NUCLEAR POWER:

A Nuclear Solution to Climate Change?

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The U.N. Framework Convention on Climate Change calls for the stabilization of greenhouse gas concentrations at a level that would prevent dangerous changes in climate. An ambitious target would be stabilization at an equivalent doubling of the preindustrial CO_2 concentration. To achieve this, fossil-fuel carbon emissions in 2050 should not exceed their current level, despite an expected doubling or tripling in world demand for energy (1).

Lacking a crystal ball that tells us the future, we simply select one possible scenario that achieves the emissions target (see the table on the right) (2). We assume that by 2050, world population and average per-capita energy consumption each rise by 50%, with annual world primary energy consumption reaching 900 EJ (exajoules, 10^{18} joules). A roughly equal contribution of 300 EJ each is assumed for conventional fossil fuels, for renewable and "decarbonized" fossil fuel sources, and for nuclear fission (3).

This is a challenging scenario, especially because restraining the increase in average per-capita energy consumption in the face of the economic aspirations of developing countries will require substantial improvements in energy efficiency.

Obtaining 300 EJ from renewable energy sources and "decarbonized" fossil fuels will also be difficult. A major expansion of hydropower is precluded by environmental considerations. A major expansion in the use of biomass fuels would require vast land areas, in competition with increasing food production and the preservation of natural ecosystems. It is unclear whether solar photovoltaics can be made economically competitive, even with subsidies, and supplying a substantial fraction of electricity demand with either solar- or wind-based power would require massive and inexpensive energy storage or very-long-distance transmission. Fossil fuels can be "decarbonized" by removing and sequestering carbon dioxide, but this approach is still in an early stage of development. Thus, the 300 EJ target requires success with technologies that are in early stages of development, with highly uncertain costs and environmental impacts (4).

SCENARIO FOR ENERGY CONSUMPTION IN 2050, WITH COMPARISONS TO 1997

	1997 World	1997 U.S.A.	1997 France	2050 World
Population (millions)	5857	268	59	9000
Total primary energy* (EJ/year)	400	99	10.3	900
Fossil fuel (EJ/year)	343	85	6.2	300
Renewable (EJ/year)	30	5.2	0.7	300†
Nuclear (EJ/year)	25	7.1	4.1	300

Total per capita (EJ/year)	68	371	175	100
Fossil fuel fraction (%)	86	85	61	33
Nuclear energy				
Generation (GW-year/year)	259	72	43	3300
Per capita (kW-year/year)	0.04	0.27	0.73	0.36
Fraction of electricity (%)	17	18	79	>50
CO_2 emissions (MTC)	6232	1489	102	5500

*The reported total energies for 1997 differ slightly from the sum of the components, largely due to the treatment of biomass energy (for the United States) and electricity exports (for France). The reported renewable energy data for 1997 omit most biomass energy. †Energy from "decarbonized" fossil fuel use is included here.

The indicated 300 EJ nuclear contribution corresponds to roughly 3300 gigawatt-years (GW-year, the output from a large electric plant) per year. World per-capita nuclear output would then be half the current rate in France, where most of the growth in nuclear output took place in the 20 years following 1977. Reaching half of France's present per-capita output by the midpoint of the century should be possible in principle, but only if there is strong government and popular support in many countries and a major commitment of industrial resources.

Nuclear Reactor Safety

The present generation of nuclear reactors has had a good safety record, with the major exception of the Chernobyl-type reactors. Outside the former Soviet Union, about 8500 reactor-years of commercial nuclear power-plant operation have been realized until now, with no accident involving a large external release of radioactivity and only one accident with fuel melting: the 1979 accident at Three Mile Island (TMI).

These numbers suggest that the risk of an accident with fuel damage has averaged approximately 10^{-4} per reactor-year, corresponding under common assumptions to a large external release of radioactivity at a rate of 10^{-5} per reactor-year. But this performance would not suffice for a world with ~4000 reactors, because the expectation would then be for a TMI-scale nuclear accident every several years.

However, changes in equipment and operating procedures since TMI suggest considerably improved safety. The likelihood of an accident that proceeds all the way to core damage can be estimated by analyzing data on the occurrence of individual system malfunctions (precursor events). Such analyses of actual U.S. reactor performance show a drop of roughly a factor of 100 in the inferred core damage probability, when comparing the 1994-1998 record with that for the pre-TMI period of 1974-1978 (5, 6).

There are also well-developed designs for a next generation of reactors, which promise still greater safety. Of these, the advanced boiling water reactor (ABWR) is the first to have been ordered, with two now operating in Japan. The probability of core damage is estimated by the ABWR designers to be 2×10^{-7} per reactor-year and by the staff of the U.S. Nuclear Regulatory Commission to be "on the order of 10^{-6} or less" if the plant is built and operated as specified (7, 8).

Research is under way to design a further generation of advanced reactors that differ from previous generations in that they make greater use of passive safety systems, based on simple physical laws. Because they will require no immediate operator intervention in the case of malfunction, they are expected to operate with extremely low levels of risk to the public.

Nuclear Economics

The competitive posture of nuclear power needs to be improved by reducing both construction time and capital cost.

The existence of competitive electricity markets requires each new plant to make economic sense on a relatively short time scale. In these circumstances, no carbon-free energy source can compete in the United States with the combined-cycle gas-fired plants, given the low cost of natural gas, the short lead times for the construction of these plants, and their high thermal-to-electric conversion efficiency.

This competitive situation is likely to change only if natural gas prices rise significantly or if the government intervenes, for example, with a carbon tax placed on fossil fuels or with subsidies provided for "clean" fuel. Our estimates indicate that new nuclear plants could compete in the market if there were a tax of ~$100 per ton of carbon placed on fossil fuels (9). We do not advocate such a high tax now; rather the tax should start at a low level and be phased in gradually so as to reach its full value over several decades.

In the meantime, the U.S. Department of Energy and other agencies worldwide should increase reactor research efforts aimed at simplified designs and economies of scale in construction. Governments need to make institutional and regulatory reforms to reduce lead times for plant deployment.

Nuclear Waste Disposal

Plans for waste disposal in almost all countries are based on their eventual placement in deep geological repositories. In the United States, advisory groups such as the National Academy of Sciences have consistently endorsed this approach (10). The effort in recent years has been directed toward the study of the disposal of spent nuclear fuel in a National Repository located at Yucca Mountain, Nevada (11).

This site is intended to provide an environment in which little water will reach the wastes, which will consist mostly of spent fuel rods enclosed in rugged protective canisters. The canisters and the fuel pellets within them will corrode only very slowly, retaining their integrity for thousands of years. During this time, most of the radioactivity will decay away. Further protection is provided by the slowness of the migration of escaping radionuclides through the surrounding media to the accessible environment.

The U.S. Environmental Protection Agency has proposed a rigorous standard for protection of people living near the repository (12). For the next 10,000 years, the radiation dose must not exceed 0.15 millisieverts [15 milli-roentgen-equivalent-man (mrem)] per year for a hypothetical "reasonably maximally exposed individual." This dose is 5% of the average annual dose to an individual in the United States from natural sources.

If the U.S. repository is found to meet the standard and is opened, it will be able to handle all the U.S.

wastes expected through the next few decades. However, a large expansion of nuclear power may require using alternative disposal approaches; studies of these alternatives should then be intensified.

Any nuclear waste project will have to fight legal challenges. Politics will certainly be a significant component. For instance, the state of Nevada has already spent considerable effort fighting the Yucca Mountain Project, which the state claims has been forced upon it. Public support for these claims could decrease if nuclear energy were seen as a necessary part of a solution for climatic problems and, overall, as environmentally beneficial. Nevadans might then be more willing to accept the miniscule risks resulting from having a repository in their state.

Nuclear Proliferation

There must be international confidence that nuclear power can be used throughout the world without increasing weapon proliferation. To date, commercial nuclear power has played little, if any, role as a bridge to national entry into the nuclear arms race, nor are there any known cases in which individuals or subnational groups have stolen materials from nuclear power facilities for use in weapons. However, development of nuclear weapons has been aided in at least three countries (India, Iraq, and Israel) by use of research reactors obtained under the cover of peaceful research programs. In the absence of effective safeguards, nuclear power could provide a similar cover to future weapons efforts.

Additional fears are raised by the possibility that with a major nuclear expansion, plutonium-fueled breeder reactors will be widely used to stretch uranium resources, creating risks of plutonium diversion for weapons purpose. However, the recovery of uranium from seawater, which has been performed on a laboratory scale in Japan, may be possible on a commercial scale at a cost that postpones indefinitely the need for a breeder program. Another possibility is the use of thorium and uranium blends to stretch reserves (13). Pending a fuller understanding of the resource prospects, both closed and open fuel cycles (that is, with and without reprocessing) should be kept as options for the future if an expansion of nuclear power is needed.

However, all fuel cycles pose some proliferation risk, and even the elimination of nuclear power would not eliminate the possibility of a country embarking on a nuclear weapons program. Thus, improved institutions for international safeguards are needed, with strength and responsibility at an entirely new level of capability, even in the absence of a major expansion of nuclear power.

Conclusions

Nuclear power can play a significant role in mitigating climate change. There are no insurmountable technical barriers to nuclear expansion, but the expansion must be performed under very high safety standards. Additionally, capital cost reductions from advanced designs and production methods will be required. It is therefore important to maintain and intensify current programs of research and development on power reactors, waste disposal, and nuclear safeguards to assure that safe nuclear power is available when it is needed.

References and Notes

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2. "International energy annual report 1997," report DOE-EIA-0219(97) [U.S. Department of Energy (DOE), Washington, DC, 1999].
3. It is assumed in the table that the mix of fossil fuels does not change. If the coal share decreases and the natural gas share increases, still less CO_2 will be produced.

4. For example, for the United States in 1998, the contributions of renewable sources to total electricity generation (by utility and nonutility producers) were hydroelectric, 9.0%; biomass, 1.5%; geothermal, 0.4%; wind, 0.1%; and direct solar (including photovoltaic), 0.02%. See "Annual energy review 1998," report DOE-EIA-0384(98) (DOE, Washington, DC, 1999), Table 8.2.
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7. *The ABWR General Plant Description* (GE Nuclear Energy, San Jose, CA, 1999).
8. "Final safety evaluation report related to the certification of the advanced boiling water reactor design," main report, NUREG 1503 (NRC, Washington, DC, 1994), vol. 1, p. 19-6.
9. This tax level is about 30 cents per gallon of petroleum or 2.8 cents per kilowatt-hour of electricity from coal.
10. See, for instance, "A study of the isolation system for geological disposal of radioactive wastes," Waste Isolation Systems Panel, National Research Council (National Academy Press, Washington, DC, 1983).
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