

Weapons Proliferation

The chain reaction transforms some of the U238 in the reactor core to various plutonium isotopes. What is of concern is fissionable plutonium 239 that remains in the spent fuel when about 75 percent of the U235 has been consumed. A typical light-water reactor breeds about 8 kilograms of plutonium 239 per month of operation, although one-third undergoes fission, supplying more power to the reactor. A fast breeder reactor is designed to create more plutonium 239 from irradiating uranium 238 than the fissionable material consumed. A fast breeder reactor depends only on prompt or fast neutrons, not delayed or slow neutrons, to maintain a chain reaction, requiring a greater degree of technological sophistication for reactor control. Fast breeder reactors can extend uranium reserves forever, at least from the perspective of human existence. Three fast breeder reactors exist and two more are being built in India and Russia.

The possibility of nuclear weapons made from plutonium 239 extracted from spent fuel has been of concern to the world community for many years. With regard to weapons proliferation, only fifteen kilograms of plutonium 239 can make a crude nuclear weapon and more sophisticated varieties require less, which represents about two or three months of reactor operation. Plutonium 239 can be separated chemically from spent fuel after it is ground up and dissolved in acid. The International Atomic Energy Agency (IAEA) was set up to ensure that nuclear materials at reactor sites and at enrichment and reprocessing facilities are not diverted to nuclear weapons manufacture. The potential, real or otherwise, for diversion of plutonium 239 from spent fuel from a reactor in Iran and another in North Korea for nuclear weapons is unsettling the world community.

In recent years, a new weapon of mass destruction has arisen for the terrorists' arsenal. It consists of a metal container filled with highly radioactive spent fuel ground to fine particles surrounded by conventional explosive. When detonated, the explosion vaporizes and disperses the particles as an aerosol, spreading lethal amounts of radioactivity over a wide area. Only a few micrograms of ingested or inhaled plutonium 239 are fatal. The knowledge that terrorists have seriously considered flying an airliner into a nuclear power plant is another disincentive for building nuclear power plants. Containment systems, with walls typically four feet thick made of steel-reinforced concrete, are designed to sustain the accidental crash of a jet liner. However, intentionally ramming a jet liner at full speed into a reactor may be another matter.

Disposal of Spent Fuel

About one-third of the fuel assemblies are removed from nuclear reactors each year as spent fuel and replaced with fresh fuel. Spent fuel still contains about 96 percent of its original uranium, although its fissionable U235 content has been reduced to less than 1 percent. Highly radioactive spent fuel gives off heat and is normally stored in a spent fuel pool at the reactor site; the water shields the environment from radiation and absorbs the heat. This has to be considered temporary storage, however, because the radioactivity will persist for thousands of years, far beyond the life of the plant.

Spent fuel can either be sent to permanent storage or reprocessed. Reprocessing plants, located in Europe, Russia, and Japan, separate the uranium and plutonium. Recovered uranium is converted back to uranium fluoride and re-enriched with U235. Plutonium can be blended with enriched uranium to produce a mixed oxide fuel. About thirty European reactors can be loaded with 20–50 percent mixed oxide fuel, and Japan plans to have one-third of its reactors capable of using mixed oxide fuel. This recycling of spent fuel greatly reduces the demand for uranium and the volume of spent fuel. After recycling, the remaining 3 percent of highly radioactive wastes is mixed in liquefied Pyrex glass, which contains neutron-absorbing boron, and poured into steel canisters. One ton of reprocessed waste is embedded in 5 tons of glass.

The problem is now where to store the canisters. Final disposition sites for these canisters have not been built, but geological formations made of granite, volcanic tuff, salt, or shale are being examined. One proposal is to drop the boron impregnated glass canisters into ocean trenches for "natural" disposal. The glass prevents any escape of radioactive material into the environment. The canisters are adequately shielded with five to seven miles of ocean water. If the ocean trench is also a subduction zone, over millions of years the canisters will be dragged into the earth's mantle, melted, and dispersed. It is possible that the waste could return to the earth's surface in volcanic lava in some tens or hundreds of millions of years; but by that time, its radioactivity will be gone.

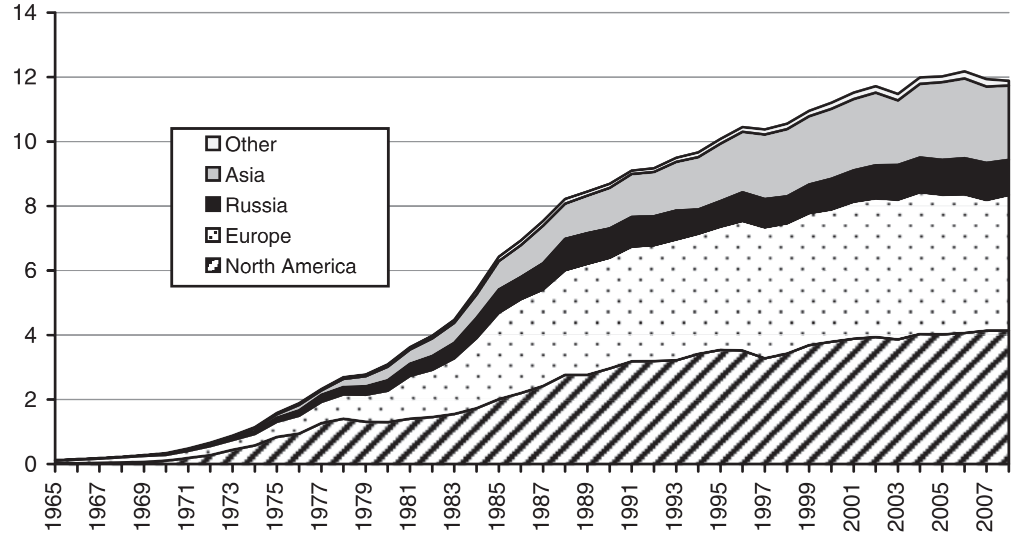
Public objections to dumping nuclear toxic waste in ocean trenches have ruled out what may be a very practical solution to nuclear waste. Yet, there is a precedent. About 2 billion years ago, at a place called Oklo in Gabon, West Africa, six "nuclear reactors" operated naturally within a rich vein of uranium ore that went critical after being saturated with water. The water acted as a moderator and the "reactors" remained critical, producing heat and radioactive fission byproducts before running out of fuel about a half million years ago. The radioactive residue, which totals over 5 tons of fission products and 1.5 tons of plutonium, has all decayed into harmless nonradioactive isotopes. It has also been theorized that another natural reactor exists in the earth's core, maintaining its high temperature and keeping its outer layer liquid to induce the enormous flow of electricity responsible for the earth's magnetic field.

The problem with land storage is that the radioactivity will persist for many thousands of years, far exceeding recorded history. Any water seepage into the storage area could become contaminated and affect the surrounding water table. Sweden, Finland, and Germany are in the process of developing permanent storage facilities. The most publicized proposed permanent storage site is Yucca Mountain in Nevada. The U.S. Congress approved this site in 2002 after $4 billion and twenty years of study. It was to be licensed by the Nuclear Regulatory Commission after it had examined the suitability of Yucca Mountain's geology, hydrology, biology, and climate. The factors favoring Yucca Mountain were its remote location with regard to population centers, its dry climate, and the deep depth of the underlying water table. An unexpected source of opposition was the state of Nevada, which had second thoughts about becoming the nation's sole nuclear waste depository (dumpsite). The state filed a lawsuit against the U.S. Department of Energy for using public rail transport to ship spent fuel to the site. This suit became moot when in 2009, the Obama administration cut off further funding that supported studying the feasibility of Yucca Mountain as a national depository for nuclear waste. Consequently several utilities have filed suit as a result of this decision since the Federal government agreed to provide a permanent storage facility as a precondition for building nuclear reactor plants. As of now, spent fuel is kept in cooled water at nuclear plant sites.

COMMERCIAL REACTORS

The first reactor was a small boiling water reactor (BWR) built for a nuclear submarine, a project spearheaded by Admiral Hyman Rickover in 1954. The first commercial reactor was a pressurized water reactor (PWR) built in 1957. Others were to follow, but these early reactors were really prototypes built to gain expertise to build larger plants. A BWR feeds steam directly from the reactor to the turbines that drive the generators. This introduces a low level of radioactivity to the steam turbines, condensers, and associated piping. A PWR operates under higher pressure; a heat

Figure 8.1 **Growth in Nuclear Power in Terms of Displaced Fossil Fuels** (MM Bpd)



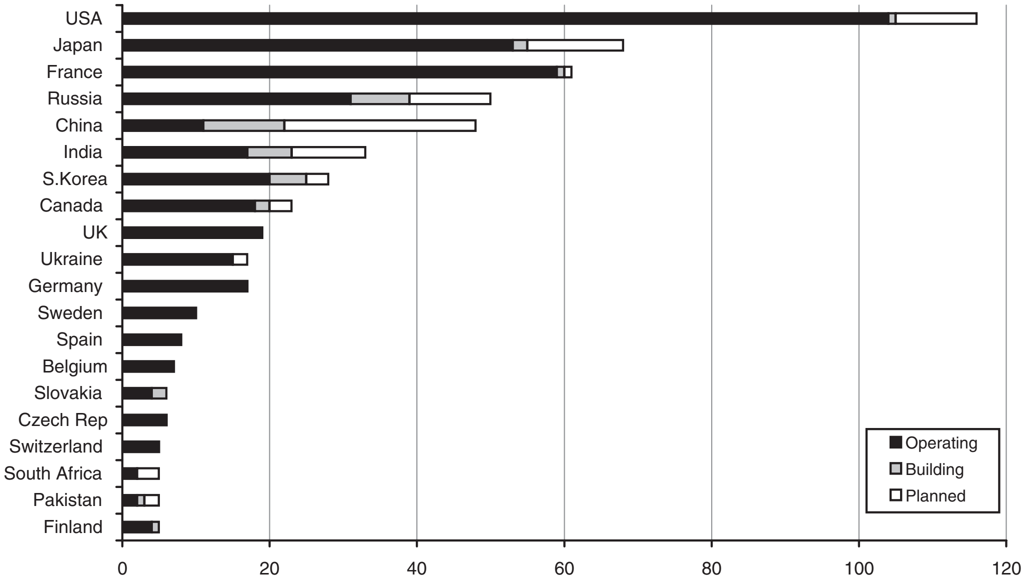
exchanger between the reactor coolant and water in a steam generator precludes any reactor coolant from entering the steam generator, turbine, and associated equipment. The higher temperatures possible with a PWR design make it more thermally efficient than a BWR. Most reactors in the United States are BWRs built by General Electric and PWRs built by Westinghouse that use light or normal water as a moderator.

Figure 8.1 shows the historical growth in nuclear power in terms of the amount of fossil fuel that would have been burned to generate the equivalent amount of electricity, assuming a thermal efficiency of 38 percent for converting fossil fuel to electricity. Generating electricity equivalent to burning 12 million barrels per day of fossil fuel is a significant reduction in carbon dioxide emissions. On a global scale, fossil fuel plants (mainly coal but also natural gas and a smaller amount of oil) emitted 11.4 billion tons of carbon dioxide in 2006 making up 41 percent of carbon dioxide emissions. Because of the growth in coal-fired plants, power plants are projected to contribute 45 percent of carbon emissions by 2030.[5] This trend cannot be reversed unless there is a resurgence in nuclear power augmented by wind and solar.

The upward sweep in nuclear power output for North America shown in Figure 8.1 did not result from building more nuclear plants. The reorganization of the electricity industry from a regulated cost-plus regime to a more liberalized competitive business environment was chiefly responsible for the higher nuclear power output. Under a cost-plus regulatory regime, there was no incentive to get more out of a nuclear power plant than what was convenient. In a liberalized competitive environment, as in the United Kingdom and the United States (and spreading elsewhere), the profit motive residing within deregulation (or liberalization) improved capacity utilization. In the case of the United States, nuclear power plant utilization increased from 65 percent in 1980 to 90 percent in 1990, from the result of better scheduling of maintenance and refueling to reduce downtime and relying more on nuclear power to take advantage of its low variable cost.

In 2009, there were 436 operating reactors: 42 under construction and 110 in the planning stage with proposals for a whopping 272 reactors with 77 in China, 20–25 each in Russia, Ukraine,

Figure 8.2 **World Population of Commercial Nuclear Reactors**



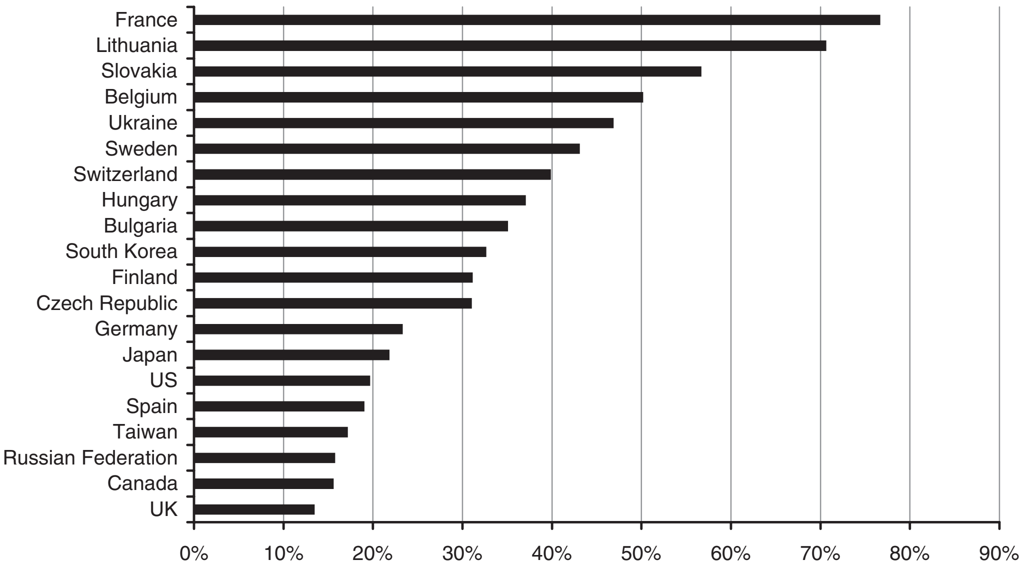
the United States, and South Africa, 15 in India, and 10 in Italy, and 1–2 in a number of other nations. Figure 8.2 shows the number of existing nuclear reactors plus those under construction or in the planning stage.[6]

Nuclear reactors are found in thirty nations, with half in the United States, Japan, and France. Of the 436 reactors, 260 are PWRs and 92 are BWRs. There are also twenty-six gas-cooled reactors, nineteen pressurized heavy-water reactors (popular in Canada), seventeen light-water graphite reactors (found only in FSU), and three fast breeder reactors in Japan, France, and Russia. The U.K.-designed gas-cooled reactor has a graphite moderator and carbon dioxide coolant. Carbon dioxide circulates through the core, where it is heated before passing through steam generator tubes contained within the concrete-and-steel pressure vessel. Steam from the generator passes through the pressure vessel to steam turbines that drive electricity generators. The Canadian-designed heavy-water reactors use natural, not enriched, uranium as fuel, but require a more efficient heavy water moderator where some water molecules have a deuterium atom (one proton and one neutron in the nucleus) rather than a hydrogen atom (one proton in the nucleus). Thus, there is a cost trade-off whether to enrich the fuel with U235 or enrich the moderator with deuterium.

France is a world leader in nuclear power, generating 77 percent of its electricity needs plus exporting electricity to other nations. Lithuania's single reactor is sufficient to cover 71 percent of its electricity needs. Slovakia (4 operating reactors) and Belgium (7 operating reactors) generate over half their electricity demand from nuclear power. Figure 8.3 shows the nations with the highest percentage of electricity generated by nuclear power.

India has six times more thorium than uranium and is independently advancing nuclear technology to take advantage of its ample thorium supplies. India has inaugurated a three-stage reactor program of building a pressurized heavy-water reactor to produce plutonium. In the second stage, plutonium will be the fissionable fuel for a fast breeder reactor to breed uranium 233 from thorium. In the third stage, uranium 233 will be the fissionable fuel for an advanced heavy-water reactor.

Figure 8.3 **World's Largest Nuclear Producers** (Percent of Total Electricity Output)



Advances in nuclear technology have not been curtailed by Chernobyl. Members of Generation IV International Forum (GIF), organized in 2001, include Argentina, Brazil, Canada, China, Euratom, France, Japan, South Korea, Russia, South Africa, Switzerland, United Kingdom, and the United States. The objective of the GIF is to obtain a standardized design for various types of nuclear reactors to expedite licensing and reduce capital costs and construction time. The intended design is to be simple and rugged, have a long life, be easy to operate, and less vulnerable to operator errors and circumstances that could lead to a nuclear accident. Technologies under consideration include a gas-cooled fast reactor, lead-cooled fast reactor (an adaptation of Russian submarine reactors), sodium-cooled fast reactor, supercritical water-cooled reactor, and the very high temperature reactor.[7]

European Pressurized (Evolutionary Power) Reactor

France has been a leader in nuclear power and is still a leader in the post-Chernobyl world. The major differences between nuclear power in the United States and in France are public attitudes towards nuclear power and the organization of nuclear power activities.[8] After the oil crisis of 1973, France did not have the requisite coal and natural gas reserves of the United States to rely on for electricity generation. The French people accepted the government decision to pursue nuclear power because of their respect for and trust in their civil servants and government officials, many of whom were scientists and engineers by training. Moreover, the organization of the nuclear power industry was placed under government oversight for every facet of its activities. The government was responsible for selecting a reactor design, which comes in three sizes (1,450, 1,300, and 900 megawatts of electricity). The "cookie-cutter" approach by limiting reactors to three varieties of a single design reduces manufacturing and construction costs of nuclear components and facilities and simplifies the process of licensing and permitting. Efficiencies gained from progressing down the learning curve of permitting, building, and licensing multiple units of essentially identical plants reduce scheduling delays, cost overruns, and capital costs. All nuclear electricity-generating facilities and reprocessing plants are in government-owned companies. The government is responsible for dealing with nuclear wastes. Government ownership reduces the risk premium that would have to be paid by publicly owned nuclear facilities for financing nuclear plants. Government control ensures a simpler regulatory regime and positive guidance over the future role of nuclear power in satisfying the nation's electricity needs.

In the United States, the Three Mile Island reactor nuclear incident in 1979 brought an abrupt end to nuclear power construction, already plagued with cost overruns and construction scheduling delays by each utility essentially building one-of-a-kind nuclear facilities. Nuclear power plants in the United States satisfy base-load needs, which means that they operate close to full capacity at all times. French reactors supply power for both base and variable needs. Some contend that the continual cycling of power output affects safety from potential power surges and stressing of internal components.

The third-generation European Pressurized Reactor is called the Evolutionary Power Reactor (EPR) manufactured by a joint venture between the French companies Areva and Electricité de France and the German company Siemens. Two EPRs are currently under construction in Finland and France, and both are scheduled for completion in 2012. The EPR reactor has been scaled up to an output of 1,650 megawatts (1.65 gigawatts) using a 5 percent enriched uranium oxide fuel or a 50 percent mixed uranium plutonium oxide fuel. In addition to enhanced output, the major improvement incorporated in the EPR is safety. The nuclear power plant foundation is built to withstand the largest potential earthquake, and four independent emergency cooling systems provide ample redundancy. In addition to a leak-tight containment system surrounding the reactor, an extra or secondary containment and cooling area has been built under the reactor base to handle the potential accident of a molten core penetrating the bottom of the primary reactor containment. The outer containment has a two-layer concrete wall, each layer 2.6 meters thick, designed to withstand impact by aircraft and the internal pressures from a reactor accident. These safety enhancements increase the cost of the EPR, but the economy of scale associated with its greater output can still reduce the cost of electricity by 10 percent from existing plants. In common with building the first of anything, the Finnish EPR is suffering from cost overruns and scheduling delays. But the learning curve associated with series production guarantees that cost overruns and scheduling delays would be experienced to a far lesser degree with follow-on orders such as the two ordered by China's Guangdong Nuclear Power Company. As seen by China's orders, the EPR is being marketed throughout the world.

Pebble Bed Reactor

The concept of the pebble bed reactor is not new. It was proposed at the dawn of the nuclear age in 1943 when the Manhattan Project team led by Enrico Fermi sustained the first nuclear chain reaction in a pile of uranium blocks at the University of Chicago. Farrington Daniels, a chemist, who joined the effort a short time later, proposed the harnessing of nuclear power for cheap, clean electricity using a reactor containing enriched uranium "pebbles"—a term borrowed from chemistry—cooled by helium transferring energy to a turbine driving an electricity generator. Under President Eisenhower's "atoms for peace" program, the newly created General Atomics division of General Dynamics assembled forty top nuclear scientists in 1956 to brainstorm reactor designs. Edward Teller, godfather of the H-bomb, argued that reactors must be inherently safe and advocated that the only acceptable design being one where every control rod could be pulled out without causing a meltdown. But Admiral Hyman Rickover's competing idea of building a water-cooled and moderated pressurized reactor with control rods to power submarines prevailed over a gaseous pebble bed reactor that satisfied Teller's criterion. Rickover's proposed design was adopted by the utility industry until the partial meltdown at Three Mile Island in 1979, and the reactor explosion at Chernobyl in 1986 essentially brought nuclear reactor construction to an abrupt halt other than for warships.[9]

The pebble bed reactor idea did not entirely die with Rickover's decision. Rudolf Schulten, a German physicist, picked up on the pebble bed idea and spearheaded the building of a 15 megawatt demonstration reactor known as the AVR (Arbeitsgemeinschaft Versuchsreaktor) at the Julich Research Center in West Germany. The reactor was online in 1966 and ran for over twenty years before being decommissioned in 1988 because of the Chernobyl disaster plus certain operational problems that occurred at that time. The AVR was originally intended to breed uranium-233 from the much more abundant thorium-232, but the pebbles of the AVR contained the fuel so well that the transmuted fuels could not be economically extracted. The background radiation given off by the AVR was only one-fifth of that which would have been given off by a conventional reactor. Following this, a 300 megawatt thorium fueled pebble bed reactor was built in 1985 and operated for three years with over 16,000 hours of operations. It too was decommissioned as a result of the Chernobyl disaster, along with the consequences of a jammed pebble in a feeder tube that released radiation.

Although there were research activities in the United States and the Netherlands on pebble bed reactors, the baton of actual development passed to South Africa. In the mid-1990s, the national utility company, Eskom, petitioned to build a pebble bed reactor both for domestic use and for export. Opposition from the environmental group EarthAfrica effectively killed the ultimate objective of the program to build 20–30 165 megawatt pebble plants, each holding 450,000 pebbles to produce an aggregate output between 4 and 5 gigawatts of electricity. Though the South African development program for pebble bed reactors is still active, the baton of leadership has been handed over to China. The prototype pebble bed reactor HTR-10 fueled by 27,000 pebbles achieved initial criticality at Tsinghua University in 2003 under the leadership of Qian Jihui, a scientist. Based on the continuing successful operation of this prototype, two 250 megawatt pebble bed reactors are scheduled to begin construction in 2009 at the Shidaowan plant (Huaneng Power International) in Shandong Province for completion in 2013. These plants will produce electricity for the national grid and for cracking steam to produce hydrogen for fuel-cell powered motor vehicles. While China's massive expansion of nuclear energy will be primarily traditional pressurized water reactors, a small portion of the nuclear energy will be satisfied by pebble bed reactors. If successful in a commercial environment, pebble bed reactors are intended to fulfill a larger share of nuclear energy production.

A pebble is a tennis ball sized micro-reactor made primarily of graphite with a diameter of 60 millimeters. The outer 5 millimeters of the pebble is pure graphite. Within this graphite shell is a graphite matrix containing 10,000–15,000 microspheres of coated particles within which is the uranium fuel. The coated microspheres consist of an outer shell of pyrolytic carbon, then a barrier shell of silicon carbide, then inner shells of pyrolytic carbon and a porous carbon buffer. Within these shells in the center of the microsphere is the enriched uranium-235 or some combination of thorium and plutonium with unenriched uranium, or MOX (a mixture of uranium and plutonium) from reprocessing conventional nuclear fuel assemblies or decommissioned nuclear weapons. Any release of radioactivity from a coated particle would be extremely small.

The primary safety feature of a pebble bed reactor is its low fuel density with a power density only one-thirtieth of that of a pressurized water reactor. The reactor is inherently safe when there is a total loss of coolant—no core meltdown occurs as in a pressurized water reactor. A loss of coolant causes the pebbles to heat up to a maximum temperature of 1,600 degrees Centigrade, well below that of the 2,000 degrees Centigrade needed to melt the ceramic coating surrounding each bit of fissionable fuel. As the pebbles heat up, the frequency of fissions drops which lowers the power output of the reactor to a level where more heat escapes through the reactor wall than is produced by nuclear reactions. The reactor cannot crack, explode, melt, or spew hazardous materials—it simply remains at an "idle" temperature with the pebbles intact and undamaged. Known as passive nuclear safety, the reactor's low fuel density allows more heat to escape than is generated in the absence of coolant rather than having to depend on an active nuclear safety feature such as inserting control rods. The pebble bed reactor is inherently safer than traditional reactors. It is impossible to have a runaway reaction as occurred at Chernobyl by a sudden withdrawal of the control rods that caused the reactor to go supercritical or to have a partial core meltdown as occurred at Three Mile Island by a loss of coolant.

In order to ensure this inherent safety, the output capacity of pebble reactors is kept relatively small between 100 and 250 megawatts versus 1,650 megawatts for the EPR. Six or seven pebble reactors would be built at a single site for the same power output of an EPR. These increments in reactor capacity can be added at a central facility in response to growing demand obviating the building of a large facility that must operate at partial power until demand grows to utilize its full capacity. Alternatively, pebble reactors can be built at diverse locations for a more distributive form of electricity-generating system reducing transmission costs. The modular design of pebble reactors allows for mass production at a central location for shipment by truck or rail to the facility site. Modular construction of a single design at a central site can significantly lower construction costs and safety certification costs.

Criticality is achieved by loading several hundred thousand pebbles in a reactor. Helium, an inert gas, is heated by passing through the spherical pebbles to a temperature of 500° C (932° F) at a pressure of 1,323 pounds per square inch (psi). The helium can be directly fed into turbines that drive generators to produce electricity, but this exposes the turbines to low levels of radioactivity. An indirect system eliminates this problem by exchanging heat from the reactor helium with helium fed to the generators, but this adds to costs. Helium, being less dense than steam, requires larger-sized turbines. The energy output of the reactor is controlled by the flow of helium coolant passing through the pebbles. The higher temperature and lower pressure of a HTGR (high-temperature gas reactor) results in greater thermal efficiency (nearly 50 percent) than conventional reactors. As with conventional turbines, energy exchange is a function of the pressure drop across the turbine, which can be maximized by cooling the exhaust helium with air. It is possible that the hot helium exhaust from the turbines can be used as a source of energy to heat water via a heat exchanger and generate more electricity or be a source of hot water for industrial purposes. The cooled exhaust helium is then pressurized by compressors for recycling through the reactor. The lower operational pressure reduces the cost of protecting against pressure breaks and hydrogen embrittlement of the reactor vessel and components. Redundant safety systems found in conventional nuclear reactors are not required, and the core is far less radioactive. However, water and air must be kept isolated from the pebbles in the reactor as their presence with hot graphite would lead to a hazardous condition. The containment building must be capable of resisting aircraft crashes and earthquakes.

Inside the containment building is a thick-walled room containing the pebble reactor. Fuel replacement is a continuous process where pebbles are recycled from the bottom of the reactor to the top. The center pebbles are pure graphite to act as moderators to slow down and reflect neutrons into the pebbles containing fuel. The inner wall of the reactor container has a graphite lining to also reflect neutrons back into the reactor. A pebble will recycle through the reactor ten times over its normal three-year life and is examined and tested for integrity when removed from the bottom of the reactor. If expended of fuel or damaged, the pebble is removed to a nuclear waste area and replaced by a new one. Unlike spent fuel rods, it is exceedingly difficult to extract plutonium from a pebble. A 165 megawatt plant will produce about 32 tons of spent fuel pebbles per year of which 1 ton is spent uranium. Storage is easier than spent fuel rods from conventional reactors as no safety cooling system is needed to prevent fuel failure. A pebble reactor plant facility will have sufficient storage for spent pebbles to cover its forty-year operational life.

The potential cost savings in modular design where plant components are built at a single site for transport by truck or rail to the facility site is no longer restricted to the pebble reactor. The proposed Westinghouse (now a division of British Nuclear Fuels) AP600 design of 600 megawatts of electricity output represents the latest generation of light water reactors. The Westinghouse plant has a simpler design incorporating standardization and modularity to reduce costs. The plant has both passive and active safety means to shut down the reactor. The passive safety means depend on natural driving forces such as gravity flow, natural circulation, and pressurized gas to react to a hazardous condition with less operator intervention than active systems. Westinghouse is also offering an improved version of an existing design called System 80+, which has an output of 1,350 megawatts. Whereas Westinghouse is noted for its pressurized water reactors that require a steam generator to produce the steam that powers the turbines, General Electric is known for its boiling water reactors where steam from the reactor directly feeds the steam turbines. This eliminates the need for a steam generator but results in low level radioactivity of the steam turbines. As a result of General Electric's partnership with Hitachi and Toshiba of Japan, an advanced boiling water reactor of 1,350 megawatts of electricity generation has been introduced with improvements in efficiency, safety, reliability, and cost.

Thirty-two reactors are listed in twenty-three applications for new nuclear plants in the United States, six are the U.S. version of the EPR, fourteen are Advanced Pressurized Water Reactor manufactured by Westinghouse, two are Economic Simplified Boiling Water Reactors manufactured by GE-Hitachi, four are Advanced Boiling Water Reactors manufactured by GE, and the remainder are yet to be determined.

FUSION POWER

Whereas fission is the splitting of heavy atoms, fusion is the uniting of light atoms. The sun and other stars produce heat when hydrogen atoms fuse to form helium, transforming matter into energy. Thus, for fusion to work on Earth, an environment equivalent to being in the center of the sun has to be created, requiring temperatures over 15 million degrees Celsius and pressures over 340 billion times greater than atmospheric pressure. Hydrogen fusion on Earth is obviously quite a technological challenge, but fusion of deuterium and tritium, isotopes of hydrogen, is less demanding than hydrogen. Deuterium can be extracted from seawater and tritium is a byproduct of fission. The challenge is to design a magnetic field strong enough to contain plasma, a heated mix of electrons and ions, under conditions conducive to fusion (100 million degrees Celsius, much hotter than the center of the sun, to compensate for the sun's much higher pressure).

Neutrons are produced when fusion takes place and become a source of heat when trapped in a stainless steel containment vessel wall. This heat is transferred to water to produce steam to run an electricity generator. Once fusion is triggered, it has to be controlled and kept self-sustaining by adding more fuel from a surrounding blanket of lithium in which neutrons react with lithium to produce tritium and helium. Leakage of plasma from the magnetic field is a major problem because this can stop the fusion process. So far, more energy (electricity) is consumed to maintain the plasma than is extracted from fusions. If and when this technical challenge is overcome, it is estimated that half of the electricity produced by fusion will be consumed to contain the plasma within the magnetic field.

The fusion process is inherently safe. A hydrogen bomb environment cannot be created because any "runaway" condition stops the fusion process by removing the plasma. The trick is knowing how to keep the plasma together long enough for fusion to occur. Alternative approaches to magnetic confinement as a means of trapping the hot plasma are lasers or particle beams. The energy source for fusion is virtually inexhaustible. Radioactivity is limited to high-energy neutron bombardment of the containment system. This radioactivity is short-lived (100 years) compared to the radioactivity of a fission reactor (thousands of years). An additional health hazard is the possibility of tritium leaking into the environment. Tritium, with a half-life of 12.4 years, is easily absorbed by the human body and, once ingested, remains a serious threat to human health for a long time. The advantage of the deuterium-deuterium fusion process is that no tritium is involved.

In 1989 there was great excitement over the possibility of cold fusion, creating energy in a test tube (so to speak), which turned out to be either a case of vain hope or scientific sleight of hand. The idea of cold fusion is trying to get back in the limelight. Researchers at a U.S. Navy laboratory announced that there is significant evidence of cold fusion (low-energy nuclear reaction) producing neutrons and other subatomic particles at room temperatures.[10] Research in nuclear fusion is being conducted in the United States, Russia, various European nations, Japan, Korea, China, Brazil, and Canada. In 2005, France was selected as the host nation for a $10–$13 billion experimental nuclear fusion reactor, the ITER (International Thermonuclear Experimental Reactor), to be funded by the European Union, the United States, Japan, South Korea, Russia, and China. Its goal is to produce 500 megawatts of power for hundreds or thousands of seconds at a time. Construction began in 2006 for completion in 2013. It may take as long as twenty-five years before an acceptable design for a commercial fusion plant can be developed.

The National Ignition Facility is a consortium of government and private organizations dedicated to creating conditions found in the cores of stars for fusion to occur. Housed in a ten-story building covering an area of three football fields, a spherical plastic capsule the size of a small pea filled with 150 micrograms of two heavy isotopes of hydrogen, deuterium and tritium, will be exposed to the combined output of 192 giant lasers of 500 trillion watts lasting 20 billionth of a second. For 10 billionth of a second, the capsule will be compressed to a density 100 times greater than lead and heated to 100 million degrees Celsius, hotter than the center of the sun. It is hoped that fusion will result producing ten to one hundred times the energy consumed. If this project is successful, the world energy problem will be potentially solved, but the solution will take time. The project would have to be scaled up to prove that fusion can safely generate enough energy for commercial electricity generation and fusion plants would have to go through the long drawn-out process of receiving permission to be built.[11]

FUTURE OF NUCLEAR POWER

In spite of new plants under construction, most expect nuclear power output either to level off as older plants are phased out, something already in progress, or on a more optimistic note to maintain its share as a source of energy. Yet, at the same time, global demand for electricity continues to rise, although not as rapidly as in the past. In the 1950s annual growth averaged 8.7 percent, 7.3 percent in the 1960s, 4.1 percent in the 1970s, 2.6 percent in the 1980s, and 2.1 percent in the 1990s with a continued growth of about 1.8 percent per year. Even a modest 1.8 percent annual growth would require the addition of about 190 gigawatts of new electricity-generating capacity net of plant retirements per year out to 2030. Roughly 130 new electricity-generating plants of about 1.5 gigawatts each will have to be constructed annually to meet this demand.[12] Large plants of this order of output are invariably coal-fired or nuclear powered. There are plentiful domestic reserves of coal to meet the challenge, but coal has its environmental problems, unless clean-coal technology takes hold. Although wind will play some role, it is unrealistic to expect wind power to fulfill a significant portion of this shortfall in base-load demand.

It is difficult to imagine building this much electricity-generating capacity with no contribution from nuclear power. Moreover, the hydrogen economy will require large numbers of nuclear power plants to produce hydrogen through electrolysis of water. Producing the requisite electricity by burning fossil fuels defeats the whole purpose of the hydrogen economy, which is to do away with carbon dioxide emissions (unless they can be sequestered). The potential generation of electricity from carbon dioxide-free hydro, wind, solar, and geothermal energy sources is not even close to meeting the demands of the hydrogen economy.

The public should become aware that something has to be done before the lights go out. Those opposed to large electricity-generating plants, be they nuclear or coal, do not have a viable alternative other than wind and solar power. Certainly wind and solar power should be encouraged, but even here environmentalists have stopped the building of wind farms off the coasts of Massachusetts and Long Island. Yet no one, including the environmentalists, is advocating letting the lights go out. If nuclear power plants are to play a role in satisfying the demand for electricity, a technology should be selected that makes it possible to reduce capital costs by building a large number of essentially identical plants from modules built in a centralized manufacturing facility. The learning curve of building standard designed nuclear plants can generate further cost savings by eliminating the mistakes and inefficiencies associated with the construction of the first plants in a series. Siting and licensing have to be streamlined, and a cadre of well-trained operators has to be created. Having the same basic nuclear plant design would ease training requirements and allow operators to be easily transferred from one plant to another. Moreover, plants of a standard design are not only cheaper to build but also less expensive and safer to run because equipment, skills, and experience can be shared among the plants.[13] However, the problem of disposing of spent fuel has to be resolved and serious consideration should be given to reprocessing to reduce the quantity of radioactive waste and extend the effective life of uranium reserves. What is needed is public support for nuclear power, which can only come about if doubts over safe operation can be resolved.

The U.S. Energy Policy Act of 2005 provides significant incentives for ending the thirty-year moratorium on licensing new nuclear power plants. The most important is a 1.8 cents per kilowatt hour production tax credit for the first eight years of plant operation. This is a substantial tax credit, considering that the average U.S. retail price of electricity was 9.75 cents per kilowatt hour in January 2009.[14] A tax credit is not a cash subsidy, but a reduction in tax payments that the government would otherwise receive. The tax credit is for a maximum of 6 gigawatts of new plant capacity (six new plants of 1-gigawatt or 1,000-megawatt capacity) of not more than three separate designs. Financial support for certain specified delays caused by litigation or delayed Nuclear Regulatory Commission (NRC) approvals is also available. While the Obama administration initially included nuclear power and clean-coal technology in its green energy plan during the 2008 election campaign, both were surreptitiously dropped in 2009 from the green energy plan without public comment. Clearly, the future of nuclear power has shifted from the United States to China, India, and Europe.

HYDROPOWER

Dams have a long history of supplying water to meet human needs. Ancient dams in Jordan, Egypt, Yemen, Greece, and Turkey were built to supply water for human and animal consumption, irrigate crops on land too dry to sustain agriculture, and control flood waters; the same purposes for building dams now. What is new is using hydropower to generate electricity. A few of these ancient dams have been in more or less continual operation for two or more millennia. The ruins of the Jawa Dam built around 3000 BCE still stand in Jordan. The Ma'rid Dam in Yemen in operation today was originally constructed over 2,700 years ago. Beginning in the first century, the Romans built a number of dams to impound river waters around the Mediterranean such as the Cornalvo and Proserpina dams in Spain still in service after 1,700 years.

Waterwheels turned by running water have lifted water for irrigation and ground grain since Roman times; a definite improvement over tread wheels operated by humans or animals. The first waterwheels were horizontal and drove a vertical shaft to rotate millstones that ground grain on a floor above the waterwheel. Vertical waterwheels were vastly superior to horizontal waterwheels because they could more efficiently translate the momentum of moving or falling water into power. Gearing was now necessary to change the direction of a rotating shaft from horizontal to vertical in order to operate millstones, something that different societies found not always technically feasible. Over the centuries waterwheels were applied to a variety of tasks such as sawing wood, crushing ore, stamping, cutting, grinding, polishing, and powering bellows to force air into a furnace to refine metals. In the 1680s, a large installation of waterwheels pumped water to supply the fountains at the palace at Versailles, France. Factories in England and New England, the first centers of industrialization, continued to be powered by waterwheels long after the invention of the steam engine. Waterpower had the virtue of being free, but steam from burning coal eventually overtook waterpower in the nineteenth century because steam could deliver a lot more power with greater reliability.[15]

There are 45,000 dams in the world with a vertical distance of fifty feet or more. These dams catch 14 percent of precipitation runoff, provide 40 percent of water for irrigated land and more than half of the electricity for sixty-five nations.[16] Many of these are in developing nations in Central and South America, Africa, and Asia. Central America is nearly fully reliant on hydropower. The Gilgel Gibe III hydroelectric dam being built in Ethiopia will rise 240 meters above the Omo River and have an upstream reservoir 150 kilometers long to accommodate the river's annual flooding. The dam will control the river's flow downstream of the dam and will produce 1.8 gigawatts of electricity, doubling the nation's generating capacity. When completed in 2012, the dam will solve Ethiopia's energy (electricity) problems and allow Ethiopia to become an energy exporter to Sudan and Kenya. The dam faces criticism over its potential environmental impact on Lake Turkana, the world's largest desert lake that depends on the river for 80 percent of its water inflow and on the people who depend on the river for their livelihoods.[17] Africa is home to two dams with the world's largest reservoirs: the Owen Falls Dam in Uganda whose reservoir goes by the name Lake Victoria and the Kariba Arch Dam on the border of Zimbabwe and Zambia whose reservoir is known as Lake Kariba.

One hundred and fifty dams are considered major in terms of generating electric power, reservoir capacity, and height. As a group they generate 40 percent of the energy produced by hydropower, but not all dams generate electricity. Some are built to provide water for some combination of human consumption and recreation, irrigation, and flood control. Flood control dams contain heavy rains and snowmelt to reduce flooding of low-lying areas such as those built by the Tennessee Valley Authority (TVA) in Appalachia. Smaller dams span rivers to allow navigation of larger-sized vessels. Ships sailing on major rivers, such as the Mississippi and its tributaries and the Danube, bypass the dams via locks that raise and lower a vessel to the height of the water on either side of a dam. Large vessels could not navigate these rivers were it not for these dams eliminating rapids and controlling the depth of the water.

Hydroelectric dams raise the level of water to create a hydraulic head to power electricity-generating turbines. Reservoirs compensate for fluctuations in the inflow and outflow of water. Inflow is determined by the amount of rainfall in a dam's watershed. Spillways and gates control the discharge of excess water from the reservoir while intake valves control the flow of water through a tunnel (penstock) to the hydraulic turbines that drive the electricity generators. Long-distance transmission lines are generally necessary as many dams are located far from population centers. A few hydroelectric dams have locks that allow ships to pass around them and others have steps, called ladders, to allow fish to get to and from their spawning grounds. Some small, low-powered hydroelectric dams are being dismantled as the economic benefit of restoring fisheries destroyed by the dam now outweigh the value of generated electricity.

The principal advantage of hydropower is that it utilizes a cost- and pollution-free renewable source of energy. However some environmentalists maintain that hydroelectric dams built in tropical regions contribute to carbon dioxide emissions since pre-existent forests now covered by their reservoirs no longer absorb carbon dioxide. Though hydropower has no fuel cost and a low operating cost, it has a high capital cost and is site-specific. Unlike fossil-fueled plants, hydropower dams are not built where they are needed. Prospective dam sites require ample supplies of water plus favorable geological conditions suitable for building a dam whose reservoir is sufficiently large with a bottom that limits water absorption. The capital cost of a dam includes the preparation of a site, the construction of the dam, and the installation of an electricity-generating plant and long-distance transmission lines. From a fuel standpoint, hydropower is environmentally friendly, but other environmental concerns still have to be addressed such as the impact of dams on fish and wildlife, resettlement of people living upstream of the dam, and the potential of catastrophic structural failure for those living downstream.

With tens of thousands of dams, some fail each year, mostly without catastrophic results other than local flooding. The 1889 Johnstown flood was caused by the failure of the South Fork Dam with a loss of over 2,200 lives. The rich folk living along the reservoir, which served purely as a recreational lake, did not bother to spend the money necessary to fix a deteriorating dam. Nor were they held financially responsible for the consequences of their neglect. In 1928, the two-year-old St. Francis Dam in California failed, leaving more than 450 dead. This occurred twelve hours after the builder (always a good source for an unbiased opinion) declared the dam safe, even though water was passing through the dam in spots where it was not supposed to. The cause of the dam failure turned out to be the unsuitable geology of the site. In 1975, unprecedented rainfall caused the Shimantan Dam in China to fail and its floodwaters destroyed the downstream Banqiao Dam. The combined deluge of water and dam debris carried away other downstream dams and dikes, drowning over 85,000 people. In 1976, after seven months of filling the newly constructed Teton Dam in Idaho, with the reservoir only three feet below the spillway, three leaks were found: one at the bottom of the gravel-filled cement dam, another alongside one of its abutments, and still another about 100 feet below the top of the dam. Less than two hours later, the dam was breached and water poured through the dam. In a matter of hours the breach widened, carrying away a large portion of the dam and emptying a seventeen-mile-long reservoir over a wide area of Idaho with a loss of fourteen lives.

Heavy rainfall can cause dams to fail, but dams are also affected by a lack of rainfall or a drought that fails to replenish the waters they hold. The California energy crisis in 2001 was sparked by a drought in Oregon and Washington that curtailed the export of hydroelectricity to California. That same year Brazil suffered power disruptions from a drought that significantly cut hydroelectricity generation, the primary source of that country's electricity. Hydropower in Brazil and other nations with a high dependence on hydropower fulfills both base and variable load. Hydropower is amenable to satisfying variable power because its output can be easily controlled by varying the flow of water through the turbines. In the United States, base-load electricity demand is satisfied primarily with coal and nuclear power. A large coal-fired plant takes days to reach full power and days to shutdown. Since coal and nuclear power cannot handle quick changes to power demand easily, these plants generally run at full power to satisfy base-load demand while hydropower (despite its free energy) and natural gas primarily satisfy variable demand,

Unlike other forms of energy, electricity cannot be stored. Electricity capacity must be able to meet peak demand without consumers experiencing brownouts or blackouts. Batteries cannot store sufficient quantities of electricity to smooth out the operations of an electric utility by supplementing supply when demand is high and being recharged when demand is low. Hydropower provides a way to "store" electricity through pumped storage plants. These plants have reversible pump-turbines that pump water up to a storage reservoir during periods of low demand. During periods of high demand, water flows from the storage reservoir through reversible pump-turbines to generate electricity. Motors that pump water to the storage reservoir become generators to produce electricity. Pumped storage plants reduce variability in electricity demand by pumping water to the reservoir during periods of low demand and by generating electricity during periods of high demand. This increases the base-load demand and reduces the need to invest in costly peaking plants.

The first commercial site for generating electricity was New York City's Pearl Street station built by Thomas Edison in 1882. The plant produced direct current electricity from generators driven by coal-burning steam engines and was the progenitor of other plants to electrify the city. The second commercial site for generating electricity was Niagara Falls, where a hydropower plant built by George Westinghouse produced alternating current electricity. Construction of a tunnel to divert water upstream of the falls to a downstream power plant began in 1890. Commercial sales started in 1895, and the plant's generating capacity was continually expanded until the 1920s. With increasing availability of electricity generated from hydropower, industry rapidly developed along the Niagara River.

The first recorded public outcry over the environmental consequences of energy was the ban on burning coal in London during the thirteenth century. At the turn of the twentieth century, New Yorkers demonstrated against black smoke emissions from the early electricity-generating plants. While the environmental movement can be traced back in time to a number of such public outcries over polluted air and water, the major thrust that propelled environmentalism to the forefront of public awareness was a dam powered by one of the cleanest sources of energy.

The Saga of the Hoover and Glen Canyon Dams

The Hoover and Glen Canyon dams mark the beginning and the end of a dam-building spree in the United States. When built, the Hoover Dam ranked first in the world in size and power generation. Although the Glen Canyon has the same electricity-generating capacity as the Hoover Dam, and is similar in size and structure, a few far larger dams were built in the thirty-year interim separating the two.[18] The Hoover dam was built during the Great Depression in the 1930s to jump-start the U.S. economy as were dams built in Appalachia under the Tennessee Valley Authority. Other major dam projects were the Shasta Dam across the Sacramento River and the Grand Coulee Dam across the Columbia River. The Shasta and Grand Coulee dams supply water for irrigation and flood control, but of the two only the Grand Coulee Dam generates electricity; more than twice the combined output of the Hoover and Glen Canyon dams.

The Hoover and Glen Canyon dams straddle the Colorado River, discovered by Coronado in

1540 in his quest for the fabled seven cities of gold (actually Cardenes, a member of Coronado's party, was the first to discover the Colorado River from the rim of the Grand Canyon). Coronado named the river after the Spanish word for "red," the color of the silt-laden river. Coronado did not explore the Colorado River; in fact, the Colorado River presented an insurmountable barrier to further exploration. Exploring the river would not take place for another 300 years, when a daring individual led the first recorded expedition down the river.

The Colorado River falls 14,000 feet from the Rocky Mountains to sea level in the Gulf of California and carries more silt than any other river in the world, including the "muddy" Mississippi. The original time estimate for Lake Powell, the reservoir in back of Glen Canyon Dam, to fill up with silt was 400 years, but this was subsequently revised to 1,000 years by later estimates of the silt-capturing capacity of other dams upstream of where the Colorado River enters Lake Powell. The primary advantages of the Colorado River from the point of view of dam building are that the river flows through a canyon whose geology is ideal for damming and through a region desperate for water. The disadvantage of the Colorado is its relatively low average water flow, which varies from a summer trickle to a springtide flood that carries away the snowmelt of a large area of the Rocky Mountains.

In the early part of the twentieth century, the original idea was to build a dam at Glen Canyon first, followed by three more downstream dams whose construction would be made easier by building the upstream dam first. The problem was that the Glen Canyon reservoir would serve Arizona, which had a small population at the time. Population growth was centered in California, and by the 1920s it was clear that further development hinged on having an adequate and dependable supply of water to support agriculture and urbanization. California politicians prevailed at deliberations as to where to build the first dam—it would be built at Boulder Canyon, whose reservoir water could be easily diverted to California. It was understood at the time that another dam would eventually be built to serve Arizona.

The name Boulder Dam stuck after the original site was changed to a better location in nearby Black Canyon, about thirty miles southeast of Las Vegas. Boulder Dam was renamed Hoover Dam in 1930 after the president who authorized its construction. In 1933, New Deal bureaucrats decided that the world's most monumental dam project should not be named after the president who presided over the onset of the Great Depression and changed the name back to Boulder. The dam was completed in 1936 and another six years were to pass before its reservoir, Lake Mead, was filled. In 1947, a Republican-controlled Congress under President Truman passed a law to reinstate the name Hoover.

Dams and other capital-intensive projects cannot be funded from private sources; too much money is at risk. The risk private investors shun is accepted by the government because the risk of loss can be spread among the taxpaying public. Moreover, government cooperation is needed for land condemnation to clear the way for the reservoir, particularly when much of the land is already in the public domain. The responsibility for dam building fell under the auspices of the Bureau of Reclamation of the Department of the Interior. "Reclamation" was interpreted to mean "reclaiming" unproductive land for agricultural use by building dams to provide water for irrigation. Earlier reclamation projects were financial failures because the revenue from growing crops on irrigated land fell far short of justifying the cost of building a dam. It was the discovery that dams could also generate electricity that changed the financial equation in favor of dam building. The Department of Interior was also the administrative home for the Bureau of National Parks Service, charged with preserving and protecting wilderness areas, and the Bureau of Indian Affairs, which establishes and administers American Indian reservations. One bureau built dams whose reservoirs, at times, submerged lands set aside by a sister bureau to preserve wilderness areas or by another to establish American Indian reservations. Talk about dichotomy of purpose!

There are marked similarities between the Hoover and Glen Canyon dams. Both generate 1.3 million kilowatts or 1,300 megawatts or 1.3 gigawatts of output, enough electricity to supply a U.S. city of 1 million people. Both rise 587 feet above the riverbed, although the Hoover Dam is taller by sixteen feet when measured from bedrock. Like most dams, both had huge tunnels built around the dam site to divert the waters of the Colorado River at full flood during Dam construction. These were eventually plugged when the dams were completed to start filling the reservoirs, although both have diversion tunnels to reduce excessively high reservoir levels. Each required the building of a new town for the construction workers, one that started out as a disorganized tent city at the Hoover Dam site and the other an equally disorganized trailer park at the Glen Canyon Dam site. Tents and trailers were eventually replaced by carefully laid-out company towns for the construction workers and both survived the completion of the dams as Boulder City, Nevada, and Page, Arizona.

The reservoir behind Hoover Dam (Lake Mead) holds two times the annual flow of the Colorado River; enough to irrigate 1 million acres of farmland in southern California and southwestern Arizona and 400,000 acres in Mexico, and supply more than 16 million people with water in Los Angeles and portions of Arizona and southern Nevada. Lake Mead is 110 miles in length with 550 miles of shoreline. The reservoir behind Glen Canyon Dam (Lake Powell) covers 252 square miles, is 186 miles long, and has 1,960 miles of shoreline. Considering the area and the length of Lake Powell, its average width can only be slightly over a mile of flooded canyons. Lake Mead was named after Elwood Mead, a commissioner in the Bureau of Reclamation. Lake Powell was named after John Wesley Powell, the one-armed Civil War veteran who in 1869 successfully led the first recorded expedition of ten men in four boats down the Colorado River. Although Powell did mention developing the area along with the need for preserving its natural beauty, what he had in mind in terms of development was far different than the development posed by the lake that bears his name. Mead is a fitting name for a dam's reservoir; Powell is not.

Both dams were built in a similar fashion—in blocks, the smallest being the size of a house. One-inch copper pipes for pumping refrigerated water through the wet cement were incorporated in the construction of the dam to speed up curing from an estimated 150 years to nineteen or so months. Most dams built before the Hoover dam were gravity dams; pyramidal in shape (thick at the bottom and narrow at the top), so that the weight of the dam held back the water. They were commonly cement or masonry on the outside and filled with rock or gravel. Arch dams of pure concrete or masonry, first built in the late nineteenth century, were thin in comparison with gravity dams. A gravity dam depends on its massiveness to hold back the pressure of the water in a reservoir whereas the arch dam transfers the pressure on the dam to thrust on the canyon wall abutments. The Hoover and Glen Canyon dams were an innovative combination of both the gravity and arch designs. Though curved, they are still pyramidal, thick at the base and narrow at the top. (A third type is the buttress dam where the face of the dam is supported by buttresses on its downstream side.) While similar, there are differences between the two. The intake towers at Hoover Dam were built on the canyon walls, and tunnels (penstocks) were cut through the canyon walls for water to flow to the turbines whereas the intake towers and penstocks were incorporated within the Glen Canyon Dam. One can drive across Hoover Dam, but there is a bridge for vehicle traffic alongside Glen Canyon Dam, whose construction was a feat in itself.

Parenthetically, Las Vegas was built on the electricity generated by Hoover Dam. The gangster Bugsy Siegel saw "easy-going" Nevada, with its legalized gambling, as a land of opportunity, and built the first gambling palace, the Flamingo. Bugsy saw before others that Hoover Dam could supply cheap and plentiful electricity for air conditioning and lights and water for casino fountains built in the middle of a hot, dry, inhospitable desert. The Flamingo was the first step in transforming a backwoods desert town into the gambling Mecca of the world and one of the fastest-growing cities in the United States.

Glen Canyon Dam, started in 1958, was completed four years later when the gates to the lower tunnel were closed to begin filling Lake Powell. While the reservoir was filling, much work remained. The generators and transmission lines had to be installed, and the tunnels that diverted the flow of the Colorado River had to be permanently sealed. The fill rate was slow because a minimum quantity of water must flow through Glen Canyon Dam to ensure an adequate supply of water to Lake Mead, which in turn supplies water to California and powers Hoover Dam's generators. With light snowfall in the Rockies in 1963 and 1964, Lake Mead was rapidly dropping while Lake Powell was hardly filling. The return of normal snowfalls sped up the fill, but a court injunction in 1973 temporarily stopped the filling of Lake Powell when its reservoir water was about to invade the Rainbow Bridge National Monument. A congressional law was subsequently passed that allowed water to flood land previously set aside as part of a National Monument, violating a prior agreement with environmentalists that allowed Glen Canyon Dam to be built. In 1980, seventeen years after the completion of the dam, Lake Powell was finally filled.

Hoover Dam was planned in the late 1920s in response to California developers who saw a lack of water as an impediment to further development of agriculture and urban areas. By harnessing a mighty river for the common good—making deserts bloom, lighting cities, and providing power to industry and commerce—Hoover Dam was "concrete" proof of America's engineering skill and industrial might. No one opposed the building of the Hoover dam. Supporters included the federal government via the Bureau of Reclamation, private construction companies, and California politicians and developers. Thirty years later the Glen Canyon dam was also viewed favorably by the same coterie of supporters, except the politicians and developers were from Arizona. But a new entity was involved: the first environmentalist group to capture the nation's attention, the Sierra Club.

The Sierra Club was formed in the late nineteenth century by John Muir, a naturalist, to preserve the Sierra Nevada Mountains in their original pristine condition. Ever interested in preserving nature, Muir persuaded Theodore Roosevelt to declare a portion of the Grand Canyon as a national monument, at the same time chiding Roosevelt for his habitual trophy-hunting of game animals. Sierra Club members were mainly conservative businessmen and academics dedicated to preserving the wilderness areas of the high Sierras. After Muir lost a fight to prevent building a dam on a national preserve in the Sierras, the Sierra Club vowed that they would never allow this to happen again—in the Sierras. The transformation of the Sierra Club to openly fighting for conservation and preservation of wilderness beyond the Sierras started in 1949 when the Bureau of Reclamation publicized its intention to build a dam across the Colorado in Dinosaur National Monument. This marked the beginning of a dramatic change in the makeup of the membership of the Sierra Club, from one of conservative businessmen and academics to a more politically active constituency that advocated the preservation of the wilderness and conservation of natural resources far beyond the high Sierras.

To its everlasting regret, the Sierra Club acquiesced to the building of the Glen Canyon dam on condition that no more dams would be built in national parks and that something would be done to prevent flooding the Rainbow Bridge National Monument. The ban on dams in national parks also included two more intended for the Grand Canyon between the Glen Canyon and the Hoover dams. These dams (Bridge Canyon and Marble Canyon) were to be smaller in size and less intrusive than their larger counterparts. They were intended to generate electricity to pump water over intervening mountains from Lake Powell to Tucson and Phoenix. With the agreement not to build these dams, a substitute source of electricity was needed. It was first proposed that a nuclear power plant be built (this was in the 1960s, when nuclear power was considered safe and cheap). In the end, the Navajo Generating Station was built near Glen Canyon with a 2.5 gigawatt output, about equal to the combined output of the Hoover and Glen Canyon dams. The plant, started in 1970 and completed in 1976, is fueled by Black Mesa coal strip-mined on Navajo reservation land and shipped in by rail. It is ironic that the environmentalists' success in preventing the building of two clean and sustainable hydropower dams led to the building of one of the world's largest coal-burning plants that spews carbon dioxide and other emissions into the atmosphere. It is also ironic that current attempts by environmentalists to dismantle Glen Canyon Dam ignore that Lake Powell draws far more tourists than Yellowstone and Yosemite Parks. The debate that continues to this day over Glen Canyon Dam has prevented any other large hydropower projects in the United States from moving ahead.

The building of the Glen Canyon dam marks a watershed in the change of attitudes toward large-scale industrial development. Once viewed as signs of the improvement of humanity's material well-being, dams became viewed as an irretrievable loss of wilderness. The Sierra Club gave birth to innumerable environmental groups dedicated to stopping not only dams but just about anything that can be stopped: from oil refineries in Texas to wind farms off the coasts of Massachusetts and Long Island. Environmentalists maintain that building one dam leads to the building of another because the industrial and agricultural development allowed by the construction of the first dam creates the demand for electricity and water to justify building a second, then a third, and a fourth, and so on until the entire wilderness is submerged in reservoirs.

This phenomenon of progress creating its own demand was first observed when Robert Moses built a parkway on Long Island to give New Yorkers easy access to the "country." Once built, so many New Yorkers moved to suburbia that the subsequent highway congestion created a demand for a second parkway. This opened access to other parts of Long Island, creating more urban sprawl, more road congestion, and the need for building yet another parkway until, presumably, all of Long Island would eventually be paved over. The same is true for power plants—building one allows a community to expand in population, commerce, and industry until there is a need for another. As one community experiences the economic benefits of a power plant, others copy it and the process continues until the nation is covered with power plants and the horizon cluttered with transmission lines. This is one of the chief complaints of environmentalists—progress continues until the last vestige of natural life is irretrievably lost. What the alternative vision of life under the rule of environmentalists would be like is left largely unanswered.

Aswan High Dam

The environmental consequences of the Aswan High Dam best exemplify what environmentalists fear most—the consequences are largely unknown before something is built; once built, little can be done to counter them. The first Aswan dam, built in 1889 when Egypt was under British control, was to irrigate cash crops such as cotton. The height of the dam was increased in 1912 and 1933 to enhance its water storage capacity. The sluice gates of the original Aswan dam were opened during the flood season to let the floodwaters proceed unimpeded downstream. As the flood season neared its end, the sluice gates were closed, trapping water behind the dam for crop irrigation.

The Nile flood originates in the Ethiopian highlands, the source of the Blue Nile, during the monsoon season. Silt deposited by the floodwaters formed a thick, fertile layer of alluvium that made the Nile valley and delta one of the most productive agricultural regions on Earth. After the Egyptian revolt in 1952 brought Nasser to power, the Soviet Union sponsored the building of the Aswan High Dam, five kilometers long, one kilometer wide at its base, and rising 107 meters in height. This dam, called the Pyramid for the Living by President Nasser, permanently stopped the annual flooding of the Nile valley and delta.

The dam was supposed to be a major source of hydroelectric power for Egypt, but unfortunately this potential was never fully realized. Lake Nasser did not rise to its anticipated level because of its high rate of evaporation, the volume of water diverted to irrigate cropland, and possibly leakage through the reservoir bottom. Electricity was necessary, not only to supply the needs of the people, but also to provide energy for the production of fertilizer as a substitute for the alluvial deposits formerly left behind by the annual floods. The alluvial deposits were free, but fertilizer is not. In addition to affecting the productivity of the Nile valley and delta, agricultural land has been lost by erosion of the Nile delta by the Mediterranean Sea, which had previously been replenished by the annual inundations. Penetration of saline waters from the Mediterranean into the Nile delta further decreased productivity and reduced the local fish population. Agricultural land upstream of the dam, now part of Lake Nasser, was lost, along with the livelihoods for 120,000 Nubians, who had to be resettled, but this was more than made up by bringing into production other lands bordering on Lake Nasser.

There also appears to be a correlation between Lake Nasser's water level and earthquake activity. Some geologists feel that the weight of Lake Nasser is affecting underlying faults; a phenomenon that has been observed at other dam sites. The sediments that once fertilized the Nile delta now accumulate in the bottom of Lake Nasser, over time reducing the volume of irrigation water stored in the lake. The presence of large bodies of water behind dams can affect the local climate, although this can be benign. The Aswan High Dam has also been blamed for the spread of schistosomiasis, a parasitic disease that leads to chronic ill health that has also been associated with other large-scale water development projects. Where once the annual inundation of the Nile flushed the delta and river of snails that carry the parasite, now the snails are moving further upstream and affecting larger numbers of people.[19]

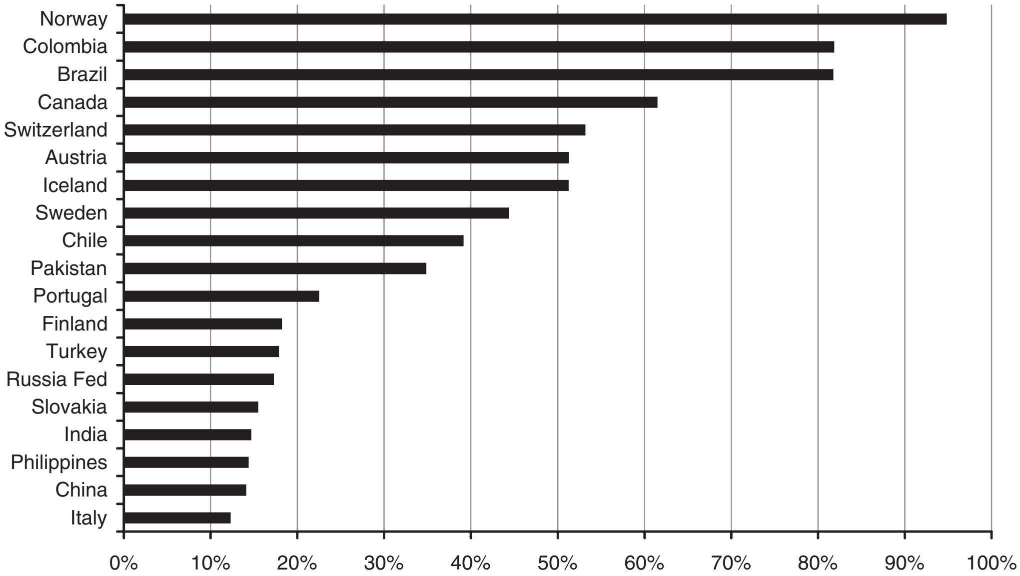
This avalanche of environmental objections over the building of the Aswan High Dam has to be counterbalanced by what the proponents say. They point out that the water in Lake Nasser saved Egypt from famine in 1972 and 1973 and maintained its agricultural output during nine successive years of drought between 1979 and 1987. Lake Nasser has provided irrigation for enough new land to be brought into cultivation and to partially support a doubling of the population; but not quite enough to prevent Egypt, once a net food exporter, from becoming a net food importer. Moreover, the dam protected the Nile valley from major floods in 1964, 1975, and 1988.[20]

HYDROPOWER: TODAY AND TOMORROW

Hydropower once provided a significant portion of electricity-generation capacity in the United States (40 percent in 1920 increasing to over half during the 1930s). Since the Second World War, fossil-fueled and nuclear generating plants were built in large numbers, pushing hydropower to the background. North American hydropower development is now centered in eastern and western Canada. Hydropower plants in eastern Canada are built and operated by Hydro-Québec with 59 hydropower generating stations encompassing 560 dams and 25 large reservoirs with an installed capacity of 34.1 gigawatts.[21] The company has access to another 5.4 gigawatts of output at Churchill Falls plus 2.3 gigawatts of output from a nuclear and several conventional plants and another 1.8 gigawatts through purchase agreements with independent power producers including wind farm operators.

The company owns and operates a 33,000-kilometer transmission system with interconnections to other transmission systems in Ontario and Québec Provinces, the Midwest, Middle Atlantic,

Figure 8.4 **World's Largest Hydropower Producers** (Percent of Total Electricity Output)



and New England states. This arrangement helps to even out the base load where the winter peak to heat homes and office buildings in Canada is balanced by a summer peak to cool homes and office buildings in the United States. The company has spearheaded technological advances in long-distance transmission to reduce transmission losses (an imperative considering the remote location of its hydropower plants), and shares its expertise by getting involved with hydropower projects in other lands. On the other side of Canada in British Columbia, BC Hydro, a government-owned company, produces 11 gigawatts of electricity of which 90 percent is hydroelectric at 30 integrated generating stations. Like Hydro-Québec, a significant portion of its electricity output is consumed in the United States.

The leading hydroelectric regional producers are Asia with a 29 percent share of which a 19 percent share is in China, Europe and Russia each with a 25 percent share, and North and South America each with a 21 percent share. Figure 8.4 shows those nations with the greatest dependence on hydropower for electricity generation.

Norway is almost entirely dependent on hydropower for electricity generation. Brazil, with a noteworthy 82 percent dependency on hydropower, had a national energy policy to become entirely dependent. In pursuit of this objective, the Itaipu hydroelectric power project was built between 1975 and 1991 with eighteen generating units for a total output of 14 gigawatts of electricity. This single dam complex has an output equivalent to about fourteen nuclear or large coal-power plants of 1,000 megawatts or 1 gigawatt each. Itaipu is a binational development project on the Paraná River between Brazil and Paraguay, not far from the border with Argentina, and provides 25 percent of the electricity supply in Brazil and 80 percent in Paraguay. The height of the dam is 643 feet (196 meters) with a length of nearly 5 miles (7.8 kilometers) and a reservoir 106 miles (170 kilometers) long. The dam has become a major tourist attraction as a construction marvel, much like Hoover and Glen Canyon dams. While being built, wet cement was refrigerated before pouring to decrease the setting time rather than installing refrigerated water pipes as was done at the Hoover and Glen Canyon dams. Whereas it took seventeen years to fill the Glen Canyon res-

Table 8.3

World's Twenty Largest Dams in Terms of Electricity Generation

Name	Location	Rated Capacity (GW)	Built/Capacity Expanded
Three Gorges	China	22.5	2009
Itaipu	Brazil/Paraguay	14.0	1984/1991/2003
Guri–Simon Bolivar	Venezuela	10.2	1986
Tucurui	Brazil	8.0	1984
Grand Coulee	U.S.	6.8	1942/1980
Sayano-Shushenskaya	Russia	6.7	1983
Krasnoyarskaya	Russia	6.0	1972
Robert-Bourassa	Canada	5.6	1981
Churchill Falls	Canada	5.4	1971
Bratskaya	Russia	4.5	1967
Ust Ilimskaya	Russia	4.3	1980
Yacireta	Argentina/Paraguay	4.1	1998
Tarbela	Pakistan	3.5	1976
Ertan	China	3.3	1999
Ilha Solteira	Brazil	3.2	1974
Xingo	Brazil	3.2	1994/1997
Gezhouba	China	3.1	1988
Nurek	Tajikistan	3.0	1979/1988
La Grande-4	Canada	2.8	1986
W.A.C. Bennett	Canada	2.7	1968

ervoir, the Itaipu reservoir was filled in a matter of weeks—the water rose so fast that an intensive effort had to be made to save animals from drowning.

Brazil's dream of achieving full reliance on hydropower for generating electricity was shattered in 2001 when a severe drought lowered reservoir levels throughout the nation to the point of cutting electricity generation by 20 percent, causing widespread power disruptions and economic dislocations. Brazil is now pursuing a policy of energy diversification for electricity generation rather than total reliance on hydropower.

Dams are ranked all sorts of ways such as by height, reservoir size, and the material consumed in their construction. In terms of electricity-generating capacity, the Three Gorges Dam in China is by far the world's largest dam as shown in Table 8.3.[22] While currently at 22.5 gigawatts, the Three Gorges Dam will generate 25.6 gigawatts in 2011 when the whole project is completed.

On a global scale, hydropower supplied 18.5 percent of electricity between 1990 and 1997. Then a slow decline set in that reduced its contribution to 15.7 percent in 2008, which meant that other means of electricity generation were favored over hydropower. This trend may be reversed by hydropower projects in India and China. The potential for hydropower is enormous in both nations because their major rivers start 15,000 feet above sea level on the Tibetan plateau. The Indian government is a strong advocate of hydroelectricity as an alternative to coal-burning plants to reduce air pollution by utilizing a free source of clean energy. However, the government faces strong environmental opposition to its plans for hydropower and it is not clear how these projects will fare in the future.[23]

Three Gorges Dam on the Yangtze River stretches a mile (1.5 kilometers) across and towers close to 2,000 feet (600 meters) above the world's third longest river. Its reservoir will eventually cover land 350 miles upstream of the dam, forcing the resettlement of close to 2 million people. Its installed capacity of 22.5 gigawatts is the largest in the world, equivalent to twenty-three nuclear power plants, and will supply 6 percent of China's electricity needs. A system of locks allows ships to pass around the dam. The Three Gorges dam is also a flood-control measure for a river notorious for disastrous floods.

The benefit of flood control, along with the substitution of clean hydropower for dirty-burning coal in electricity generation, has made little impact on those opposed to the dam. Human rights organizations criticized the resettlement plans, archaeologists were concerned about the submergence of over 1,000 historical sites, and others mourned the loss of some of the world's finest scenery. Moreover, millions of Chinese downstream of the dam would be at risk if there were a catastrophic structural failure (memories of the Shimantan dam disaster still persist). The Three Gorges dam is but one project underway in China's quest to double its hydropower potential.

Large-scale dam projects are underway in Turkey at the headwaters of the Euphrates River to irrigate agricultural land, supply water to towns and cities, and generate electricity. These projects have strained relations with Iraq because the Euphrates is also the principal source for irrigation and drinking water in Iraq along with the Tigris River. Turkish dam projects have also spurred opposition from Kurds and other indigenous people who are being displaced by the reservoirs. Once fully operational in 2010, a grouping of five dams in Turkey and three in Syria have the potential to severely reduce the water flow to Iraq depending on the amount of water diverted for irrigation.

In mid-2009, what was feared most happened. The flow in the Euphrates River fell from 950 cubic meters per second to 230 cubic meters. Part of the decreased flow was blamed on the dams in Turkey and Syria plus the repercussions of a two-year drought, which also affected the flow in the Tigris River. Moreover, water-management practices in Iraq are generally poor resulting in wasteful consumption. The lack of water has destroyed a large swath of Iraqi agriculture and forced Iraq to import fruits, vegetables, and grain once homegrown. Poisonous snakes, losing their natural habitat in the reed beds, are now attacking cattle and humans. Desertification of once fertile land has begun. Although an appeal to Turkey to release more water was successful, Turkey is under no obligation to maintain the increased flow.[24] The problem of water flow will worsen with Turkey's plans to build the Ilisu dam on the Tigris, Iran's building of dams on tributaries to the Tigris, and Iraq's building of a 230 meter tall dam at Bekhme Gorge in a Tigris tributary in Kurdistan.

Another potential problem is the Nile River. Currently, Sudan is permitted 13 percent of the Nile flow with the remaining 87 percent for Egypt. Now other nations in the Nile basin (Burundi, Democratic Republic of Congo, Ethiopia—source of 85 percent of the Blue Nile—Eritrea, Kenya, Rwanda, Tanzania, and Uganda) want a share of the Nile waters. Some believe that access to water will be the next source of conflict between nations after oil. A water conflict has already erupted between Lebanon and Israel because some Israelis felt that a plan to divert the headwaters of a stream in Lebanon, used for irrigation and drinking water in Israel, was tantamount to an act of war.

Prospective sites for large hydropower projects are nearly exhausted in the United States and Europe. South America still has a great deal of potential that can be tapped as does Asia, the present world center of dam building. In contrast, mini and micro hydro plants are considered nonthreatening plants, not disruptive to people or the environment. Small may be back in style, but small dams lack the inherent economies of scale of megadams.

One potentially huge hydropower project under consideration is associated with the Dead Sea, 1,370 feet below sea level, the lowest spot on Earth. It is bordered by Israel and Jordan and the West Bank under the control of the Palestinian Authority. For thousands of years, the flow of the Jordan River was sufficient to replenish water lost to evaporation. Being "at the end of the road," the Dead Sea accumulates salts carried by the Jordan River. Whereas the world's oceans have a salinity content (salts of sodium, magnesium, calcium, potassium, and others) of 3.5 percent and the Great Salt Lake in Utah has a salinity of 27 percent, the Dead Sea's 33 percent is almost ten times that of ocean waters. Dead Sea waters are thought to have therapeutic properties and have an oily sensation. A person floating in the Dead Sea finds it hard to stand up and leaves the water caked with salt.

The problem is that the Dead Sea is no longer being replenished with water. The Jordan River and its tributaries have been thoroughly tapped by Israel, the Palestinian-controlled West Bank, Jordan, and Syria for the region's scarcest resource, which has cut the flow of the Jordan River by nearly 90 percent. What now flows into the Dead Sea is mainly sewage and other waste waters dumped into the Jordan River after its clean waters have been drawn off. Depending on where it is done, baptism by submergence in the Jordan River can be hazardous to one's health. The idea to build sewage-treatment plants to remove wastes being dumped into the Jordan actually worsens the problem. Once treated, the water would probably be diverted for irrigation, reducing the flow in the Jordan from a trickle to nothing.

With this massive diversion of water for irrigation, the Dead Sea is falling about 1 meter per year and its shoreline has retreated 500 meters over the last few decades, resulting in the loss of one-third of its area.[25] To counter this, the possibility of building a 108-mile (174-kilometer) system of canals and pipelines to bring seawater via gravity flow from the Gulf of Aqaba on the Red Sea to the Dead Sea has long been considered. Pipelines would siphon water over intervening highlands. Siphoning occurs when water leaves the pipeline at a lower elevation than where it enters the pipeline, eliminating the need for pumping. The end point of the Red-to-Dead project would be a hydropower plant with a hydraulic head of 500 or more meters, higher than most dams. The potential output of electricity, presently envisioned at 0.55 gigawatts, can be far larger depending on the flow of water from the Red Sea. Electricity generation can be partly dedicated to desalinizing water for human and agricultural use. The project requires the cooperation of Israel, Jordan, and the Palestinian Authority to arrive at a way of fairly sharing the electricity and desalinized water and its estimated $5 billion cost. The project has to deal with environmental objections over potential damage to coral reefs in the Gulf of Aqaba caused by diverting waters to feed the Red-to-Dead Project and potential chemical and biological consequences of pouring vast quantities of Red Sea water into the Dead Sea basin. On the other hand, doing nothing means another environmental calamity when, in about 150 years, continued evaporation transforms the Dead Sea into a supersaturated solution of salt incapable of further evaporation.

NOTES

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2. Nuclear Energy Institute Web site www.nei.org.

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4. Edward S. Cassedy and Peter Z. Grossman, *Introduction to Energy* (Cambridge, UK: Cambridge University Press, 1998).

5. *World Energy Outlook* (Paris: International Energy Agency, 2008).

6. Figure 8.2 from World Nuclear Association Web site www.world-nuclear.org/info/reactors.html; Figures 8.1, 8.3, and 8.4 from *BP Energy Statistics* (London: British Petroleum, 2009).

7. The Generation IV International Forum Web site www.gen-4.0rg/index.html and the Nuclear Energy Institute Web site www.nrc.gov/reactors/new-reactors/col.html.

8. “Why the French Like Nuclear Energy” by Jon Palfreman Web site www.pbs.org/wgbh/pages/frontline/shows/reaction/readings/french.html; Areva NP Web site www.areva-np.com.

9. Pebble Bed Reactor topic in Absolute Astronomy Web site www.absoluteastronomy.com/ topics/ Pebble_bed_reactor; safety issues from Web site web.mit.edu/pebble-bed/Presentation/ HTGRSafety.pdf; also, “A Future for Nuclear Energy: Pebble Bed Reactors” by Andrew Kadek (2005) and “Nuclear Power Plant Design Project” by Andrew Kadak and others (1998), Massachusetts Institute of Technology Web site www.mit.edu/pebble_bed.

10. “Scientists in Possible Cold Fusion Breakthrough,” Newsmax.com (March 24, 2009) Web site www.newsmax.com.

11. National Ignition Facility and Photon Science Web site lasers.llnl.gov.

12.*World Energy Outlook* (Paris: International Energy Agency, 2008).

13. As a former engineering officer onboard a nuclear submarine, I could easily be transferred from one submarine to another because the reactor and steam-propulsion systems were essentially identical. There was only one plant layout and one set of manuals to learn for operating instructions and emergency procedures. Frankly, I always felt comfortable and secure with the power produced by a nuclear plant. It was safe, reliable, and gave me and other crew members confidence in a safe return (nuclear submarine casualties have been related to seawater pipe failures, accidental torpedo detonations, and navigational errors, not problems with the nuclear plant). The only time I felt nervous was when we secured the nuclear plant and ran on diesel power to ensure that the diesel engine would function if the nuclear plant became inoperative, which never (in my experience or knowledge) ever happened.

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16. Fen Montaigne, “Water Pressure,” *National Geographic* (September 2002), vol. 202, no. 3, p. 29.

17. “Ethiopia: Ministers condemn Gibe III dam critics as Bank finalizes evaluation,” Web site en.afrik.com/article15536.html.

18. Russell Martin, *A Story That Stands Like a Dam* (Salt Lake City, UT: University of Utah Press, 1999).

19. World Health Organization Web site at www.who.int/ctd/schisto/index.html.

20. International Commission on Large Dams Web site www.icold-cigb.net.

21. Hydro-Québec Annual Report for 2009 Web site www. hydro. qc.ca.

22. All-rankings.com Web site www.all-rankings.com/rank.php?r=82c27c146b.

23. An example of the opposition to hydropower projects is Friends of the River Narmada Web site www.narmada.org. For a rebuttal, go to International Commission on Large Dams Web site www.icold-cigb.net.

24. The Independent Web site www.independent.co.uk/environment/nature/as-iraq-runs-dry-a-plague-of-snakes-is-unleashed-1705315.html and Campbell Robertson, “Iraq, a Land Between 2 Rivers, Suffers as One of Them Dwindles,” *New York Times* (July 14, 2009), p. A1; see also “Fertile Crescent will Disappear this Century” at Website www.newscientist.com/article/dn17517-fertile-crescent-will-disappear-this-century.html?DCMP=OTC-rss&nsref=climate-change.

25. Joshua Hammer, “The Dying of the Dead Sea,” *Smithsonian Magazine* (October 2005), vol. 36, no. 7, p. 58.