THE NEED FOR NUCLEAR POWER

VIEWPOINT ON THE WORLD'S CHALLENGING ENERGY FUTURE

BY RICHARD RHODES AND DENIS BELLER

The world needs more energy. Energy multiplies human labor, increasing productivity. It builds and lights schools, purifies water, powers farm machinery, drives sewing machines and robot assemblers, stores and moves information. World population is steadily increasing, having passed six billion in 1999. Yet one-third of that number — two billion people — lack access to electricity. Development depends on energy, and the alternative to development is suffering: poverty, disease, and death. Such conditions create instability and the potential for widespread violence. National security therefore requires developed nations to help increase energy production in their more populous developing counterparts. For the sake of safety as well as security, that increased energy supply should come from diverse sources.

"At a global level," the British Royal Society and Royal Academy of Engineering estimate in a 1999 report on nuclear energy and climate change, "we can expect our consumption of energy at least to double in the next 50 years and to grow by a factor of up to five in the next 100 years as the world population increases and as people seek to improve their standards of living." Even with vigorous conservation, world energy production would have to triple by 2050 to support consumption at a mere one-third of today's US *per capita* rate. The

Photo: Maintaining electric power lines in Indonesia. (Credit:UNDP)

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International Energy Agency (IEA) of the Organization for Economic Cooperation and Development (OECD) projects 65% growth in world energy demand by 2020, two-thirds of that coming from developing countries.

"Given the levels of consumption likely in the future," the Royal Society and Royal Academy caution, "it will be an immense challenge to meet the global demand for energy without unsustainable long-term damage to the environment." That damage includes surface and air pollution and global warming.

A CLEAN BREAK TO THE FUTURE

Most of the world's energy today comes from petroleum (39%), coal (24%), natural gas (22%), hydroelectric power (6.9%), and nuclear power (6.3%). Although oil and coal still dominate, their market fraction began declining decades ago. Meanwhile, natural gas and nuclear power have steadily increased their shares and should continue to do so.

Contrary to the assertions of anti-nuclear organizations, nuclear power is neither dead nor dying. France generates about 75% of its electricity with nuclear power; Belgium, 58%; Sweden, 47%; Switzerland, 36%; Japan, 36%; Spain, 31%; the United Kingdom, 29%; and the United States (the largest producer of nuclear energy in the world), 20%. The Republic of Korea and China have announced ambitious plans to expand their nuclear-power capabilities — in the case of Korea, by building 16 new plants, increasing capacity by more than 100%. With 433 operating reactors worldwide, nuclear power is meeting the annual electrical needs of more than a billion people.

In America and around the globe, nuclear safety and efficiency have improved significantly since 1990. In 1998, and again in 1999, unit capacity factor (the fraction of a power plant's capacity that it actually generates) for operating reactors reached record levels. The average US capacity factor in 1999 was 85% for about 100 reactors, compared to 58% in 1980 and 66% in 1990. Despite a reduction in the number of power plants, the US nuclear industry generated 9% more nuclear electricity in 1999 than in 1998. Average production costs for nuclear energy are now just 1.9 cents per kilowatt-hour (kWh), while electricity produced from gas costs 3.4 cents per kWh.

By improving capacity and performance alone, nuclear power already has made the largest contribution of any American industry to meeting the US Kyoto commitment to limiting carbon dioxide releases into the atmosphere. Meanwhile, radiation exposure to workers and waste produced per unit of energy have hit new lows.

Because major, complex technologies take more than half a century to spread around the world, natural gas will share the lead in power generation with nuclear power over the next hundred years. Which of the two will command the greater share remains to be determined. But both are cleaner and more secure than the fuels they have begun to replace, and their ascendance should be endorsed.

Even environmentalists should welcome the transition and reconsider their infatuation with renewable energy sources.

CARBON-BASED ENERGY

Among sources of electric-power generation, coal is the worst environmental offender. (Petroleum, today's dominant source of energy, sustains transportation, putting it in a separate category.) Recent studies by the Harvard School of Public Health indicate that pollutants from coal-burning cause about 15,000 premature deaths annually in the United States alone. Used to generate about a quarter of the world's primary energy, coal-burning releases amounts of toxic waste too immense to contain safely. Such waste is either dispersed directly into the air or is solidified and dumped. Some is even mixed into construction materials.

Besides emitting noxious chemicals in the form of gases or toxic particles — sulfur and nitrogen oxides (components of acid rain and smog), arsenic, mercury, cadmium, selenium, lead, boron, chromium, copper, fluorine, molybdenum, nickel, vanadium, zinc, carbon monoxide and dioxide, and other greenhouse gases — coal-fired power plants are also the world's major source of radioactive releases into the environment. Uranium and thorium, mildly radioactive elements ubiquitous in the earth's crust, are both released when coal is burned.

Radioactive radon gas, produced when uranium in the earth's crust decays and normally confined underground, is released when coal is mined. A 1000-megawatt-electric (MWe) coal-fired power plant releases about 100 times as much radioactivity into the environment as a comparable nuclear plant. Worldwide releases of uranium and thorium from coal-burning total about 37,300 tonnes (metric tons) annually, with about 7300 tonnes coming from the United States. Since uranium and thorium are potent nuclear fuels, burning coal also wastes more potential energy than it produces.

The overlooked radioactive waste that is generated while burning coal emphasizes the political disadvantages under which nuclear power labors. Current laws force nuclear utilities, unlike coal plants, to invest in expensive systems that limit the release of radioactivity. Nuclear fuel is not efficiently recycled in the United States because of proliferation fears. These factors have warped the economics of nuclear power development and created a politically difficult waste-disposal problem. If coal utilities were forced to assume similar costs, coal electricity would no longer be cheaper than nuclear.

RENEWABLE ENERGY: CHANGING REALITIES

Renewable sources of energy — hydroelectric, solar, wind, geothermal, and biomass — have high capital-investment costs and significant, if usually unacknowledged, environmental consequences. Hydropower is not even a true renewable, since dams eventually silt in. Most renewables collect extremely diluted energy, requiring large areas of land and masses of collectors to concentrate. Manufacturing solar collectors, pouring concrete for fields of windmills, and drowning many square miles of land behind dams cause damage and pollution.

Photovoltaic cells used for solar collection are large semiconductors; their manufacture produces highly toxic waste metals and solvents that require special technology for disposal. A 1000-MWe solar electric plant would generate 6850 tonnes of hazardous waste from metals-processing alone over a 30-year lifetime. A comparable solar thermal plant (using mirrors focused on a central tower) would require metals for construction that would generate 435,000 tonnes of manufacturing waste, of which 16,300 tonnes would be contaminated with lead and chromium and be considered hazardous.

A global solar-energy system would consume at least 20% of the world's known iron resources. It would require a century to build and a substantial fraction of annual world iron production to maintain. The energy necessary to manufacture sufficient solar collectors to cover a half-million square miles of the earth's surface and to deliver the electricity through long-distance transmission systems would itself add grievously to the global burden of pollution and greenhouse gas. A global solar-energy system without fossil or nuclear backup would also be dangerously vulnerable to drops in solar radiation from volcanic events such as the 1815 eruption of Tambura, which released 40 cubic kilometers of ash into the atmosphere. This ash significantly reduced solar radiation for several years afterward, which resulted in widespread crop failure during the "year without a summer" that followed.

Wind farms, besides requiring millions of pounds of concrete and steel to build (and thus creating huge amounts of waste materials), are inefficient, with low (because intermittent) capacity. They also cause visual and noise pollution and are mighty slayers of birds. Several hundred birds of prey, including dozens of golden eagles, are killed every year by a single California wind farm; more eagles have been killed by wind turbines than were lost in the disastrous Exxon Valdez oil spill. The National Audubon Society has launched a campaign to save the California condor from a proposed wind farm to be built north of Los Angeles. A wind farm equivalent in output and capacity to a 1000-MWe fossil-fuel or nuclear plant would require the installation of more than 4000 large windmills and occupy several hundred thousand square miles of land and, even with substantial subsidies and ignoring hidden pollution costs, would produce electricity at double or triple the cost of fossil fuels.

Although at least one-quarter of the world's potential for hydropower has already been developed, hydroelectric power — produced by dams that submerge large areas of land, displace rural populations, change river ecology, kill fish, and risk catastrophic collapse — has understandably lost the backing of environmentalists in recent years. The US Export-Import Bank was responding in part to environmental lobbying when it denied funding to China's 18,000-MWe Three Gorges project. Generating hydroelectric energy can actually release more greenhouse gases into the atmosphere than does fossil generation: vegetation submerged in the water impounded behind many dams decomposes anaerobically, which releases copious quantities of methane, a worse greenhouse gas than carbon dioxide.

Meanwhile, geothermal sources — which exploit the internal heat of the earth emerging in geyser areas or under volcanoes — are inherently limited and often coincide with scenic sites (such as Yellowstone National Park in the USA) that conservationists understandably want to preserve.

Because of these and other disadvantages, organizations such as the World Energy Council and the IEA predict that hydroelectric generation will continue to account for no more than its present 6.9% share of the world's primary energy supply, while all other renewables, even though robustly subsidized, will move from their present 0.5% share to claim no more than 5% to 8% by 2020. In the United States, which leads the world in renewable energy generation, such production actually declined by 9.4% from 1997 to 1998: hydro by 9.2%, geothermal by 5.4%, wind by 50.5%, and solar by 27.7%.

Like the dream of controlled thermonuclear fusion, then, the reality of a world run on pristine energy generated from renewables continues to recede, despite expensive, highly subsidized research and development. The 1997 US federal R&D investment per thousand kWh was only 5 cents for nuclear and coal, 58 cents for oil, and 41 cents for gas, but was more than $4700 for wind and $17,000 for photovoltaics. This massive public investment in renewables would have been better spent making coal plants and automobiles cleaner.

According to Robert Bradley of Houston's Institute for Energy Research, US conservation efforts and non-hydroelectric renewables have benefited from a cumulative 20-year taxpayer investment of some $30-$40 billion — "the largest governmental peacetime energy expenditure in US history." And Bradley estimates that "the $5.8 billion spent by the Department of Energy on wind and solar subsidies" alone could have paid for "replacing between 5000 and 10,000 MWe of the nation's dirtiest coal capacity with gas-fired combined-cycle units, which would have reduced carbon dioxide emissions by between one-third and two-thirds." Replacing coal with nuclear generation would have reduced overall emissions even more.

Despite the massive investment, conservation and non-hydro renewables remain stubbornly uncompetitive and contribute only marginally to US energy supplies. If the most prosperous nation in the world cannot afford them, who can? Not China, evidently, which expects to generate less than 1% of its commercial energy from non-hydro renewables in 2025. Coal and oil will still account for the bulk of China's energy supply in that year unless developed countries offer incentives to convince the world's most populous nation to change its plans.

COMPARING THE CHOICES

Natural gas has many virtues as a fuel compared to coal or oil, and its share of the world's energy will assuredly grow in the first half of the 21st century. But its supply is limited and unevenly distributed, it is expensive as a power source compared to coal or uranium, and it pollutes the air. A 1000-MWe natural gas plant releases 5.5 tonnes of sulfur oxides per day, 21 tonnes of nitrogen oxides, 1.6 tonnes of carbon monoxide, and 0.9 tonnes of particulates. In the United States, energy production from natural gas released about 5.5 billion tonnes of waste in 1994. Natural gas fires and explosions are also significant risks. A single mile of gas pipeline three feet in diameter at a pressure of 1000 pounds per square inch (psi) contains the equivalent of two-thirds of a kiloton of explosive energy; a million miles of such large pipelines lace the earth.

The great advantage of nuclear power is its ability to wrest enormous energy from a small volume of fuel. Nuclear fission, transforming matter directly into energy, is several million times as energetic as chemical burning, which merely breaks chemical bonds. One tonne of nuclear fuel produces energy equivalent to 2 to 3 million tonnes of fossil fuel. Burning 1 kilogram of firewood can generate 1 kilowatt-hour of electricity; 1 kg of coal, 3 kWh; 1 kg of oil, 4 kWh. But 1 kg of uranium fuel in a modern light-water reactor generates 400,000 kWh of electricity, and if that uranium is recycled, 1 kg can generate more than 7,000,000 kWh. These spectacular differences in volume help explain the vast difference in the environmental impacts of nuclear versus fossil fuels. Running a 1000-MWe power plant for a year requires 2000 train cars of coal or 10 supertankers of oil but only 12 cubic meters of natural uranium. Out the other end of fossil-fuel plants, even those with pollution-control systems, come thousands of tonnes of noxious gases, particulates, and heavy-metal-bearing (and radioactive) ash, plus solid hazardous waste — up to 500,000 tonnes of sulfur from coal, more than 300,000 tonnes from oil, and 200,000 tonnes from natural gas.

In contrast, a 1000-MWe nuclear plant releases no noxious gases or other pollutants* and much less radioactivity *per capita* than is encountered from airline travel, a home smoke detector, or a television set. It produces about 30 tonnes of high-level waste (spent fuel) and 800 tonnes of low- and intermediate-level waste — about 20 cubic meters in all when compacted (roughly, the volume of two automobiles). All the operating nuclear plants in the world produce some 3000 cubic meters of waste annually. By comparison, US industry generates annually about 50,000,000 cubic meters of solid toxic waste.

The high-level waste is intensely radioactive, of course (the low-level waste can be less radioactive than coal ash, which is used to make concrete and gypsum — both of which are incorporated into building materials). But thanks to its small volume and the fact that it is not released into the environment, this high-level waste can be meticulously sequestered behind multiple barriers. Waste from coal, dispersed across the landscape in smoke or buried near the surface, remains toxic forever. Radioactive nuclear waste decays steadily, losing 99% of its toxicity after 600 years — well within the range of human experience with custody and maintenance, as evidenced by structures such as the Roman Pantheon and Notre Dame Cathedral.

Nuclear waste disposal is a political problem in the United States because of widespread fear disproportionate to the reality of risk. But it is not an engineering problem, as advanced projects in France, Sweden, and Japan demonstrate. The World Health Organization has estimated that indoor and outdoor air pollution cause some three million deaths per year. Substituting small, properly contained volumes of nuclear waste for vast, dispersed amounts of toxic wastes from fossil fuels would produce so obvious an improvement in public health that it is astonishing that physicians have not already demanded such a conversion.

The production cost of nuclear electricity generated from existing US plants is already fully competitive with electricity from fossil fuels, although new nuclear power is somewhat more expensive. But this higher price tag is deceptive. Large nuclear power plants require larger capital investments than comparable coal or gas plants only because nuclear utilities are required to build and maintain costly systems to keep their radioactivity from the environment.

If fossil-fuel plants were similarly required to sequester the pollutants they generate, they would cost significantly more than nuclear power plants do. The European Union and the IAEA have determined that "for equivalent amounts of energy generation, coal and oil plants...owing to their large emissions and huge fuel and transport requirements, have the highest externality costs as well as equivalent lives lost. The

**Uranium is refined and processed into fuel assemblies today using coal energy, which does of course release pollutants. If nuclear power were made available for process heat or if fuel assemblies were recycled, this source of manufacturing pollution would be eliminated or greatly reduced.*

external costs are some ten times higher than for a nuclear power plant and can be a significant fraction of generation costs." In equivalent lives lost per gigawatt generated (that is, loss of life expectancy from exposure to pollutants), coal kills 37 people annually; oil, 32; gas, 2; nuclear, 1. Compared to nuclear power, in other words, fossil fuels (and renewables) have enjoyed a free ride with respect to protection of the environment and public health and safety.

Even the estimate of one life lost to nuclear power is questionable. Such an estimate depends on whether or not, as the long-standing "linear no-threshold" theory (LNT) maintains, exposure to amounts of radiation considerably less than preexisting natural levels increases the risk of cancer. Although LNT dictates elaborate and expensive confinement regimes for nuclear power operations and waste disposal, there is no evidence that low-level radiation exposure increases cancer risk. In fact, there is good evidence that it does not. There is even good evidence that exposure to low doses of radioactivity improves health and lengthens life, probably by stimulating the immune system much as vaccines do (the best study, of background radon levels in hundreds of thousands of homes in more than 90% of US counties, found lung cancer rates decreasing significantly with increasing radon levels among both smokers and nonsmokers). So low-level radioactivity from nuclear power generation presents at worst a negligible risk. Authorities on coal geology and engineering make the same argument about low-level radioactivity from coal-burning; a US Geological Survey fact sheet, for example, concludes that "radioactive elements in coal and fly ash should not be sources of alarm." Yet nuclear power development has been hobbled, and nuclear waste disposal unnecessarily delayed, by limits not visited upon the coal industry.

No technological system is immune to accident. Recent dam overflows and failures in Italy and India each resulted in several thousand fatalities. Coal-mine accidents, oil- and gas-plant fires, and pipeline explosions typically kill hundreds per incident. The 1984 Bhopal chemical plant disaster caused some 3000 immediate deaths and poisoned several hundred thousand people. According to the US Environmental Protection Agency, between 1987 and 1996 more than 600,000 accidental releases of toxic chemicals in the United States killed a total of 2565 people and injured 22,949.

By comparison, nuclear accidents have been few and minimal. The recent, much-reported accident in Japan occurred not at a power plant but at a facility processing fuel for a research reactor. It caused no deaths or injuries to the public. As for the Chernobyl explosion, it resulted from human error in operating a fundamentally faulty reactor design that could not have been licensed in the West. It caused severe human and environmental damage locally, including 31 deaths, most from radiation exposure. Thyroid cancer, which could have been prevented with prompt iodine prophylaxis, has increased in Ukrainian children exposed to fallout. More than 800 cases have been diagnosed and several thousand more are projected; although the disease is treatable, three children have died. LNT-based calculations project 3420 cancer deaths in Chernobyl-area residents and cleanup crews. The Chernobyl reactor lacked a containment structure, a fundamental safety system that is required on Western reactors. Post-accident calculations indicate that such a structure would have confined the explosion and thus the radioactivity, in which case no injuries or deaths would have occurred.

These numbers, for the worst ever nuclear power accident, are remarkably low compared to major accidents in other industries. More than 40 years of commercial nuclear power operations demonstrate that nuclear power is much safer than fossil-fuel systems in terms of industrial accidents, environmental damage, health effects, and long-term risk.

REASSESSING RECYCLING

Most of the uranium used in nuclear reactors is inert, a non-fissile product unavailable for use in weapons. Operating reactors, however, breed fissile plutonium that could be used in bombs, and therefore the commercialization of nuclear power has raised concerns about the spread of weapons. In 1977, President Carter deferred indefinitely the recycling of "spent" nuclear fuel, citing proliferation risks. This decision effectively ended nuclear recycling in the United States, even though such recycling reduces the volume and radiotoxicity of nuclear waste and could extend nuclear fuel supplies for thousands of years. Other nations assessed the risks differently and the majority did not follow the US example. France and the United Kingdom currently reprocess spent fuel; Russia is stockpiling fuel and separated plutonium for jump-starting future fast-reactor fuel cycles; Japan has begun using recycled uranium and plutonium mixed-oxide (MOX) fuel in its reactors and recently approved the construction of a new nuclear power plant to use 100% MOX fuel by 2007.

Although power-reactor plutonium theoretically can be used to make nuclear explosives, spent fuel is refractory, highly radioactive, and beyond the capacity of terrorists to process. Weapons made from reactor-grade plutonium would be hot, unstable, and of uncertain yield. India has extracted weapons plutonium from a Canadian heavy-water reactor and bars inspection of some dual-purpose reactors it has built. But no plutonium has ever been diverted from British or French reprocessing facilities or fuel shipments for weapons production; IAEA inspections are effective in preventing such diversions. The risk of proliferation, the IAEA has concluded, "is not zero and would not become zero even if nuclear power ceased to exist. It is a continually strengthened nonproliferation regime that will remain the cornerstone of efforts to prevent the spread of nuclear weapons."

Ironically, burying spent fuel without extracting its plutonium through reprocessing would actually increase the long-term risk of nuclear proliferation, since the decay of less-fissile and more-radioactive isotopes in spent fuel after one to three centuries improves the explosive qualities of the plutonium it contains, making it more attractive for weapons use. Besides extending the world's uranium resources almost indefinitely, recycling would make it possible to convert plutonium to useful energy while breaking it down into shorter-lived, nonfissionable, nonthreatening nuclear waste.

Hundreds of tons of weapons-grade plutonium, which cost the nuclear superpowers billions of dollars to produce, have become military surplus in the past decade. Rather than burying some of this strategically worrisome but energetically valuable material — as Washington has proposed — it should be recycled into nuclear fuel. An international system to recycle and manage such fuel would prevent covert proliferation. As envisioned by Edward Arthur, Paul Cunningham, and Richard Wagner of the Los Alamos National Laboratory, such a system would combine internationally monitored retrievable storage, the processing of all separated plutonium into MOX fuel for power reactors, and, in the longer term, advanced integrated materials-processing reactors that would receive, control, and process all fuel discharged from reactors throughout the world, generating electricity and reducing spent fuel to short-lived nuclear waste ready for permanent geological storage.

THE NEXT NEW THING

A new generation of small, modular power plants — competitive with natural gas and designed for safety, proliferation resistance, and ease of operation — will be necessary to extend the benefits of nuclear power to smaller developing countries that lack a nuclear infrastructure. The Department of Energy has awarded funding to three designs for such "fourth-generation" plants. A South African utility, Eskom, has announced plans to market a modular gas-cooled pebble-bed reactor that does not require emergency core-cooling systems and physically cannot "melt down." Eskom estimates that the reactor will produce electricity at around 1.5 cents per kWh, which is cheaper than electricity from a combined-cycle gas plant. The Massachusetts Institute of Technology and the Idaho National Engineering and Environmental Laboratory are developing a similar design to supply high-temperature heat for industrial processes such as hydrogen generation and desalinization.

Petroleum is used today primarily for transportation, but the internal combustion engine has been refined to its limit. Further reductions in transportation pollution can come only from abandoning

petroleum and developing nonpolluting power systems for cars and trucks. Recharging batteries for electric cars will simply transfer pollution from mobile to centralized sources unless the centralized source of electricity is nuclear. Fuel cells, which are now approaching commercialization, may be a better solution. Because fuel cells generate electricity directly from gaseous or liquid fuels, they can be refueled along the way, much as present internal combustion engines are. When operated on pure hydrogen, fuel cells produce only water as a waste product. Since hydrogen can be generated from water using heat or electricity, one can envisage a minimally polluting energy infrastructure, using hydrogen generated by nuclear power for transportation, nuclear electricity and process heat for most other applications, and natural gas and renewable systems as backups.

Such a major commitment to nuclear power could not only halt but eventually even reverse the continuing buildup of carbon in the atmosphere. In the meantime, fuel cells using natural gas could significantly reduce air pollution.

Photo: Forsmark nuclear plant in Sweden. *Credit: Göran Hansson*

POWERING THE FUTURE

To meet the world's growing need for energy, the Royal Society and Royal Academy report proposes "the formation of an international body for energy research and development, funded by contributions from individual nations on the basis of GDP or total national energy consumption." The body would be "a funding agency supporting research, development and demonstrators elsewhere, not a research center itself." Its budget might build to an annual level of some $25 billion, "roughly 1% of the total global energy budget." If it truly wants to develop efficient and responsible energy supplies, such a body should focus on the nuclear option, on establishing a secure international nuclear-fuel storage and reprocessing system, and on providing expertise for siting, financing, and licensing modular nuclear power systems to developing nations.

According to Arnulf Gruebler, Nebojsa Nakicenovic, and David Victor, who study the dynamics of energy technologies, "the share of energy supplied by electricity is growing rapidly in most countries and worldwide." Throughout history, humankind has gradually decarbonized its dominant fuels, moving steadily away from the more polluting, carbon-rich sources. Thus the world has gone from coal (which has one hydrogen atom per carbon atom and was dominant from 1880 to 1950) to oil (with two hydrogens per carbon, dominant from 1950 to today). Natural gas (four hydrogens per carbon) is steadily increasing its market share. But nuclear fission produces no carbon at all.

Physical reality — not arguments about corporate greed, hypothetical risks, radiation exposure, or waste disposal — ought to inform decisions vital to the future of the world. Because diversity and redundancy are important for safety and security, renewable energy sources ought to retain a place in the energy economy of the century to come. But nuclear power should be central. Despite its outstanding record, it has instead been relegated by its opponents to the same twilight zone of contentious ideological conflict as abortion and evolution. It deserves better. Nuclear power is environmentally safe, practical, and affordable. It is not the problem — it is one of the best solutions. ❐