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The Prospects for Nuclear Energy

20.1 The Nuclear Debate

20.1.1 Nature of the Debate

Debates about nuclear energy have sometimes appeared to have the aspect of a religious war, especially in the 1970s and 1980s when an expanding nuclear enterprise came into conflict with a growing antinuclear movement. Nuclear energy was discussed as if it were intrinsically good or evil, and for many of the protagonists, it became instinctive to oppose or support it.

That debate has since become more muted. This does not mean that the basic issues are settled. Rather, it means that less attention is being paid to nuclear energy. Fossil fuel energy has been plentiful, energy problems are not at the center of the world's attention, and nuclear energy is not at the center of what consideration is given to energy. In discussions of U.S. energy policy, nuclear power is sometimes just ignored.

However, as discussed in Chapter 1, the world's heavy dependence on fossil fuels creates serious problems, and nuclear power can help in addressing them. So too, at least in principle, can a number of alternatives, but none of these can be fully counted on to serve as a large-scale source of additional energy. Each either is too limited in the scope of its potential expansion—as in the case of hydroelectric power—or lacks the proven ability to provide energy in the amounts that will be required. Some, particularly wind power, show promise (see Section 20.2.3), but it is premature to rely on wind or other alternatives to provide a sure solution. Under these circumstances, nuclear power remains a contender as a needed contributor to future energy supplies.

Ingredients in the decisions that will be made about the utilization of nuclear power include the following:

- The demand for energy—particularly energy in the form of electricity.
- The practicality and the environmental, economic, and national security implications of the alternative energy sources.
- The success that nuclear power has in avoiding reactor accidents, safely handling nuclear wastes, and reducing reactor construction costs.
- Assessments of the relationship between nuclear power and nuclear weapons and terrorism.

It is impossible to know how these considerations will play out. They raise technical and economic questions that are, in principle, resolvable. However, they also involve issues where the answers depend primarily on individual surmises and values and are perhaps impossible to resolve by "objective" analysis.

National policies toward nuclear energy evolve in part with advice from organizations, within and outside government, that study the issues in a somewhat neutral and technically oriented spirit and in part in response to pressures from groups and individuals with strong and often unyielding positions for or against nuclear power. There is also an element of chance in the political processes by which the policies are ultimately determined. Broadly speaking, "conservatives" tend to lean to the "pro-nuclear" side, whereas "liberals"—especially when allied with "greens" as in Germany—tend to lean against it. Nuclear power is rarely the central issue in elections, and political parties may gain power for reasons independent of nuclear or other energy considerations. Nonetheless, the electoral results may have—as an incidental effect—a crucial impact on energy policy.

Thus, in discussing the prospects of nuclear power, we face two major sources of uncertainty. We do not know how the alternative energy contenders will compare on technical, economic, and environmental grounds. We know even less how public and political attitudes will evolve. There are also differences among countries that sometimes have no clear explanation. It is easy to understand why Norway has no nuclear power while Sweden has employed it extensively. The answer lies in Norway's ample hydroelectric resources that have been providing over 99% of its electricity [1]. However, it is hard to find such straightforward explanations for Italy's abandoning of nuclear power while France was emphasizing it, or the difference between substantially nuclear Switzerland—which in 2003 referenda voted against giving up nuclear power—and nuclear-free Austria.

In the remainder of this chapter, we will discuss some of the factors that will influence the future development of nuclear power. However, at every turn, it will be necessary to recognize that there are large uncertainties on both the technical and political sides.

20.1.2 Internal Factors Impacting Nuclear Power

The future acceptability of nuclear energy, which we restrict to energy from nuclear fission here, will depend, in part, on internal factors—the strengths and weaknesses of nuclear power itself. Key factors are as follows:

- *Nuclear accidents.* The sine qua non for the acceptance of nuclear power is a long period of accident-free operation, worldwide. Any major nuclear accident will heighten fears of nuclear power and each decade of accident-free operation helps to alleviate them.
- *Reactor designs.* For nuclear power to be attractive, next-generation reactors must be manifestly safe and also must be economical to build. These could be either large evolutionary reactors, of the sort recently built in France, Japan, and South Korea, or smaller reactors that may be a better match to markets of modest size.
- *Waste disposal.* The completion of integrated and fully explained waste disposal plans would encourage people to believe that the problem is “solved.” In particular, smooth progress with the Yucca Mountain project would suggest that waste disposal problems are surmountable. However, for a large expansion of nuclear power, it will be necessary to demonstrate the ability to handle the wastes from many more years of reactor operation.
- *Resistance to proliferation and terrorism.* For nuclear power to be acceptable, its facilities must be well protected against terrorists and the nuclear fuel cycle must be proliferation resistant.
- *Assessments of radiation hazards.* Most professionals believe that public fears of radiation—and, in particular, radiation from nuclear power—are out of proportion to the actual risks. A more realistic understanding of the dangers would, in this view, lessen some of the opposition to nuclear power.

20.1.3 External Factors Impacting Nuclear Energy

Verdicts on the “internal factors” discussed earlier will be influenced by perceptions of need. Here, factors external to nuclear power determine the apparent need. These include the following:

- *Energy and electricity demand.* Economic expansion and population growth act to increase the demand for additional energy, including nuclear energy. Effective conservation measures reduce it.
- *Limitations on oil and gas resources.* The need for alternatives is enhanced if these resources are seen to be inadequate.
- *Global climate change.* If the increasing concentration of carbon dioxide in the atmosphere looms large in the public consciousness as an environmental threat, then the pressures to find alternatives to fossil fuels will intensify. Complicating the equation is the prospect of carbon sequestra-

tion, which, at least in principle, offers the possibility of "carbon-free" coal. (We will return briefly to this prospect in Section 20.2.2.)

- *Renewable energy.* The technical and economic feasibility of renewable sources and assessments of their environmental impacts are critical to judging the need for nuclear power.
- *Fusion energy.* If the hopes for fusion energy are fulfilled, the need for alternatives will be greatly lessened.

Some of these matters have already been discussed in Chapter 1. Others are discussed further in subsequent sections of this chapter.

An additional factor, which might be called "external," is that of government initiative. In principle, government decisions are shaped by a weighing of the internal and external factors cited earlier, and by the public's views on these issues. The public's attitude is decisive when the future of nuclear power becomes a referendum issue. However, a government can sometimes act on its own, resolving complexity with a decisive action. As alluded to earlier, the importance of the Green party to the governing coalition led to a decision to phase out nuclear power in Germany. The U.S. Congress, in this instance at the urging of the President, took critical action in favor of the Yucca Mountain project in 2002. These decisions were not inevitable. For example, a different U.S. administration might have put off indefinitely a decision on Yucca Mountain. Firm government leadership, obviously in autocratic states but also in democracies, can play a role in deciding the future of nuclear power—effectively determining by fiat how all the contributing factors should be balanced.

20.2 Options for Electricity Generation

20.2.1 Need for Additional Generating Capacity

The worldwide demand for electricity will almost certainly increase substantially in the coming decades. The increase will partly be driven by an expansion in conventional uses, as world population grows and the underdeveloped countries strive to raise their presently very low per capita use of electricity. It may also be driven by the expanded use of electricity in relatively new applications—such as the production of hydrogen and the desalination of water. The demand for electricity would also grow if fossil fuels are replaced by electrical power (from non-fossil-fuel sources) in heating and transportation.[1]

Successes in conservation may diminish the need for additional electricity but are unlikely to eliminate it. The amount of electricity that will be required—or wanted—cannot be projected with any certainty, but it appears

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[1] This has been contemplated for transportation using hydrogen as an intermediary, but it could, in part, be done directly, for example with electrified mass transportation.

probable that over the next 50 years, there will be a doubling or tripling in world electricity demand, with a still greater increase not excluded (see Section 20.3.1). However, although it is valuable to have a sense of scale, it is neither important nor possible to pin down an accurate estimate. With any plausible estimate, it is clear that a great deal of additional generating capacity will be needed to meet new demand and replace existing equipment.

The potential role of nuclear energy in providing the needed energy is considered in Section 20.3. As a prelude, in the remainder of this section, we review briefly the main alternative energy sources—particularly natural gas, coal with carbon sequestration, and renewable energy. These various sources, nuclear and non-nuclear, can be viewed either as competing options or as complementary ones.

20.2.2 Fossil Fuels with Low CO_2 Emissions

Natural Gas

The combustion of coal in electricity generation was responsible in 2001 for about one-third of the U.S. man-made CO_2 emissions (see Section 1.2.3). These emissions would be greatly reduced if natural gas were to be substituted for coal. There are two gains: (1) The CO_2 production using natural gas is about 56% of the production using coal, at the same thermal energy output (see Section 1.2.3). (2) Gas-fired combined-cycle combustion turbines can operate at a thermal efficiency of over 50%, compared to a typical efficiency of 33% for coal-fired steam plants today. Therefore, with modern natural gas plants, the CO_2 output per kilowatt-hour is less than 40% of what it is with standard coal-fired plants.

There are two major difficulties with this solution (as previously discussed in Section 1.2): (1) The carbon dioxide output is reduced but not eliminated, as it would be with nuclear or renewable sources;[2] and (2) the world supply of natural gas, at moderate prices, may prove to be too limited to sustain the contemplated expanded uses of natural gas—in particular, its use as a large-scale replacement for coal. Nonetheless, whether or not switching from coal to natural gas can provide a major long-term solution, it has already been helpful in some countries. For example, total CO_2 emissions in the United Kingdom have dropped in the past decade largely due to a switch from coal to North Sea natural gas [2].

Sequestration of Carbon Dioxide

The reduction of carbon dioxide production would be less of a priority were it possible to sequester the carbon dioxide after it is produced (i.e., to capture

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[2] It is often pointed out that fossil fuel energy is used in constructing the non-fossil-generating facilities. However, at most, this is a small "correction."

it before it enters the atmosphere and permanently dispose of it in a secure location). The amounts involved are large. For each GWyr of coal-fired electric power, there is a release of about 8.5 million tonnes of CO_2, or, in the units that are commonly used, 2.3 million tonnes of carbon. For the year 2002, U.S. electricity generation from coal amounted to 220 GWyr, corresponding to over 0.5 gigatonnes of C (GtC) and almost 2 Gt of CO_2.

One possibility for storing this CO_2 is to capture it at the generating plant and move it in pipelines to locations where it can be pumped underground. Sam Holloway, of the British Geological Survey, suggested in a review of underground sequestration that the volume of caverns or mines is insufficient to handle the amounts of CO_2 that are produced, but that there is a larger capacity in porous sedimentary rocks or "reservoir rocks" [3, p. 149]. The CO_2 can be injected by pumping it into wells drilled in the rock. The CO_2 then permeates the rock, where it displaces some of the water that is commonly present. For deep rocks, this water is usually saline and the formations are termed saline water aquifers. At high temperatures and pressures (above 31.1°C and 72 atm), CO_2 becomes a supercritical fluid with a specific gravity of 0.2–0.9. This condition can be reached deep underground. Even at the low end of this range, the density is more than 100 times that of gaseous CO_2 (at standard temperature and pressure), greatly reducing the required storage volume [3, p. 151].

The total holding capacity of the potential sites for CO_2 is not well established. The global capacity has been estimated by Ted Parson and David Keith to be approximately 200–500 GtC for depleted oil and gas reservoirs, 100–300 GtC for deep coal beds, and 100–1000 GtC for deep saline aquifers [4]. World CO_2 production from fossil fuel combustion is now about 6.6 GtC/yr [2, p. 234], so the capacity might suffice for many years. However, more experience and study are needed to judge the difficulties of large-scale extraction, transportation, and storage of CO_2, as well as to gauge storage capacity.

There is already some experience with both pipeline transport of CO_2 and small-scale sequestration. For example, at the Sleipner West natural gas field in Norwegian North Sea waters, substantial amounts of CO_2 are extracted from the natural gas—which otherwise is mostly methane. This waste CO_2 is injected into sandstone below the seabed.[3] Holloway concludes that this formation "appears to be an excellent repository for CO_2" [3, p. 156]. However, it is only receiving 1 million tonnes of CO_2 per year, which is about one-eighth the output from 1 GWyr of coal plant operation.

An alternative to injecting CO_2 into the ground is pumping it into the deep ocean. The natural content of inorganic carbon in the ocean is about 40,000 GtC, primarily in the form of carbonic acid (H_2CO_3) and bicarbonate and carbonate ions (HCO_3^- and CO_3^{2-}) [5, p. 178]. The injection of several billion

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[3] This experience illustrates the efficacy of a "carbon tax." When this sequestering project was inaugurated in 1996, Norway had a carbon tax of $170/tonne of carbon and the project was a response to the tax [4].

tonnes of CO_2 annually would not change the total carbon content of the ocean appreciably, although the local concentrations will be increased near the points of injection. The CO_2 may be injected from pipelines extending from the shore or from tankers carrying liquified CO_2 [6, p. 3–4]. Locally, the water would become more acidic. Further research is needed to explore both injection techniques and environmental impacts.

It may also be possible to convert the CO_2 into a solid, e.g., calcium bicarbonate [$Ca(HCO_3)_2$] or magnesium carbonate ($MgCO_3$). Klaus Lackner suggests that with this approach, the CO_2 would be sequestered "safely and permanently" in a form that requires less volume than is needed in the other various burial approaches [7]. Conversion to solid form would, in principle, make possible the handling of vast amounts of CO_2.

Sequestration would be most practical where the source of the CO_2 is localized, as in a power plant. It has the attraction of offering a possible way to exploit the very large resources of coal that are available and the possibly large resources of natural gas. However, at best, assuming that it proves practical, it is a clumsy approach, requiring the handling of enormous amounts of material. The eventual cost of large-scale carbon sequestration is not well known, but estimates are in the rough neighborhood of \$100/tonne of carbon, with an apparent uncertainty of more than a factor of 2 [3, 4]. A cost of \$100/tonne corresponds to 2.7¢/kWh for a coal-fired power plant. This would not be a prohibitive cost if there were no alternatives, but would be a significant penalty in a competitive market.

An adequate evaluation of the potential role of sequestration cannot be made without further investigation of the economic costs and environmental impacts, including consideration of the long-term stability of the storage under normal and abnormal (e.g., an earthquake) conditions. As a step toward testing the potential of sequestration in the context of electricity generation, the U.S. Secretary of Energy announced in February 2003 a one-billion-dollar plan to build a prototype coal-fired plant that would produce hydrogen and generate 275 MWe of electricity [8]. The plan calls for the sequestering of over 90% of the CO_2 produced by the plant. This project was expected to take about 10 years to design, construct, and evaluate.

20.2.3 Renewable Sources

Overview of Renewable Sources

In principle, renewable energy sources offer an alternative that avoids the CO_2 produced by fossil fuels and the radionuclides produced by nuclear power. The terms "renewable energy" and "solar energy" are sometimes used interchangeably, but renewable energy includes the nonsolar sources of tidal and geothermal power. Tidal power ultimately is based on gravitational forces, with the tides arising from the motions of the Earth and Moon. Geothermal power is ultimately derived from the decay of long-lived radionuclides in the interior of the Earth. These are nonsolar, renewable sources. However, although both have been used to some extent, especially geothermal power, neither appears to be a leading candidate for a major expansion.

Solar energy sources are both direct and indirect. Direct sources, in which sunlight is converted to energy with no intermediary, include photovoltaic devices, systems for heating fluids with focused light to generate electricity, and growth of biomass to use as a fuel. Indirect sources include hydroelectric power, where solar energy evaporates water that eventually returns as rain, and wind power where solar energy heats the atmosphere to produce air currents.

Direct Use of Solar Energy

All direct uses of solar energy for electricity generation suffer from the "dilute" nature of the solar source. The average flux of solar energy at the surface of the Earth is about 200 W/m^2. Thus, it requires about 5 km^2 to collect 1 GW of incident solar energy. The area required for electricity generation depends on the efficiency of conversion from solar energy to electricity.

One potential source of electricity is biomass, used as a fuel in a steam turbine plant. The main source of biomass now used in electricity generation is wastes, including wastes from the forest product industry. However, the amounts of such wastes are limited. A major increase in biomass use for electricity generation would require dedicated biomass plantations and adequate supplies of water and fertilizer. As estimated by David Hall and colleagues, the "practical maximum yields" of biomass in temperate climates corresponds to an annual average efficiency of about 1% for conversion from solar energy to chemical energy in the plants [9, p. 600]. The thermal efficiency for biomass combustion is unlikely to reach the 33% efficiency achieved for coal, and some of the plantation area must be used for nonproductive purposes such as roads. Thus, an optimistic estimate—probably unrealistically optimistic—of the area required for biomass production of electricity is 2000 km^2/GWe. More typical estimates are roughly a factor of 2 higher, and some are still higher.[4] In any estimate, however, the demands on land and water are high.

Solar photovoltaic power is suitable for use in remote locations, but, at present, it is too expensive to be a candidate for supplying large amounts of power to the electric grid. If the cost is eventually reduced to an acceptable level, the land requirement would be substantial, but much less than for

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[4] For example, an estimate made by Eric Larson for a large plantation in Brazil assumes a yield of 1000 dry tonnes of biomass/km^2, 20 GJ/tonne, and a 60% use of land. This corresponds to 1.2×10^{13} J/km^2 of thermal energy per year or an average electric output of about 0.12 MWe/km^2, which translates to 8000 km^2/GWe [10, p. 579]. In *Global Energy Perspectives*, projections of future biomass energy yields of 4–10 toe (tonnes oil equivalent) per hectare are indicated, corresponding to roughly 2000–6000 km^2/GWe at a 33% thermal conversion efficiency [11, p. 82].

biomass. It would depend on the solar flux at the site chosen, the efficiency of the photovoltaic cells and associated electronics, the orientation of the solar panels with respect to the sun (including possible tracking of the sun), and the fraction of the land occupied by the panels. If one assumes an overall module efficiency (i.e., for conversion of sunlight to usable electricity) of 10%, an average solar flux of 250 W/m^2, and a 50% coverage of the ground by the solar modules, then the area required would be 80 km^2/GWe. This is only a crude, order-of-magnitude estimate and future systems may be more efficient. However, this may not be an appropriate way of looking at the matter. For the near future, solar photovoltaics are most likely to be used in niche markets, extending down to arrays as small as rooftop modules for individual homes, rather than in very large arrays. Thus, the area occupied may not be an immediate concern.

Neither of these direct sources, or other less conspicuous candidates, should be excluded from consideration, but among renewable sources of electrical power, they at present appear less promising than wind (see later subsection). This is reflected in the differences in the rates at which new facilities are being installed.

Hydroelectric Power

Hydroelectric power is the most important renewable energy source, and it dominates the renewable contribution to electric power generation. It has played an important role in many countries, including the United States, where in the past it accounted for a large share of all electricity generation (e.g., 32% in 1949 [12]). Some major new hydroelectric dams are still being developed, notably China's project on the Yangtze River, which is expected to provide an annual output of about 10 GWyr. However, the most desirable sites throughout the world have been exploited and there is an increasing awareness of the negative impacts of the displacement of people and the interruption of natural stream flows. In fact, in the United States, it appears that there is more interest in removing dams that interfere with the migration of fish than in building new ones. Hydropower provided 7% of U. S. electricity in 2002, and although the amounts vary somewhat from year to year with water conditions, it appears unlikely that hydroelectric capacity will be significantly increased in the United States or that it could make a major contribution to meeting the world's need for additional energy sources.

Wind Power

Wind is a rapidly growing source of electricity in some countries, particularly in Denmark, and the available resource is large. For the OECD as a whole, wind energy output rose from 0.5 GWyr in 1992 to 3.9 GWyr in 2001, an average rate of increase of 25% per year [1]. Some studies indicate that the wind resources in the United States are adequate to produce more electricity than is generated today from all sources.[5] However, wind still makes only a very small contribution in most of the world—0.3% of U.S. electricity generation in 2002 and 0.4% of generation in all OECD countries in 2001 (see Table 1.2). Its exploitation was originally impeded by growing pains in developing reliable and economically competitive wind turbines, and it still faces some environmental objections and the problem of the intermittency of a wind-dependent output.

The power delivered by a wind turbine is proportional to the area swept out by the turbine and the cube of the wind speed.[6] The power varies as the wind speed varies, sometimes dropping to zero. The capacity factor is the ratio of the actual output over the year to the output were the turbine to operate continuously at its rated power. Typical values are in the range of 30% to 40%.

A sense of scale can be obtained by considering a specific example of a large turbine that might be placed in the upper Midwest, where there are extensive areas with favorable wind conditions—in particular, a 1500-kW unit, with a rotor diameter (i.e., a turbine blade diameter) of 77 m [14]. For this case, the indicated capacity factor is about 0.38 and the annual output is about 0.57 MWyr. In the envisaged arrangement, there would be an array of these turbines with about six turbines per square kilometer.[7] To provide 1 GWyr of power each year would require about 1750 turbines, each with blades extending to about 90 m above the ground and occupying almost 300 km^2 in all.[8] Only a small fraction of this area is preempted by the turbine facilities themselves, and most of it is available for farming or grazing.

Wind power appears to have considerable promise, but until it grows further it may not be possible to have a good picture of its actual potential or of possible difficulties that might be created by a truly large-scale exploitation

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[5] For example, a study at the Pacific Northwest Laboratories indicates that with "moderate exclusions" on the land that can be used, and using winds of "class 4" and higher, the annual potential is about 630 GWyr [13]. This is roughly 40% more than total U.S. generation in 2002.

[6] The so-called power in the wind P_W equals the product of the volume of air passing through the turbine area per second (Av) and the kinetic energy carried per unit volume ($\rho v^2/2$), where A is the area swept out by the turbines and ρ is the density of air. (It is assumed that the turbine is properly oriented to face the wind.) Thus, $P_W = \rho A v^3/2$. The power output of the turbine can be expressed as $P = C_p P_W$, where C_p is the *coefficient of performance*. Its theoretical limit, known as the *Betz limit*, is $C_P = 16/27 = 0.593$; actual systems reach about 0.4.

[7] The contemplated arrangement would have staggered rows of turbines with a spacing of $7d$ within a row and of $4d$ between rows, where d is the rotor diameter [15]. Thus, each turbine would require an area of $28d^2$, or 0.166 km^2.

[8] This estimate corresponds to about 0.11 km^2/MWe of capacity, which falls in the middle of the range suggested in a recent review article of 0.04–0.32 km^2/MWe [16, p. 166].

of wind resources. One obvious problem is that of intermittency. In addition, there is conflict between those who value it as a clean resource and those who consider it a visual blight, especially in otherwise scenic off-shore locations, and too noisy.

20.2.4 Fusion

Fusion energy is, in principle, a long-term alternative to fission energy and renewable energy. In the long run, success in developing fusion would have profound effects on the need for the other options. However, as suggested in the brief discussion in Section 16.7.1, it is too soon to base energy planning on any specific timetable for the successful deployment of fusion, or even to say with absolute confidence that it will become an important energy source in a predictable future.

20.3 Possible Expansion of Nuclear Power

20.3.1 Projection of Demand

Demand for Electricity

In planning for electricity growth, the time horizon is on the scale of decades, and the year 2050 has been selected in some recent publications as a target date for estimates. Such projections, although highly speculative, are useful in suggesting the scale of efforts required to meet future demand.

A number of different scenarios were analyzed in a joint study by the World Energy Council (WEC) and the Institute for Applied Systems Analysis (IIASA). The estimates for world electricity generation in 2050 range from about 2600 GWyr to 4800 GWyr, corresponding to about 155% to 285% of the generation in 2000 [11, p. 88]. The higher projection is described as corresponding to a scenario with “ambitiously high rates of economic growth and technological progress” [11, p. 7], although its average annual electricity growth from 2000 to 2050 (2.1%) is well below the rate of the previous 20 years (3.1%). The lower projection is for an “ecologically driven” scenario with “incentives to encourage energy producers and consumers to utilize energy more efficiently” [11, p. 9a]. It is described as a “normative” or “prescriptive” scenario, rather than a predictive one. In the “middle course,” or the case deemed most likely in this family of scenarios, the electricity generation in 2050 is 3500 GWyr, corresponding to an average annual growth of 1.5% from 2000 to 2050.

The WEC/IIASA scenarios all give growth rates that are more conservative than those of the U.S. DOE, which projects in its “reference case” an annual average increase of 2.7% per year in world electricity consumption from 1999 to 2020 [17, p. 188]. Were this growth rate to continue until 2050, it would mean almost a quadrupling of electricity consumption from 2000 to 2050.

These several scenarios suggest that there is likely to be a doubling (1.4% per year) or tripling (2.2% per year) in global electricity demand from 2000 to 2050, although the increase could be substantially more or somewhat less.

Conservation

Conservation, especially in the form of higher efficiency in energy use, can reduce the demand for electricity. It has already contributed importantly through the introduction of more efficient lighting, refrigeration, and motors. Further exploitation of efficient technologies can make major additional contributions. However, conservation measures are already presumed in the scenarios discussed above. For example, the WEC/IIASA scenarios assume for the OECD countries improvements in energy intensity [i.e., decreases in the ratio of primary energy to Gross Domestic Product (GDP)] averaging 1.1% per year in the two higher growth scenarios and 1.9% per year in the low-growth case [11, p. 36].[9]

Demand for Nuclear Power

Given the uncertainties in the world demand for electricity and the even greater uncertainties in the future acceptance of nuclear power, any estimate of nuclear power use in 2050 is highly speculative. However, we consider here several estimates for 2050 that suggest the possible scale of nuclear capacity and generation if there is to be a "large" expansion of nuclear power:

- In the highest of the WEC/IIASA projections discussed earlier, annual electricity generation in 2050 was projected to be 4800 GWyr. If we arbitrarily assume that nuclear power provides one-half of this, then annual nuclear generation would be 2400 GWyr.
- William Sailor and colleagues projected an annual nuclear output of 3300 GWyr in a scenario designed to stabilize CO_2 emissions at twice the preindustrial level [18].
- Harold Feiveson, in pointing to the proliferation dangers raised by a "robust" nuclear expansion, took 3000 GWe in 2050 as a benchmark for what would be necessary to "make a dent in global warming" [19]. At a capacity factor of 90%, this would mean an annual nuclear output of 2700 GWyr.

For specificity in the following discussion, we will use the last of these estimates, which lies between the other two: a nuclear capacity of 3000 GWe and an output of 2700 GWyr. Of course, a nuclear capacity of anything from

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[9] Data are reported only for the overall improvement in energy intensity, without a separate indication for electricity.

1000 to 5000 GWe would be a major expansion above the present world level of about 360 GWe.

If nuclear electricity supplies one-half of the total, then electricity generation from all sources would be at an annual rate of 5400 GWyr. This exceeds the higher of the WEC/IIASA projections cited earlier, but it would still not provide lavish electricity supplies. At this rate, world electricity use (for an assumed population of 9 billion) would be at a per capita rate of 0.6 kWyr/yr (i.e., consumption at a rate of 0.6 kWe per person). This is approximately twice the present world rate, two-thirds of the present average OECD rate, and 40% of the present U.S. rate [1, 2].

For the United States, which already uses electricity at a rate much above the world average, we will assume that total electricity generation rises in step with population, from 434 GWyr in 2000 to about 650 GWyr in 2050 (an average increase of 0.8% per year).[10] Assuming again a 50% contribution from nuclear power, this would mean an output of 325 GWyr or a U.S. capacity of about 360 GWe.

The speculative nature of any such number should be emphasized. The actual electricity consumption will depend on end-use efficiency improvements and, as suggested earlier, possibly expanded use in a variety of applications, including electronic equipment, building and industrial heating, mass transportation, hydrogen production, and desalination of ocean water. If we look backward and note that U.S. electricity use rose 12-fold from 1950 to 2000 (greatly outstripping the population growth), the 50% rise contemplated here for the next 50 years is a modest projection. The specification of a 50% share for nuclear power is in no sense a prediction. It does, however, identify a target to consider in judging what sort of expansion might be achievable.

Possible Additional Applications

The preceding discussions have mentioned the possible expanded use of nuclear energy in two important applications, namely the production of hydrogen and the desalinization of seawater. Each addresses limitations in the availability of a key resource. Hydrogen is a potential substitute for oil in transportation and desalinization offers a remedy for regional scarcities of water. They are discussed in the immediately following subsections.

In each application, depending upon the method used, the main energy input can be in the form of either electricity or heat and can be derived from either nuclear or non-nuclear sources. The nuclear community has shown considerable interest in these possibilities, as illustrated, for example, by a meeting on *Nuclear Production of Hydrogen* organized by the Nuclear Energy Agency of the OECD [21] and a report on *Introduction to Nuclear Desalinization,*

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[10] A "fairly constant" population growth rate of 0.8% per year for 2001–2025 was projected in the U.S. DOE's *Annual Energy Outlook 2003* [20, p. 50], and here we arbitrarily project the same growth rate to 2050.

A Guidebook published by the International Atomic Energy Agency [22]. If either application is implemented on a large scale, the demand for electricity and nuclear energy could be substantially increased.

20.3.2 Production of Hydrogen

Methods of Hydrogen Production

Hydrogen is sometimes referred to as the energy source of the future. This is a misnomer, or at least misleading. Hydrogen is not a fundamental energy source, in that there is very little hydrogen on Earth in a pure elemental form. Most of the hydrogen is trapped in water (H_2O) or in hydrocarbons, and energy must be provided to produce it in elemental form.

Once produced, hydrogen has the advantage of having a very high heat of combustion per unit mass: 142 megajoules per kilogram (MJ/kg) for molecular hydrogen (H_2) compared to 46 MJ/kg for gasoline and 55.5 MJ/kg for methane (the main ingredient of natural gas). On the other hand, it has the disadvantage of being a gas except at extremely low temperatures, with a density that is one-eighth that of methane (at the same temperature and pressure) and therefore a lower energy content per unit volume.

Hydrogen is now used in large amounts in the chemical industry [e.g., in the production of ammonia (NH_3) and in oil refining] [23, p. 232]. Its most interesting large-scale prospective use is as an automotive fuel (see the following subsection). The main means of producing hydrogen today is the steam reforming of methane. In this process, steam (H_2O) and methane (CH_4) combine to form carbon monoxide (CO) and hydrogen (H_2), and the carbon monoxide combines with water to form carbon dioxide and more hydrogen. The net reaction is

$$CH_4 + 2H_2O \rightarrow CO_2 + 4H_2.$$

Any process based on fossil fuels has the disadvantage of producing CO_2, although this environmental liability, in principle, could be addressed by sequestering the CO_2.

The simplest alternative to producing hydrogen from methane (or coal) is electrolysis of water, a process in which the water is dissociated into hydrogen and oxygen. Although practical, this method is relatively expensive in energy. The efficiency of electrolysis systems is indicated by Joan Ogden to be about 70–85% [23]. If electricity for electrolysis is generated at, say, 40% efficiency, this corresponds to a system efficiency of about 30% in going from the original fuel to hydrogen.

Greater efficiency is provided by a wide range of thermochemical cycles that use water as the only feedstock and produce hydrogen and oxygen as the end products. They consume less energy than electrolysis for the same hydrogen output. One possible thermochemical cycle is the I–S process which uses sulfuric acid (H_2SO_4) and hydrogen iodide (HI) in a cycle in which each neither is ultimately consumed and in which the net reaction is just the breakup of water into hydrogen and oxygen (see, e.g., Ref. [21]):

$$H_2O \rightarrow H_2 + (1/2)O_2.$$

The I–S cycle is not the only possible choice, but it appears to now be a favored one.[11] One limitation is that it requires a temperature of at least 800°C and operates more efficiently at still higher temperatures.

One of the Generation IV reactors now under consideration is particularly intended for the production of hydrogen: the Very-High-Temperature-Reactor (VHTR) (see Section 16.6.2). The estimated production capacity of a 600-MWt plant is over 2 million normal m^3 per day [25, p. 54].[12] This is equivalent to roughly 26 million MJ per day or 300 MW in the form of hydrogen fuel, corresponding to a 50% efficiency for the conversion of the reactor's thermal energy.

When there is a poor overlap between the time the electricity is produced and the time when it is needed, hydrogen production can help to address the mismatch. Thus, for nuclear reactors, which are most effectively used as base-load sources that always run at peak capacity, the output could be used for hydrogen production (probably by electrolysis for most reactors) when the demand is low—typically at night. Renewable sources such as wind and solar photovoltaic power are inherently intermittent. Again, hydrogen can be produced when there is excess output. The hydrogen then serves as an energy storage medium, for use in electricity generation or for other purposes.

The DOE included in its FY2004 budget proposal, issued in January 2003, $4 million to inaugurate a new Nuclear Hydrogen Initiative, intended to study the use of nuclear energy to produce hydrogen. A focus will be R&D on thermochemical cycles at high temperatures [26, p. 87–89]. If this program moves forward, it may lead to the construction of a VHTR at the Idaho National Engineering and Environmental Laboratory. In undertaking this initiative, the DOE is not abandoning the investigation of other approaches to hydrogen production. It is a much smaller initial commitment than the coal-based initiative announced in February 2003 (see Section 20.2.2). There are also possibilities for producing hydrogen using renewable energy sources. Therefore, although nuclear power may be used in the future to produce hydrogen, there are many competitors. If nuclear power is used, it may be to provide heat rather than electricity.

Hydrogen as a Fuel

A major attraction of hydrogen as a fuel is its cleanliness: Combustion of hydrogen leaves no "waste product" other than water (H_2O). As such, it has

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[11] An earlier review (1976) listed nine such cycles, although it did not include the I–S cycle [24, p. 287].

[12] 1 normal m^3 (Nm^3) has a mass of 0.090 kg and a combustion energy of 12.8 MJ.

been urged as an automotive fuel in vehicles powered by hydrogen fuel cells, as well as a source of electricity or heat for the home (see, e.g., Ref. [27]). The use in cars has attracted particular interest. If hydrogen could replace gasoline as the fuel to drive cars, it would both reduce the world's dependence on petroleum and eliminate cars as a source of pollution.

The enthusiasm shown by the federal government for the "FreedomCAR" initiative to develop vehicles powered by fuel cells led to the formation of a committee within the American Physical Society (APS) to "examine what is reality and what is unsupported optimism" [28]. The study concluded that for the initiative to be successful, it will be necessary to have large reductions in the costs of fuel cells and to solve the problem of hydrogen storage on vehicles. For storage, it suggested the most likely method will be compressed gas, at perhaps a pressure of 700 atm, although other methods may also prove practical.

One of the concerns that the report addressed, if only briefly, is that of safety. It cited a number of tests that suggested that "H_2 is, if anything, safer than gasoline or jet fuel" [28, p. 21]. Hydrogen is helped in this regard by its lightness, which causes it to dissipate quickly if released. Part of hydrogen's bad reputation derives from the Hindenburg accident in 1937, when the hydrogen-filled German dirigible was destroyed in a spectacular fire as it was about to land at the beginning of a visit to the United States (in New Jersey). Recent studies appear to clear hydrogen of the blame for the fire and instead implicate an "extremely flammable" paint used on the dirigible's skin.

The end-use energy efficiency of the hydrogen fuel cell is more than twice that of a gasoline-driven car. The APS study indicated that a hypothesized hydrogen fuel cell vehicle would use energy at a rate equivalent to 82 miles per gallon (mpg) of gasoline, whereas the rate with a gasoline engine (in the "probable" case) would be 38 mpg—presumably with other changes in the car's design to improve its "mileage." This is an increase in *end-use* efficiency. If the energy efficiency of hydrogen production is 30%, as it might be with electrolysis, the hydrogen advantage disappears when gauged in terms of primary energy input. However, the use of hydrogen is not motivated by the prospect of efficiency gains. It is motivated by the desire to replace oil as a primary energy input. If the hydrogen is made from natural gas rather than nuclear power—as is likely to continue to be the case for at least the near future—there would be a reduction in primary energy use, at the expense of some CO_2 emissions (albeit less than with a gasoline engine) and a possible strain on natural gas supplies.

Gasoline consumption at the rate of 82 mpg corresponds to an end-use energy of 1.60 MJ per mile.[13] Providing electricity to produce hydrogen for motor vehicles would require a substantial increase in generating capacity. Total motor gasoline demand in the United States is about 8.7 million barrels per day, corresponding to an energy of about 17 EJ per year [12, p. 152]. Considering the hypothesized "82-mpg" hydrogen car rather than today's av-

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[13] The heat content of gasoline is 5.21 MBTU per barrel or 131 MJ/gallon [29].

erage 22-mpg car, the energy requirement is reduced to about 4.7 EJ in the form of hydrogen. An annual electrical input of about 200 GWyr would be needed to produce this hydrogen by electrolysis at an electricity-to-hydrogen energy conversion efficiency of 75%. For comparison, one can note that total U.S. petroleum product use in 2002 averaged 19.3 million barrels per day and electricity generation totaled 438 GWyr. Thus, the substitution (using electrolysis) would involve a reduction in petroleum consumption of about 45% and an increase in electricity generation of about 45%. If the electricity is provided by nuclear reactors it would be necessary to more than triple the present nuclear capacity. If a thermochemical cycle is used instead of electrolysis, the demand for nuclear energy would be somewhat reduced.

For this hypothetical scenario to materialize, it will be necessary not only to solve problems of fuel cell costs and hydrogen storage but also to develop economical and reliable cars to use the fuel cells and to develop a distribution infrastructure analogous to that provided by present-day gasoline filling stations. Some test hydrogen fuel cell vehicles have been built [30, p. 316] and a number of long-distance pipelines have been in use for several decades carrying hydrogen at high pressure [23, p. 248], but establishing such an infrastructure would be a formidable challenge.

Despite the seeming attractiveness of this hydrogen scenario as a project for the future, for the near term the most effective way to reduce gasoline consumption is to build vehicles that are more fuel efficient than those in the present automobile and truck fleet (for example, by reducing weight and using hybrid gasoline–electric engines). Replacing the present passenger car fleet with 45-mpg cars, without changing fuels, would cut gasoline consumption in half. However, for the long run, if it can be achieved, the ultimate rewards of a hydrogen-based program to displace gasoline would be great—whether the hydrogen is produced with nuclear or renewable sources.

An even more ambitious hydrogen scenario has been envisaged by Chauncey Starr, who has suggested a “Continental SuperGrid” that would make possible an energy economy based on hydrogen and nuclear energy [31]. In this picture, nuclear plants would be used to produce electricity and hydrogen. Both would be transmitted throughout the country in pipes that would carry liquid hydrogen in an inner pipe and electricity in a surrounding superconductor. The liquid hydrogen would both cool the superconductor and serve as a fuel when extracted from the pipeline system. This version of a hydrogen economy is put forth as a project for the 21st century, not for the next decade or two. Nonetheless, work today on suitable nuclear reactors and on superconducting cables would help to test the practicality of the concept and, to the extent it is practical, to help launch it.

20.3.3 Desalination of Seawater

Many parts of the world are faced with water shortages, as populations and standards of living rise and groundwater resources are depleted. Desalination of seawater offers a solution that is being increasingly employed. An IAEA document published in 2000 reported that in 1997 there were about 12,500 desalination plants in the world operating or under construction, with capacities ranging from the very small to over 400,000 m^3 per day [22, Section 2.4].[14] Total world capacity was given as 23 million m^3 per day. There is steady growth in this output, and a capacity of about 38 million m^3 per day for 2010 has been projected in another IAEA paper [32]. Even this output, however, would be less than 0.5% of total world water withdrawal, so desalination is still of local rather than global importance [33, p. 374]. The largest facilities are in Saudi Arabia, but plants exist in many other countries, including the United States.

The main techniques for desalination are distillation, which requires mostly heat energy, and reverse osmosis, which requires mostly electrical energy to drive pumps. Reverse osmosis is the least costly approach. The production of 1 m^3 of water in large-scale reverse-osmosis plants is estimated to cost about \$1 and require about 6 kWh of electricity [22, pp. 64 and 154–155]. To get a sense of scale as to the implications of these costs, we can consider a hypothetical example given in a summary of IAEA nuclear desalination studies [34]. A 300-MWe plant (which would generate 6.1 million kWh per day at an 85% capacity factor) would be used to supply 1 million m^3 of water per day to a population of 3–4 million people. This corresponds to a per capita supply of about 0.3 m^3 (80 gal) per day or a little over 100 m^3 per year, at a cost of about \$100 per person per year.

For comparison, it may be noted that the average annual per capita consumption of water for household purposes in the 1980s was estimated to be about 260 m^3 in the United States, 94 m^3 in Europe, and 30 m^3 in China [33, Table H1]. Household use of water is small compared to the use in industry and agriculture, and to provide the full water needs of a country, the household use numbers should be multiplied by a factor that typically would be between 5 and 20.

At these rates of water use and cost, desalination provides an expensive way to obtain water, but—as seen by its growing use—not a prohibitively expensive one. It would be “affordable” in the United States in regions of water shortages, especially if the high prices led to reductions in the use rates. Total U.S. water use is about 2000 m^3 per year per person (mostly for agriculture), or about 6×10^{11} m^3 for the entire country. If 10% of this water were to be eventually supplied by desalination—to take an arbitrary number for purposes of illustration—this would require about 40 GWyr of electrical energy. This would be a significant increment to electricity demand, but still a modest one compared to potential other sources of increased electricity use.

Worldwide, there may be something of a mismatch at present between nuclear power and desalination. The need for desalination is now greatest in countries of the Middle East, where oil and gas are unusually plentiful, and in underdeveloped regions, where nuclear generation would probably not be

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[14] 1 cubic meter = 264 U.S. gallons.

affordable and where the amount of water locally needed is small compared to the potential output using nuclear power. However, it is not necessary to think in terms of large, dedicated nuclear reactors providing electricity for desalination alone. The waste heat from nuclear (or other) power plants could be used for distillation processes. Alternatively, for reverse osmosis, electricity could be obtained as part of the output of a general-purpose plant.

Some specifically nuclear desalination facilities have been in operation and others are being undertaken. The largest facility was in Kazakhstan, where some of the power from a 135-MWe breeder reactor (since shut down) was used to produce 80,000 m^3 of potable water per day [35]. A demonstration desalination facility is being installed at a heavy water reactor at Kalpakkam, India that will produce 6300 m^3 per day [32]. In Japan, desalination facilities supply fresh water for use at 10 reactors in amounts of 1000–3000 m^3 per day [35]. In a different variant, the possibility has been explored by Russia and China of small reactors for desalination that would be mounted on barges and which could presumably be moved where needed [22, p. 46].

To date, desalination has made only a relatively small contribution to water supplies, and the nuclear energy desalination projects are to be viewed more as demonstrations of feasibility than as significant producers. For the longer run, however, desalination is likely to be more extensively exploited as a means of providing fresh water. Adequate energy resources are the key to making this possible, and nuclear energy could provide part of this energy in some countries.

20.3.4 Possible Difficulties in Nuclear Expansion

The Pace of Reactor Construction

An expansion to 3000 GWe of nuclear capacity in 2050 may seem a very ambitious goal, especially when at present there is little reactor construction in the world. For a future world population of 9 billion people, the hypothesized per capita nuclear output would correspond to about 40% that of France in 2000. Most of the French increase in nuclear generation occurred in a 20-year period starting in about 1977. It should be possible for the world to achieve less than one-half the present French per capita nuclear output in twice the time (say, from 2010 to 2050), given the conviction that the goal is desirable and if adequate resources are dedicated to the task.

The comparison to France can also be considered in terms of the size of the economies involved, rather than population. World Gross Domestic Product (GDP) in the year 2020 is estimated to reach about 60 trillion dollars (in 1997 U.S. dollars) and the 1990 French GDP was 1.3 trillion dollars [17, Table A3]. This would make the world economy almost 50 times the size of the French economy, each taken somewhere in the middle of expansion. A target of 3000 GWe of nuclear capacity is 48 times the present French nuclear capacity of 63 GWe. Thus, the suggested world expansion is about the same as the French expansion, if normalized to the size of the respective economies. It would appear achievable in 40 years, which is twice the time of the French expansion.

In the above discussion, it was hypothesized that U.S. nuclear capacity might be about 360 GWe in 2050. This would mean an average addition of about 9 GWe of new capacity per year for 40 years—a plausible target for a revived nuclear industry.[15] It may be too conservative a target, given that it is based on a projected rate of rise in electricity consumption of less than 1% per year, or too high a target in that it assumes the nuclear fraction of electricity generation rises from 20% to 50% of the total. However, it provides a sense of scale.

Uranium Resources

An immediate concern in contemplating such an expansion is the uranium supply. World uranium resources were estimated in Section 9.5.2 to be about 20 million tonnes, enough for 100,000 GWyr of reactor operation for present reactors. This would suffice to sustain a linear buildup to 2700 GWyr in 2050 and roughly another 15 years of continued operation. However, it would make little sense to bring reactors on line in 2050 that would run out of fuel in 2065.

The hypothesized expansion could be sustained, however, if greater land resources of uranium are found at acceptable costs, if it proves practical to extract uranium from seawater, if thorium resources are exploited, or if fuel cycles are adopted that make more effective use of uranium. The most uranium-efficient fuel cycle is the breeder cycle. The prospect of breeders elicits enthusiasm in some circles, because it offers a virtually unlimited energy source. It raises concern in others, because it may allow more ready access to plutonium for nuclear weapons. A decision on breeder reactors could be deferred for a long period of time, even if a substantial nuclear expansion begins (see Section 9.5.4). However, ultimately it is an important, high stakes decision.

Nuclear Wastes

The nuclear waste problem can be considered in the context of the U.S. experience. The Yucca Mountain repository has a planned capacity of 70,000 metric tons of heavy metal (MTHM). Typical spent fuel output is now about 30 MTHM/GWyr. The contemplated expansion to an annual 325 GWyr would mean, were there no changes in reactor performance, a U.S. spent fuel output of about 10,000 MTHM per year. Thus, one Yucca Mountain scale repository would be needed every 7 years. However, future reactors may have twice the

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[15] We assume that all of today's reactors would reach the end of their operating lifetimes by 2050.

burnup, in which case the mass of spent fuel would be halved.[16] In that case, the radioactivity and heat output per unit mass will increase and it may be desirable to have a longer period of predisposal cooling, either in on-site dry storage casks or at centralized off-site facilities.

Depending on the size of the nuclear expansion and the fuel burnup achieved, a future expansion in the United States might require one "Yucca Mountain" every 5 to 20 years—if we continue with a once-through fuel cycle. The actual Yucca Mountain project pays for itself, through the 0.1¢/kWh fee paid by the reactor operators. Therefore, this would be economically affordable. Finding geologically satisfactory sites may be possible, given the large array of plausible sites under consideration before expediency led to the selection of Yucca Mountain. However, the large amount of spent fuel in an open fuel cycle creates incentives to use fuel cycles that reduce the amount of fuel and particularly the amounts of actinides that require disposal. Burning the actinides in fast reactors, as discussed briefly in Section 9.4.3 and Section 16.6.1, would reduce the magnitude of the waste disposal problem.

The global problem is similar, but on a larger scale. It may be desirable to internationalize waste disposal, with countries that have large and geologically suitable areas accepting wastes from other countries. An upsurge in the world use of nuclear energy might also eventually motivate a reconsideration of subseabed disposal (see Section 11.3.2). However, any of these approaches would have to overcome strong and perhaps insuperable opposition, unless the expansion in nuclear energy use is accompanied by a substantial change in public attitudes toward waste disposal hazards.

Weapons Proliferation

The most serious objection to nuclear power, in the view of many technical people, is its link to the spread of nuclear weapons, either to additional countries or to terrorists, as was discussed at some length in Section 18.3. A large worldwide expansion could increase proliferation risks, because the greater the number of countries with nuclear power, the greater the number of actual or latent proliferators (see, e.g, Ref. [19]). For example, more countries could assert the need for uranium-enrichment facilities, ostensibly for low-enriched uranium for civilian reactors but potentially easing the path to high-enriched uranium for weapons. An expansion could also increase the risk of plutonium diversion or theft by encouraging the reprocessing of spent fuel and the use of breeder reactors.

These risks can be reduced by the adoption of appropriate technical and institutional measures. With a large nuclear expansion, the task of inspection and monitoring would be more demanding. However, a greater economic stake

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[16] Here, we are considering once-through fuel cycles only. Some of the Generation IV reactors have much greater burnups, and in most cases, recycling the fuel is integral to the planning.

in nuclear power might make the world community more willing to give the IAEA the resources and authority that are needed to make it an effective monitor.

20.4 Regional Prospects for Nuclear Power Development

20.4.1 World Picture

There is no substantial expansion of nuclear power underway at this time outside Asia (see Chapter 2). Many countries in Europe could undertake a program of nuclear reactor construction, but most lack the political impulse. Exceptions include Finland and, if announced plans materialize, Russia. The Finnish program will perforce be small, perhaps restricted to a single reactor, whereas the Russian program potentially could be much larger. The significance of the Finnish reactor will be one of example; its impact on the world economy will be small.

Little use of nuclear power is being made in Africa and it does not appear that most African countries are in a position to undertake a substantial nuclear program. However, one of the more highly touted of the new reactors—the Pebble Bed Modular Reactor—is being developed in South Africa, with ambitions for a world market. This appears to be something of an anomaly, and for the near future South Africa is likely to be a nuclear exception in a largely non-nuclear continent. In the western hemisphere, Canada has been the one country other than the United States with a substantial nuclear program, including vigorous efforts to compete in the world market for nuclear reactors.

20.4.2 United States

The Decline in U.S. Leadership

The United States was the world pioneer in nuclear energy and, by virtue of the size of its economy, is still the world leader in total nuclear power generation. However, it is not the leader either in the fraction of electricity that comes from nuclear power, or in rate of growth. The U.S. share of world nuclear generation was 50% in 1975 [36] but had dropped to 30% by 2002, and U.S. DOE projections suggest that this share will continue to slip [17, p. 186]. Light water reactors of U.S. design provided the model initially followed by most countries, including France and Japan, but many countries now have strong reactor design and construction capabilities of their own.

This is not to say that nuclear power is unimportant in the United States or that the technical capabilities of the industry are gone, but the United States is losing the clear primacy it once had, and the size of the nuclear industry and of the university programs that educate future nuclear engineers have both diminished. One assessment of the impending situation was given about 10 years ago by an American participant at an international nuclear conference held in the United States in 1993, who suggested that the conference might be remembered as marking the passing of the "mantle" of nuclear power leadership from the United States to France and Japan [37]. This trend does not seem to have been reversed in the following decade, although the United States has taken a significant initiative with respect to new reactor designs in launching the Near-Term Deployment and Generation IV programs, which are now international in scope (see Section 16.2).

Projections for Future Growth

The long-standing uncertainty about the future of nuclear power in the United States is illustrated by alternative DOE projections made in 1993 for the growth of nuclear power up to the year 2030 [38, p. 9]. Three scenarios from these projections are presented in Figure 20.1: (1) a "no new orders" scenario, in which nuclear capacity decreases as existing reactors are phased out; (2) a "lower reference" case in which there is a cautious resumption of nuclear expansion; and (3) an "upper reference" case that assumes a vigorous economy and use of nuclear power *and* coal for new generation. U.S. nuclear capacity in the year 2030 was projected to be 5 GWe, 119 GWe, and 168 GWe in the three scenarios, respectively.

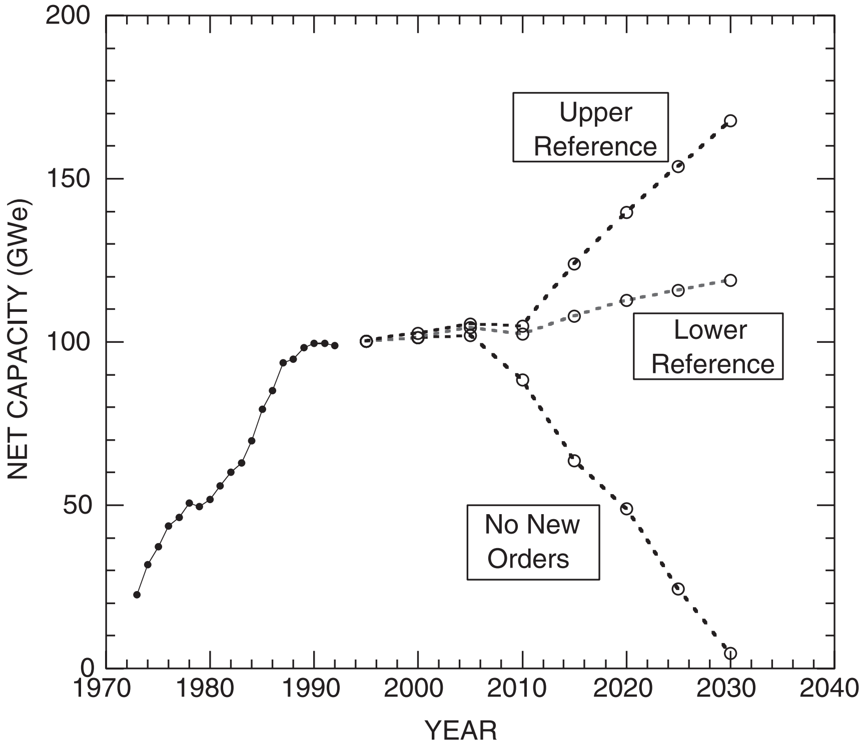

Fig. 20.1. Projected United States nuclear power capacity (in net GWe) for 1995–2030 in three 1993 DOE scenarios, together with actual capacity in prior years (1973–1992).

These projections have stood up reasonably well for the first 10 years since they were made, with their anticipation of little change before 2005. Beyond that, the spate of license extension applications (see Section 2.4.5) makes the “no new orders” estimate look unlikely, while a pessimistic or “lower reference” projection made today would not show the increase of Figure 20.1. The rapid increase shown in the “upper reference” projection appears achievable, as would an even greater increase, but the actual future for the United States remains a matter of public and industry choice.

The stated policy of the U.S. DOE is to encourage nuclear growth. More specifically, the Roadmap (discussed in Section 16.2.3) seeks an order by private industry for a new reactor by 2005, with the goal of deploying it by 2010. This is intended by the DOE to be the first stage in a revival of nuclear power in the United States, to be followed by the construction and deployment of Generation IV reactors by 2030. On the other hand, the DOE’s Energy Information Administration projected in early 2003 that no new nuclear plants will be put into operation by 2025 “because natural gas and coal-fired units are projected to be more economical” [20, p. 70]. The validity of this assessment may in large measure depend on measures taken by the DOE itself.

Institutional Issues

Some observers, including most advocates of nuclear power, believe that the crucial issues in the United States are more institutional than technical or even economic. The division of authority and initiative among many levels of government has made it difficult to adopt and implement policies that would permit rapid development of nuclear power (or even its prompt curtailment). Important roles are played by the president, Congress, the courts, and a host of federal agencies, including the Nuclear Regulatory Commission, the Department of Energy, and the Environmental Protection Agency. There is also a confusing division of powers between the federal government, the states, and, in some cases, individual cities or counties. With many opportunities for de facto vetoes, smooth progress in any direction requires a strong consensus. This does not now exist with respect to nuclear power, and existing public opposition remains a problem for the nuclear industry.

One step has been taken to reduce institutional difficulties, namely the streamlining of the licensing process so that once a plant is approved, the only remaining requirement, in terms of NRC procedures, will be the meeting of the *original* specifications. This change is reflected in new regulations, but it will not be known if this process will indeed be smooth until it is tested with an actual license application. The DOE has indicated an interest in helping to cover the costs of the first attempt of this sort.

Even if the public and institutional climate are supportive at the time a reactor is ordered, potential purchasers of nuclear reactors remain fearful that changes in the policies of the federal or state governments could make it difficult to put the reactor into operation when it is completed. The precedent of the Shoreham reactor in New York is not forgotten (see Section 2.4.1). Hence, a prudent utility is likely to be hesitant about ordering a large nuclear reactor. The hesitancy might be somewhat less for smaller reactors, especially modular reactors, because the investment is less and the lead time between an order and reactor operation is expected to be shorter. Even so, problems remain if only because the economies of modular reactors are not realized until a sizable number of them have been ordered and deployed.

It is not clear whether the measures being considered by the DOE and Congress to encourage nuclear power will suffice to overcome industry hesitation. Thus, Larry Foulke, in outlining what would be needed to reduce uncertainties (see Section 19.4.2), warned:

> The DOE's expectation that industry will lead in the introduction of new nuclear technologies is not valid. This means that the DOE is the logical leader in the development and demonstration of advanced reactor schemes with the necessary financial support. [39, p. 38]

In short, nuclear power in the United States may face difficulties without federal measures to aid prospective purchasers of reactors in meeting some of the costs and risks of being pioneers in a nuclear revival.[17]

20.4.3 Asia

In Asia, three countries obtain a substantial fraction of their electricity from nuclear power and continue to build new reactors: Japan, South Korea and Taiwan. In each of these countries, there is some degree of tension between energy planners who would like to build nuclear plants and nuclear opponents who have had some success in slowing expansion efforts. One success of the opponents has been in Taiwan, where the two reactors listed as being under construction have had an on-and-off (and now, apparently, on) history as political power has shifted.

The construction programs in India and China are large compared to what is going on elsewhere in the world (see Table 2.5), but both countries are starting from a small base and the currently committed expansion is small compared to the overall energy needs of India and China. It is not clear that they will be able to obtain the capital needed for an expansion that will have a substantial impact on their energy economies. China may be the largest question mark. Although its present program is still small for a country of its size, this could change. China's economy is growing rapidly and its heavy use of coal is contributing to serious pollution. With a centralized government, there could be a decision to undertake a major nuclear expansion, given continued economic growth and increased access to the necessary capital resources. As a sign of considerable flexibility in this program, of eight reactors under con-

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[17] The U.S. Senate took steps in this direction in June 2003, but the ultimate legislative outcome was not settled during 2003.

struction in China at the end of 2001, two reactors were coming from each of four suppliers divided among France, Canada, Russia, and China [40].[18]

The two remaining Asian countries with reactors that have been under construction are Iran and North Korea. These reactors are intertwined with weapons proliferation issues, as discussed in Chapter 18. In the case of North Korea, the reactors were proposed as an antiproliferation measure, to induce North Korea to forego the use of reactors that would lend themselves to the production of weapons-grade plutonium. In the case of Iran, the power reactor is widely viewed as a proliferation threat, with Iran's nominally civilian nuclear program suspected of being a cover for developing a weapons program.

At present, Asia is just beginning to catch up with the United States and Europe in the scale of use of nuclear power.[19] However, it may soon take the lead. This was predicted by Dr. Kunihiko Uematsu, a Japanese scientist serving as Director-General of the Nuclear Energy Agency of the OECD, who described in 1993 an expansive future for nuclear power in Asia. Citing the existing programs in Japan, Korea, Taiwan, and China and the planning and studies then underway in Indonesia, Thailand, and the Philippines, he suggested:

> . . .nuclear power generation in this region will soon reach the level of the OECD's European and North American regions. This is a striking example of the general shift in the world's energy pattern from the traditionally developed countries of the OECD to other parts of the world. . .with the increasing importance of nuclear power in this part of the world, **the future development of this energy source may no longer be spearheaded by the traditionally developed countries of Europe and North America**. [41, p. 20]

Boldface, as shown, was used in the published paper, indicating the significance the author attached to the point being made.

A more whimsical statement of the anticipated Asian leadership was made in 2002 by Dr. Chang Kun Lee, a commissioner of South Korea's Atomic Energy Commission and then the current chairman of the International Nuclear Societies Council:

> As far as power reactor deployment is concerned, the advanced nations bounded out of the starting line and hopped sprightly along at the pace of a rabbit while we Asian countries plodded along at the slow crawl of the turtle. At the moment, however, the Western nuclear rabbit is taking a nap under a roadside tree (hung with limp moratorium banners) while the Asian nuclear turtle is still toddling along on the road carrying the nuclear seed.

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[18] Four of these reactors were connected to the electricity grid in 2002.

[19] Gross generation in 2002 was 58 GWyr in Asia, 92 GWyr in the United States, and 105 GWyr in Western Europe [29].

> You could say that Asia is keeping alive a “nuclear technology shelter,” keeping the flame burning. . .these former students of nuclear technology in Asia will be ready to pay back their previous teachers in the West with state-of-the-art technical know-how and new or next generation hardwares. [42]

It is possible to question the applicability of the “turtle–rabbit” analogy. It is also possible that Asian countries will go through the same sequence experienced by Western countries—early enthusiasm followed by strong and often paralyzing public opposition. Nonetheless, the implications of his talk are clear, that, at least for the moment, the “mantle” of nuclear leadership has passed to Asia.

20.5 Issues in Nuclear Decisions

20.5.1 Categories of Issues

Resolvable Issues

Contentious as nuclear disagreements are, some of the key issues are basically technical, and, in principle, conscientious people can eventually reach a common understanding. In particular, there are strong disagreements as to the safety of nuclear reactors and nuclear waste disposal, but it is possible to localize the points of disagreement and, with enough study and patience, it should be possible to resolve them. If one chooses to be optimistic, one can look forward to an eventual convergence of views or at least to the reaching of a consensus that, even if short of unanimity, provides objective policy guidance.

Even the question of the effects of low levels of radiation can be discussed quantitatively, despite its being sometimes considered as beyond the reach of scientific analysis. Upper limits can be put on the possible rate of cancer fatalities, and one can look forward to the day when a better understanding of the underlying biological mechanisms or more comprehensive epidemiological studies can shed light on the validity of the linearity hypothesis, the possible existence of a threshold for radiation damage, and the reality of hormesis (see Chapter 4).

More Intractable Issues

If those were the only sorts of issues involved, the nuclear policy debate would be less difficult, notwithstanding the skepticism with which many people react to the conclusions of “expert” consensus. However, there are two nontechnical issues that cannot be authoritatively decided but that raise profound questions concerning nuclear power. These are the issues of weapons proliferation and of defining what might be called—for want of a better description—a "desirable society." In the former case, any conclusions are largely a matter of political guesswork. In the latter case, they involve personal philosophical or aesthetic viewpoints—with no good way to resolve differences. A dominant position may emerge on each of these issues, but, in the end, the positions may not amount to more than people voting their instincts. (These issues are discussed further in the next two subsections.)

Perceptions of Need

Overhanging all of these considerations is the question of need. Logically or not, the perception of the dangers of nuclear power correlates with the perception of the need for it, including judgments as to the promise of the alternatives. Of course, considerations of danger and need are appropriately linked when a cost–benefit analysis is being made—even an informal one. They are not appropriately linked when an estimate is being made of the absolute risk. It is therefore important to guard against having extraneous views on the desirability of nuclear power influence assessments on technical issues—for example, estimates of radiation effects, reactor accident probabilities, and the effectiveness of the various barriers at the planned Yucca Mountain repository.

20.5.2 Proliferation Risks and Nuclear Power

Some of the detailed issues bearing on the connection between nuclear power and proliferation of nuclear weapons have been discussed in Chapter 18 and earlier in this chapter. Two contrasting assessments can be made as to the nature of this connection. In one view, any country with nuclear power has a headstart as a potential proliferator. Whether or not it has nuclear weapons at the moment, possession of nuclear power makes its path to nuclear weapons easier—in terms of both professional expertise and the procurement of materials and equipment. Further, it will have more soft targets for terrorist theft. The way to reduce this threat is to phase out nuclear power. It would also be desirable to eliminate the nuclear weapons in the countries that already have them, but, even if this cannot be accomplished immediately, a phasing out of nuclear power would reduce the number of potential proliferators. Just stopping the expansion of nuclear power to new countries would avoid adding additional potential proliferators.

An opposing view is that it is too late to adopt this strategy. The argument for phasing out nuclear power is tantamount to an argument that it would be better had nuclear fission been impossible. However, by now the genie is irrevocably out of the bottle. Thirty-one countries have nuclear power, 2 countries without nuclear power have nuclear weapons (Israel and North Korea),[20] and over 20 additional countries have research reactors [43]. Even if

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[20] The North Korean case is ambiguous, in that it is not certain that it has actual weapons.

all countries gave up their equipment, the technical knowledge would remain, and a country could at any time try to develop nuclear weapons in secret. Further, a decision to phase out nuclear power would be on a country-by-country basis. It would presumably be led by the most "socially responsible" countries, but with no assurance that the less "socially responsible" countries would follow suit. A preferable course, in this view, would be for the "responsible" countries to provide leadership in the use of nuclear power and use their influence to establish fuel cycles that reduce proliferation risks and to strengthen international mechanisms to uncover and discourage proliferation efforts.

An additional argument advanced for nuclear power is that it can help to reduce the need for oil and the likelihood of military conflicts over oil, including potential nuclear conflicts. Thus, even if nuclear power increases the opportunities for developing weapons, it reduces the incentive to use them.

Each of these two overall views has a degree of plausibility, but their implications are contradictory. The choice between them cannot be determined by an orderly, analytic decision-making process, because no matter how the assessments are fleshed out, they appear in essence to only be educated guesses. No amount of new data would establish which assessment—or guess—is the more realistic.

20.5.3 Nuclear Power and a Desirable Society

Feelings About Material Development

Attitudes toward nuclear power are also influenced by aesthetic or philosophical positions on the nature of a desirable world. Is it better for us (i.e., humans) and the planet to have copious energy supplies or is it preferable for energy limitations to restrain unbridled material development? Individual answers to this rather vague question appear to influence the frame of reference in which people view energy issues.

We live with a mix of conflicting attitudes toward technology. On the one hand, we embrace many of the conveniences and applaud some of its fruits (e.g., in medicine and in reducing the drudgery of household chores). On the other hand, at least some people see attractions in a life that is less dependent on and encumbered by mechanical and electrical devices. Also, as we become more dependent on modern technology, we lose some of our sense of control. It is no longer possible for the average "handy" person to fix a car in case of a breakdown, which may or may not be outweighed by the decreased frequency of breakdowns.

Electricity is at the heart of modernization, and the discomfort that critics may have about its impact has been suggested by Amory Lovins:

> In an electrical world, your lifetime comes not from an understandable neighborhood technology run by people you know who are at

> your own social level, but rather from an alien, remote, and perhaps humiliatingly uncontrollable technology run by a faraway, bureaucratized, technical elite who have probably never heard of you. Decisions about who shall have how much energy at what price also become centralized. . . .[44, p. 55]

Whatever unease people may feel about electricity—and for electricity itself the unease appears to be less general than Lovins suggests—the concern is intensified for nuclear power. It is indeed a remote technology, with reactor development having become an international enterprise carried out by a small "technical elite" in the employ of large companies. The nuclear industry tries to put a human face upon itself, but it has a difficult task.

Since Lovins wrote those words, the idea of "globalization" has entered the popular culture. Nuclear power can be considered as the epitome of an enterprise controlled by very large corporations with international scope. It offers the world a somewhat uniform product that is expensive to install, difficult to understand, and dominated by highly industrialized countries. The concept of globalization and the objections to it are not well codified, but it is easy to expect that those who have a general distaste for globalization will have a special dislike for nuclear power.

Human Population and Impact

An underlying matter that—consciously or not—may figure in the nuclear debate is our feeling as to the desirability of satisfying the energy demands of a world population that was 2.5 billion in 1950, was 6 billion at the beginning of the 21st century, and appears headed to 9 billion or more in 2050. Nuclear power is pointed to as an aid in meeting these demands. However, some may take that as a curse instead of a blessing. It raises the question of the size of the population that we would welcome. A quotation from John Stuart Mill, written in 1848 when England and the world were much less densely populated, is pertinent today. As quoted by Joel Cohen in *How Many People Can the Earth Support?*, Mill contended:

> A population may be too crowded, though all be amply supplied with food and raiment. It is not good for man to be kept perforce at all times in the presence of his species. . . . Solitude, in the sense of being often alone, is essential to any depth of meditation or of character; and solitude in the presence of natural beauty and grandeur, is the cradle of thoughts and aspirations which are not only good for the individual, but which society could ill do without. [45, p. 397]

This attitude resonates strongly today, at least among the prosperous.

Considerations of the world's possible population are sometimes couched in terms of the "carrying capacity of the Earth." As discussed by Cohen in the book cited earlier, the carrying capacity depends not only on the material resources—such as land, water, and energy—but also on the degree of crowding that we are willing to tolerate. By providing more ample material resources, nuclear energy can help to sustain a larger population. This is one of the common arguments for nuclear energy—it will enable the world to adequately support more people. However, this can also be taken as an argument against nuclear power.

One can juxtapose the image of a densely populated world that makes extensive use of nuclear energy with one that relies exclusively on renewable energy. Carrying capacity estimates based on energy considerations were made in 1994 by David Pimentel and collaborators [46] and by Paul Ehrlich and collaborators [47]. Each group concluded that an optimal global population for a sustainable future is under 2 billion. The argument is made most explicitly in the Pimentel paper. The authors envisage a world in which fossil fuels have been exhausted and solar energy is the only sustainable energy source. They take 35 quads of primary solar energy as the maximum that could be captured each year in the United States. Assuming that the present average per capita U.S. energy consumption is halved through conservation, the 35 quads would suffice for a population of about 200 million. For the world as a whole, the total available energy in this picture would be about 200 quads. If the world per capita energy consumption were to converge to the new U.S. average, this would support a population of somewhat over 1 billion, which Pimentel et al. interpret as meaning that "1 to 2 billion people could be supported living in relative prosperity."[21]

One need not accept the details of this argument, including the maximum energy assumed for solar energy and the assumed absence of any nonrenewable energy sources. Nonetheless, it suggests alternatives of a densely populated, energy-rich world with nuclear power or a sparsely populated, energy-poor world without it. If energy limitations were accompanied by a shrinking of the world population to 2 billion without social upheavals and deep poverty, this might be a benign scenario. However, it is hard to envisage a peaceful transition of this sort on a quick enough time scale to be germane to the anticipated future energy problems.

Somewhat akin to the concern about excessive population is the concern about mankind's impact on the environment. At a time when cold fusion was being cited as a potentially unlimited source of energy, Albert Bartlett suggested that "if an abundant source of low-cost energy could be found it may be the worst thing that has ever happened to the human race" [49]. The specifically cited danger was the temperature rise accompanying untrammeled expansion of energy consumption, but a broader concern in this argument is that if mankind has unlimited options, the options may be exercised in ways that would severely damage the environment.

The overall argument, although perhaps between debaters passing in the night, is between those who most fear that without nuclear power there will

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[21] This section, and some of the neighboring sections, are closely based on Ref. [48].

not be enough energy to support the world's population at an "adequate" level and those who most fear the encouragement of population growth and the resulting damage to the environment and the quality of individual lives. This is a second issue that defies "objective" debate.

20.5.4 The Road to Decisions

One Path or Many

A variety of solutions to the world's energy problems are on the table, and each has its enthusiasts and detractors. In the background, and complementing all of the solutions, is conservation. Reduction of wasteful or inefficient uses of energy can substantially reduce the demand for energy. However, at any plausible degree of conservation, world energy consumption will rise—and even without a rise in consumption, replacing present fossil fuel use is desirable. The options for the required energy supply and their attractions when viewed optimistically, include the following:

1. *Coal and carbon sequestration.* The world's coal resources are large and widely distributed. With carbon sequestration, they can be used cleanly, assuming that more tractable emissions such as sulfur dioxide are also eliminated.
2. *Fusion.* Fusion energy, if it can be mastered, represents an ultimate solution, as an almost unlimited resource with few negative impacts.
3. *Natural gas.* The resources of unconventional natural gas may be very great, and the pollution from natural gas is small compared to that from coal (without sequestration).
4. *Nuclear energy.* Energy from nuclear fission is already a major carbon-free electricity provider and, with new fuel cycles, could provide energy for the indefinite future, assuming that waste disposal and other contentious issues are resolved.
5. *Renewable energy.* The solar energy falling upon the Earth far exceeds any possible needs. Its capture, if achievable despite the diluteness of the source, would provide clean energy in perpetuity.

However, there are powerful reasons to question these optimistic assessments and the degree to which we can rely on the listed options. In most cases, they involve a tremendous buildup of technologies whose practicality and impacts have not been tested on a large scale. This caution applies to carbon sequestration, fusion, extraction of natural gas from unconventional sources or of uranium from seawater, and each of the expandable forms of renewable energy.[22] The most tested of these options, nuclear power, is also the one that elicits the most fears and opposition.

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[22] Here, we are assuming that hydroelectric power and the use of biomass for electricity generation have only limited potential for expansion.

A choice among the options can be made in either a decisive or exploratory fashion. A decisive choice would be to now pick the winner, or winners, and abandon the others. An exploratory choice would be to pursue all plausible options, until their comparative merits are clearer. The case for a single path was made forcefully by Lovins in *Soft Energy Paths*. He argued that attempting to pursue several paths simultaneously would be a distraction and impede implementing the proper one—a mix of conservation and renewable energy [44]. The case for multiple paths reduces to the maxims of not putting all of one's eggs in one basket or of hedging one's bets. The argument is reflected picturesquely in the advice: "When you come to a fork in the road, take it."[23] If one thinks of a person in a car, the advice is intentionally absurd. However, for an army traversing unfamiliar terrain, it can make sense to explore multiple roads.

Even in the exploratory approach, de facto decisions are made by the pace at which efforts are invested in one option or another. A minimal investment is to "keep the option open." Sometimes, in recent years, the dispute over nuclear power has been reduced to one between those who want to phase it out and those who favor keeping the option alive—either because they foresee the day when the need will be recognized or because they are truly undecided about the eventual need. In the United States, the federal policy in recent years has been to keep the option open and, more recently, to encourage it, but to make only relatively minor investments in it.

Differences Among Countries

Although all countries are impacted by some of the same economic factors and resource pressures, it is not to be expected that they will all reach the same decisions. The differences in the nuclear policies of different countries can arise from basic aspects of their physical environment or from the political and economic character of their societies.

In terms of its environment, Japan is in a particularly difficult situation. It is poor in fossil fuel resources and it has a population density that is roughly 12 times that of the United States, limiting its options for use of renewable energy.[24] For Japan, nuclear power offers a path to partial energy independence that cannot be obtained in any other way. In contrast, the United States and Canada are much richer in fossil fuels and have large areas that could, in principle, be used for renewable energy. Thus, they are not under the same pressures as Japan.

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[23] This advice is attributed to Yogi Berra, the American baseball player and putative source of many pithy phrases.

[24] Japan, in 2001, obtained 59% of its electricity from fossil fuels, 31% from nuclear power, 8% from hydroelectric power, and 2% from biomass and other renewable sources [1].

The effects of differences in physical circumstances are illustrated by the previously mentioned example of Norway and Sweden, which in many ways are similar in attitudes and sociology. Sweden, with somewhat limited hydroelectric resources, has reluctantly continued to use nuclear power for roughly 40% of its electricity, despite the planned shutdown. Norway, in contrast, uses its abundant hydroelectric power to provide virtually all of its electricity and has no nuclear power. Its per capita electricity consumption is 50% greater than that of Sweden [1].

Differences in political mood, in economic opportunities, and in national institutions can also play an important role. The more legal and political avenues nuclear opponents have for contesting nuclear development, the more difficult it is to proceed with nuclear power. As several commentators have pointed out, the difficulties are greater in a country with a federal government than in a country where decisions are made by a centralized national government (e.g., Ref. [41]). A federal government offers many opportunities to raise objections, and the objections are put forth in an atmosphere in which local concerns can take precedence over national priorities. The United States is quite vulnerable in this regard, with important prerogatives held by the states and with a system of checks and balances within the federal government.

It is to be expected that differences in their objective situations and institutions, as well as possibly transient differences in popular attitudes, will continue to lead countries to differing choices. Thus, even were the United States to abandon nuclear power, there is no reason to expect that Japan and France would follow suit. Other countries (e.g., China and India), may wish to accelerate their use of nuclear power, but be held back by a lack of capital. In the end—despite globally common technology, fuel markets, and environmental concerns—decisions on energy policy will be largely national decisions.

Constituencies For and Against Nuclear Power

In reaching a national decision as to the future of nuclear power, the role of a constituency is important. At present, there is a determined and effective constituency against nuclear power, including most environmental organizations.[25] There has been the image of a comparably active and determined constituency for nuclear power, namely the nuclear industry. However, with the decrease of nuclear reactor construction, the nuclear industry has shrunk, and this has not been a valid image for some years. To be sure, there is continuing activity in the operation and improvement of existing power plants and in the completion of a few others, plus some prospect of possible future reactors. This sustains interest on the part of both utilities and manufactur-

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[25] Here, we will focus on the United States, but the general points have broader applicability.

ers. But the total scale of development is relatively small, and the utilities in countries like the United States are more interested in trouble-free operation of existing reactors than in building new ones. At present, there is no powerful and vocal constituency for the further development of nuclear power.[26]

There are, however, two potential enlarged constituencies: the technical community and the environmental community. For the most part, engineering and scientific organizations and their members support nuclear power, and if energy issues become pressing, there might be a greater sense of urgency in this support.

However, the emotional drive behind any position in the nuclear controversy is heightened when there are important environmental concerns. At present, the "environmental movement" is largely opposed to nuclear power, although with different degrees of finality in the opposition. The movement is not monolithic and there are many strands. From a somewhat extreme standpoint, the fundamental difficulty with nuclear power, or any technology that facilitates increased use of energy, is that it increases the potential impact of humans upon the natural environment—impacts that are likely, in this view, to be undesirable. Those who share this fear will always oppose nuclear power.

Other parts of the environmental movement would welcome a truly clean energy source to replace fossil fuels. Over the next years, some environmentalists might turn to nuclear power in preference to fossil fuel combustion, if they conclude these are the actual alternatives. If such a revisionist view of environmental priorities takes hold, it could provide the impetus for a nuclear revival that may not come from industry or government initiatives alone.[27]

20.5.5 Predictions and their Uncertainty

Summary of Factors Impacting Nuclear Power

As discussed earlier, the factors that will determine whether nuclear power moves ahead or regresses include the following:

- The safety record of existing reactors, the progress of the Yucca Mountain repository, and the perceived safety of next-generation reactors.
- The level of concern about global climate change, oil or natural gas shortages, and the world's dependence on Persian Gulf oil.
- The perceived prospects of renewable energy, carbon sequestration, and fusion.

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[26] However, if the federal government is sympathetic, the influence of any constituency is amplified, as was the case for conservation during the Carter presidency in the United States and may be the case for nuclear power during the present Bush administration.

[27] Author's note: This thought appears also in the 1996 edition; since then, I have become aware of an organization Environmentalists for Nuclear Energy (EFN), based in France, that has been founded by Bruno Comby [50].

- Judgments as to the extent to which nuclear power contributes to or detracts from national and world security.
- Attitudes toward technology, globalization, and growth.
- The economic competitiveness of nuclear power and the nature of government intervention (e.g., tax credits or carbon taxes).
- The orientation of individual governments as they evaluate the issues and their vigor in facilitating the adoption of one or more of the competing technologies.

Given this array of factors—many involving highly controversial or ambiguous questions—it is not possible to know how the balance of forces will affect nuclear power's evolution over the next few decades. Presently, construction of new reactors is confined largely to Asian countries, but there are renewed government expressions of interest in the United States and Russia. Although there is no hint that sudden changes are in the offing, there is no assurance that any industrialized country, wherever it now lies in the spectrum, will maintain its present energy policies over prolonged time periods—whether the changes are in the direction of phasing out nuclear power, expanding its use, or adopting it for the first time.

There are no absolute barriers to a return to a rapid growth in nuclear power. There are nuclear suppliers in North America, Europe, and Asia who are eager to build the reactors if the demand develops. The question is not whether a major expansion of nuclear power is possible, but whether it is desirable. Predicting what will appear to be desirable 10 years hence, or even 5 years hence, is very problematic, especially if the predictions attempt to embrace all countries.

A Past Failure of Prediction

It is interesting to look back almost 30 years and examine the prescience of predictions made then. Conveniently for this purpose, a conference was held in Paris in 1975, with the complacent title *Nuclear Energy Maturity.* The underlying premise of the conference was that nuclear power had arrived, and that it remained to consider how to proceed so that nuclear power could "...represent a long-term-solution, that is for thousands of years rather than the few decades set by the uranium supply required by the 'proven' reactors" [51, p. x].

This long-term issue was addressed in a panel on the Role of Breeders. One speaker gave projections for future generation in the "Western World" (for this purpose, much the same as the OECD countries). In a variety of scenarios, western capacity was projected to be 700–1000 GWe in 1990 and 2000–4000 GWe in 2005 [51, p. 328]. In actuality, total *world* capacity was only 320 GWe in 1990 and there is no possibility that it will reach even 500 GWe by 2005.

These were not atypically optimistic projections. Similar projections were presented by other speakers [51, pp. 319 and 322]. There was at least one dissenting voice [51, p. 324], but it seems to have been a voice in the wilderness. There was a clear consensus that the world was moving into a period of very substantial nuclear expansion.

The failure of this prediction carries two cautionary reminders:

- Looking into the recent past does not enable one to see the future. There is a possibility that we are repeating this mistake today, in taking nuclear power's sluggishness of recent years as an indicator of future sluggishness.
- The proponents of a newly evolving technology can have an unduly enthusiastic picture of future prospects and may underestimate the difficulties. That was true for nuclear power in 1975. It could be true for some of the emerging technologies today.

Competing Considerations

In the end, policies on nuclear power will depend on judgments of the relative risks of using it or of trying to do without it. With it, we may face risks of radioactive contamination from reactor accidents or waste disposal. Without it, we may face increased risks from climate change and energy shortages. In both cases, there are risks of nuclear bomb manufacture and use. Conclusions as to the magnitude of these risks and how they balance are likely to vary from country to country, given different national circumstances and internal political forces. Depending on the conclusions reached, nuclear power could shrink over the next several decades and remain important in only a few countries, or it could expand substantially in much of the world.

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