Is There a Sustainable Future for Nuclear Power?

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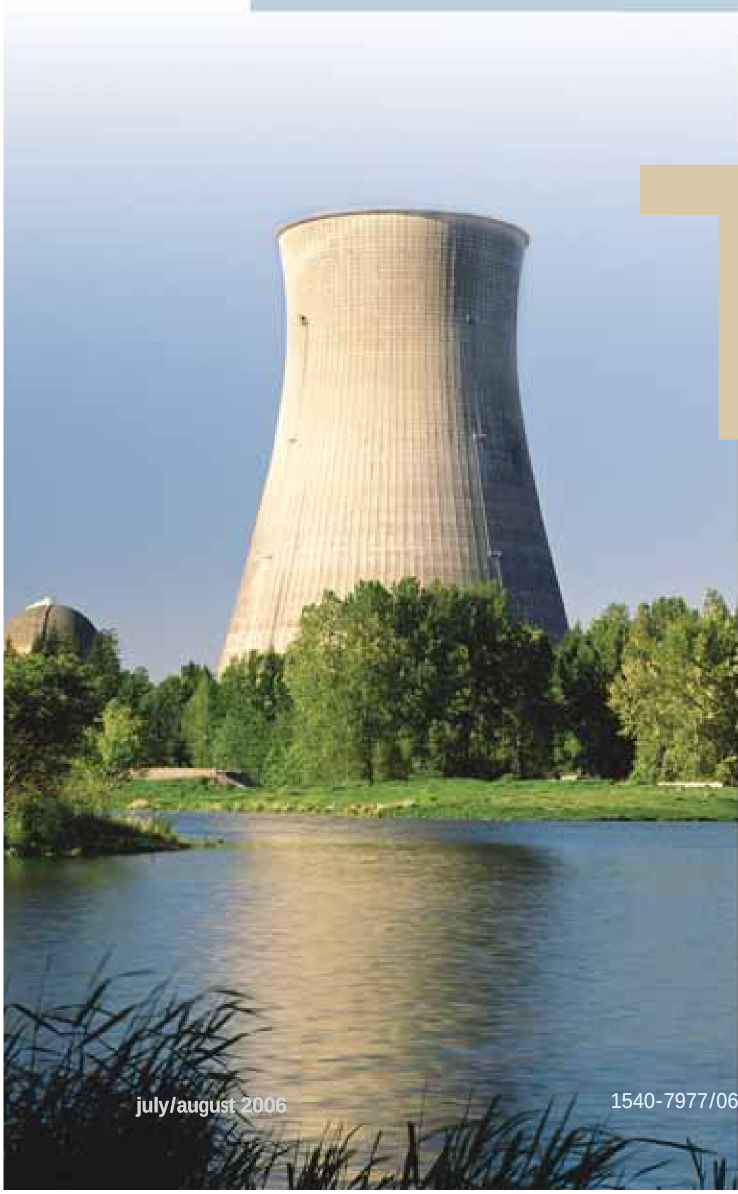
A Troubled Past and Contested Present Will Shape Its Future.



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THE HISTORICAL RECORD SHOWS THAT NUCLEAR power has a troubled past; today's media highlights its contested present and uncertain future. In this regard, nuclear power exemplifies some important characteristics of engineering:

- Engineering has a military heritage that remains influential to this day. The boundaries between its military and civilian applications are often blurred. The main difference between the process of nuclear fission for electricity generation and nuclear fission for weapon applications is only the rate at which this process takes place.
- The social, economic, and environmental dimensions of engineering can be as important as the scientific dimension. There are few significant engineering technologies that don't have important social, economic, and/or environmental consequences, which can make engineering a highly contested domain.
- Engineering is concerned with influencing the future, which is subject to uncertainty and requires the exercise of judgment. Thus, engineering projects can be regarded as social experiments for which informed consent should be sought from those who may be potentially affected. By definition, this approach will not be followed for military applications of engineering. Nor can it be followed for decisions that may have significant consequences for future generations. Thus we can expect differing views about technologies such as nuclear power.
- Once developed, successful engineering technologies tend to fall into disuse only if they are superseded. Nuclear

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power is unlikely to suffer this fate because it offers overwhelming military force and considerable foreign policy impact.

These matters are exemplified, at the time of writing (early 2006) by renewed government support for building new civilian reactors in the United States and changing public opinion regarding such developments and ongoing controversy surrounding the nuclear programs of some nations. More generally, significant uncertainties remain regarding crucial elements of any future large-scale expansion of the use of civilian nuclear power, including nuclear weapon proliferation, safety, and waste management. Wider uncertainties include nuclear power's potential to help us avert the growing risks of dangerous climate change.

Clearly the "rational decision-making" paradigm is of limited value in this context as it involves too many dimensions and too many matters of judgment on which there may be legitimate differences of opinion. Invariably, nuclear power will elicit polarized responses, and these are not considerations from which the writers of this article are immune. (The authors are engineers and social scientists on power and environmental markets and, in this context, concerned with the economic, environmental, and technical sustainability of the stationary power sector. Much of our work focuses on better understanding the various barriers and possible policy responses to facilitate our society's transition to more sustainable systems.) More pertinently, nuclear power's military and foreign policy dimensions may trump other considerations.

In this article, we focus on nuclear power's application to electricity generation, noting that its military and foreign policy implications cannot be ignored and thus must be considered. We first set out a sustainability framework for assessing electricity industry design options and discuss the key issues for nuclear power in this context. We then review nuclear power's troubled past and contested present. Nuclear power's uncertain future is explored through three general scenarios of how nuclear power might fare—broadly classified as *decline*, *business as usual*, and *renaissance*. Finally, we discuss how societies might make decisions about the future of nuclear power as well as the role of the engineering profession in that process.

A Framework for Assessing Our Energy Options

We suggest that technologies with the widespread and long-term ramifications that nuclear power exhibits should be assessed at a societal level. We propose that societies assess nuclear power using the principle of sustainable development, which states that the current human generation should not compromise the ability of future generations to meet their needs. This principle underlines the strong ethical obligations of decision makers when they consider technologies such as nuclear power.

The dominant civilian use of nuclear power is to produce electrical energy in large power stations, sometimes in conjunction with district heating schemes. Other potentially significant applications include desalination and hydrogen production. In this article we focus on its use in the electricity industry, a vitally important part of the stationary energy sector in virtually all countries.

The objective of the stationary energy sector is to deliver desired energy services for end users. The electricity industry has come to play a key role in the stationary energy sector because electrical energy is a flexible energy form that can be readily created from most primary energy forms and readily converted into most end-use energy forms. Vast electricity industries have been constructed and, because of their success, access to electrical energy has come to be regarded as an essential service. Because of its relatively low cost, little thought is now given to frugality or careful use of electrical energy.

As another product of its success, the electricity industry interacts with most members of society and most social institutions. Everybody is a stakeholder. Moreover, the electricity industry plays a vital role in modern economies and has become essential to society as well as to individuals. Safety and security of energy supply have become key issues. Institutions and governance arrangements have been created to deal with the particular characteristics of the electricity industry. Many countries are currently undertaking processes of electricity industry restructuring, in which industry structure, organization, and governance are changed to exploit competition in a more commercially oriented industry framework.

All energy technologies have a range of adverse environmental externalities. These differ from one technology to another in kind and magnitude, in geographical scale from local to global, and in time scale from short to long term. When an electricity industry is considered as a whole, its large size invariably implies large environmental impacts.

From considerations of this kind, the World Energy Council has proposed three energy goals: *accessibility* to affordable energy services; *availability* of continuous and secure supply; and *acceptability* in terms of environmental goals and public attitudes.

Existing electricity industries reflect these goals to varying degrees. However, there is considerable diversity within and between countries. The major differences in accessibility and availability are between developed and developing countries. The major differences in acceptability arise from the primary energy forms that are used to generate electricity, as this is where the most important environmental and social impacts usually arise.

As electricity industries have grown, they have become important vectors for making fossil fuels (particularly coal and, more recently, natural gas) available via electrical energy to large numbers of people for a wide range of end-use energy service applications. Fossil fuels now provide around 80% of global commercial energy supply and have underpinned the development of modern societies. Fossil fuels' attractive energy payback (energy delivered compared to the energy required for extraction), their energy density, and their handling convenience have made them extremely competitive against other options, including end-use efficiency, renewable energy, and nuclear power.

However, fossil fuels are now losing favor because of growing energy security concerns and environmental implications, climate change in particular. Furthermore, there are no ideal alternatives—all have adverse environmental, social, and cost implications. We now face hard choices in an increasingly constrained domain. It is within this context that nuclear power and all of our other energy options must be compared.

Nuclear Power's Troubled Past

The nuclear bombs dropped by the United States on the Japanese cities of Hiroshima and Nagasaki in 1945 heralded the arrival of nuclear power. No other energy technology has made such an impact on the public's mind as an astounding source of military power and foreign policy strength. Many important technologies such as aircraft have had a military launching pad, but none has been so immediately destructive or decisive.

In this context, U.S. President Dwight D. Eisenhower's "Atoms for Peace" speech to the United Nations (UN) in 1953 had revolutionary intent: "It is not enough to take this weapon out of the hands of the soldiers. It must be put into the hands of those who will know how to strip its military casing and adapt it to the arts of peace."

From the 1950s, civilian nuclear power programs accompanied (and benefited from) the ongoing development of its military applications. The USSR was the first country to connect a nuclear power station to the grid in 1953, followed by the United Kingdom and then the United Stateas. The continuing link between the military and civilian programs is illustrated by the nuclear power station installed in Shippingport, Pennsylvania, in 1957, which used a light water reactor (LWR) designed for use in submarines. Similarly, Operation Plowshare in the United States in the early 1960s explored the potential peaceful use of nuclear explosions for civil engineering projects. In 1958, Ford even announced a nuclear-powered car concept, the Nucleon. A small reactor, thoughtfully located some distance behind the passenger compartment, was to provide the car with a range of some 5,000 mi.

Meanwhile, global nuclear power station capacity rose to 100 GW towards the end of the 1970s and 300 GW by the late 1980s. By that time, public enthusiasm for nuclear power had been dampened by fallout (of various kinds) from nuclear weapon testing and accidents at nuclear facilities, most notably Three Mile Island and Chernobyl. The rate of nuclear power station construction fell sharply. Installed capacity now stands at about 370 GW with around 22 GW currently under construction.

Nuclear Power's Contested Present

Some argue that civilian nuclear power is a great success story. What began as a devastating weapons technology, a few decades later provides a significant proportion of electricity supply in over 30 developed and developing countries. There is no doubt that controlled nuclear fission represents an astounding technical achievement and an iconic technology. It is a prime example of "big science," in which massively resourced mission-oriented research and development (R&D) rapidly converted emerging scientific knowledge into a working technology.

Others argue that nuclear power represents one of our society's greatest technological failures. Not only did it not live up to some early promises of being "too cheap to meter," but it has been a vehicle for weapons proliferation and created a legacy of dangerous waste that future generations will have to manage. The accidents at Three Mile Island and Chernobyl among others show that it can threaten the safety of our communities if it is not wisely managed. The public in many countries is sceptical of the technology and the institutions that surround it. The industry is, indeed, a favorite case study for experts in what can go wrong in technological development, giving rise to notions such as the creation of a technological priesthood, so-called normal accidents, and technology lock-in.

So where does nuclear power now stand? It provides some 22% of electricity in the Organisation for Economic Cooperation and Development (OECD) countries and 6% in developing countries. Table 1 presents the current nuclear generation, plant under construction, and future plans of each of the 37 countries that currently have, or propose to have, civilian nuclear power generation.While some 20 GW of plant is now under construction, new capacity since 2000 represents barely 2% of total new global generating capacity over that time, currently averaging around 150 GW/year. Only one plant is under construction in Europe and none in the United States, although this may change soon. Energy projections by the International Energy Agency (IEA) and U.S. Energy Information Administration (EIA) forecast only modest worldwide growth in nuclear installed capacity.

However, nuclear power is clearly back on the agenda. Its revival is partly due to progress on some of the "old" issues, including economics, safety, and waste management. More

table 1. World nuclear power reactors 2004–2006 and uranium requirements. Sourced from the World Nuclear Association's online database of civilian nuclear power plants (http://www.world-nuclear.org).

	Nuclear Electricity Generation 2004		Reactors Operable Jan. 2006		Reactors Under Construction Jan. 2006		Reactors Planned Jan. 2006		Reactors Proposed Jan. 2006	
	Billion kWh	% e	No.	MWe	No.	MWe	No.	MWe	No.	MWe
Argentina	7.3	8.2	2	935	1	692	0	0	0	0
Armenia	2.2	39	1	376	0	0	0	0	0	0
Belgium	44.9	55	7	5,728	0	0	0	0	0	0
Brazil	11.5	3.0	2	1,901	0	0	1	1245	0	0
Bulgaria	15.6	42	4	2,722	0	0	2	1,900	0	0
Canada*	85.3	15	18	12,595	0	0	2	1,540	0	0
China	47.8	2.2	9	6,587	2	1,900	9	8,200	19	15,000
Czech Republic	26.3	31	6	3,472	0	0	0	0	2	1,900
Egypt	0	0	0	0	0	0	0	0	1	600
Finland	21.8	27	4	2,676	1	1,600	0	0	0	0
France	426.8	78	59	63,473	0	0	0	0	1	1,600
Germany	158.4	32	17	20,303	0	0	0	0	0	0
Hungary	11.2	34	4	1,755	0	0	0	0	0	0
India	15.0	2.8	15	2,993	8	3,638	0	0	24	13,160
Indonesia	0	0	0	0	0	0	0	0	4	4,000
Iran	0	0	0	0	1	950	2	1,900	3	2,850
Israel	0	0	0	0	0	0	0	0	1	1,200
Japan	273.8	29	55	47,700	1	866	12	14,782	0	0
Korea DPR (North)	0	0	0	0	1	950	1	950	0	0
Korea RO (South)	124.0	38	20	16,840	0	0	8	9,200	0	0
Lithuania	13.9	72	1	1,185	0	0	0	0	1	1,000
Mexico	10.6	5.2	2	1,310	0	0	0	0	0	0
Netherlands	3.6	3.8	1	452	0	0	0	0	0	0
Pakistan	1.9	2.4	2	425	1	300	0	0	2	1,200
Romania	5.1	10	1	655	1	655	0	0	3	1,995
Russia	133.0	16	31	21,743	4	3,600	1	925	8	9,375
Slovakia	15.6	55	6	2,472	0	0	0	0	2	840
Slovenia	5.2	38	1	676	0	0	0	0	0	0
South Africa	14.3	6.6	2	1,842	0	0	1	165	24	4,000
Spain	60.9	23	9	7,584	0	0	0	0	0	0
Sweden	75.0	52	10	8,938	0	0	0	0	0	0
Switzerland	25.4	40	5	3,220	0	0	0	0	0	0
Turkey	0	0	0	0	0	0	0	0	3	4,500
Ukraine	81.1	51	15	13,168	0	0	2	1,900	0	0
United Kingdom	73.7	19	23	11,852	0	0	0	0	0	0
USA	788.6	20	103	97,924	1	1,065	0	0	13	17,000
Vietnam	0	0	0	0	0	0	0	0	2	2,000
WORLD**	**2,618.6**	**16**	**441**	**368,386**	**24**	**18,816**	**41**	**42,707**	**113**	**82,220**

Sources:

Reactor data: WNA to 28 November 2005.

IAEA—for nuclear electricity production & percentage of electricity (% e) 7 July 2005.

WNA: Global Nuclear Fuel Market (reference scenario)—for U. Operating = Connected to the grid

Building/Construction = first concrete for reactor poured, or major refurbishment under way

Planned = Approvals and funding in place, or construction well advanced but suspended indefinitely

Proposed = clear intention but still without funding and/or approvals

TWh = terawatthours (billion kilowatthours), MWe = megawatt net (electrical as distinct from thermal), kWh = kilowatthour

NB: 68,357 tU = 80,613 t U_3O_8

* In Canada, "planned" figure is two laid-up Bruce A reactors.

** The world total includes six reactors on Taiwan with a combined capacity of 4,884 MWe, which generated a total of 37.9 billion kWh in 2004 (accounting for 21% of Taiwan's total electricity generation). Taiwan has two reactors under construction with a combined capacity of 2600 MWe.

important, however, are "new" issues including climate change, energy security, and evolving concerns about a new round of nuclear weapon proliferation. We now consider these in more detail and in the context of the complete civilian nuclear fuel cycle (as shown in Figure 1) and its present international distribution (as shown in Figure 2).

Nuclear Issues—Old and New

Nuclear waste management is a key issue in the social and environmental acceptability of nuclear power. The nuclear fuel cycle produces relatively small amounts of high-level wastes (typically less than a few percent by volume but the great majority of total radioactivity) requiring significant care over very long periods of time and much larger amounts of medium- and low-level wastes requiring less specialized management. Industrial societies create many wastes, including persistent organic pollutants (POPs) that are difficult to manage safely. Nevertheless, the high- and medium-level nuclear waste streams are special because of potential proliferation risks and the very long time frames of risk, where the very stability of civilization required to manage them can be questioned. Complicating matters, these waste streams also have potential value as a source of nuclear fuel should reprocessing be undertaken, The nuclear industry, from mining through to waste disposal, has a history of poor practices with significant impacts in many countries—in part because of the urgent military imperatives of its early development and consequent disregard for externalities.

Both potential solutions and additional challenges have now appeared. Deep geological disposal may offer a reasonable compromise between safety, security, economics, and possible future opportunities to treat or even reuse some of the nuclear materials. The design of the Yucca Mountain facility in the United States is shown in Figure 3. A number of countries, such as Finland and Sweden, have advanced preparations in place. However, there is, as yet, not a single authorized and operational final disposal repository for high-level wastes, and what constitutes acceptable performance is still uncertain. Countries with nuclear wastes have markedly different financial and technical capabilities in managing them appropriately. Public opposition to repository sites can be very influential.

Wider questions include the possible impact of closed fuel cycles, which would potentially reduce the levels of waste, and the impacts of power station decommissioning. Some countries have levies to "cover" decommissioning, but they still represent significant potential liabilities. For example, the United Kingdom estimates that decommissioning of existing sites will cost around US$100 billion. Note, however, that new power stations would not necessarily involve nearly such a large burden as they have been designed with decommissioning in mind.

Finally, waste management is rarely a high-status activity and is likely to be driven by regulated obligations. The issue of responsibility and accountability remains unresolved between user-pays and extended uranium producer responsibility.

Safety is another important issue for social and environmental acceptability. All energy technologies and fuel cycles have risks; consider, for example, coal mining and liquefied natural gas (LNG) tankers. Still, nuclear power is different. While many plants have excellent safety records, there have been a number of serious and near miss accidents that

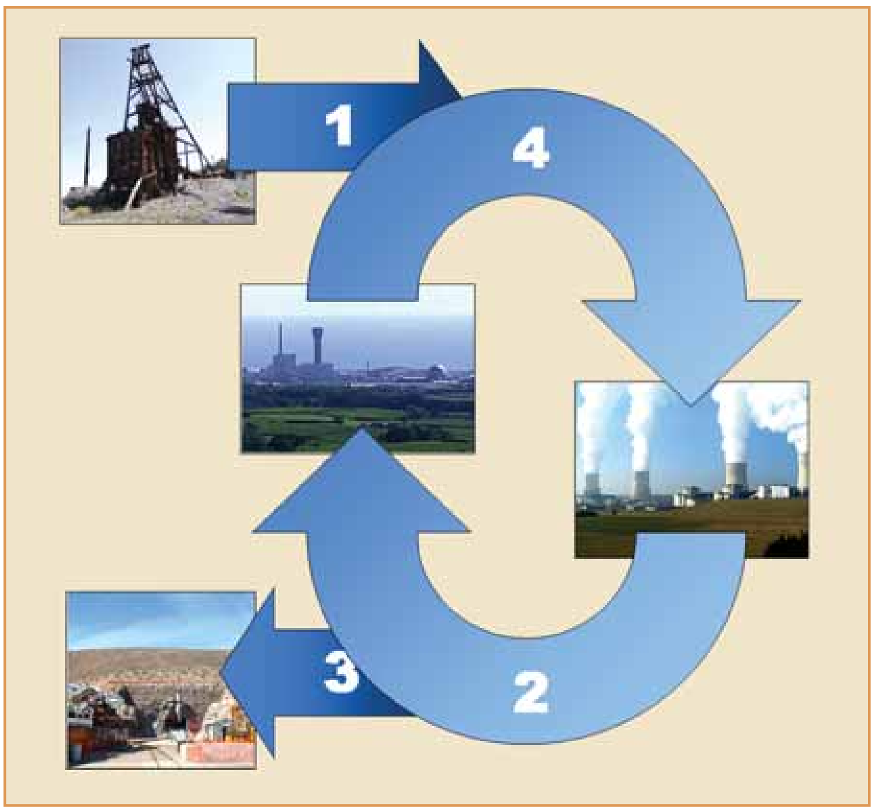

figure 1. The civilian nuclear fuel cycle. 1) Uranium is mined, enriched, and manufactured into nuclear fuel for nuclear power plants. 2) Spent fuel from the power plant is delivered to a reprocesssing plant or 3) to a final repository such as deep geological disposal. 4) In reprocessing, up to 95% of the uranium and plutonium in the spent fuel can be recovered and processed into a mixed oxide fuel suitable for reuse in nuclear power plants. Note that the enrichment and reprocessing steps represent opportunities to make nuclear materials suitable for weapons programs. (Courtesy of Tungsten.)

highlight the risks involved. It is always challenging to properly assess, let alone manage, low-probability but high-consequence risks.

The challenge is that nuclear power stations must maintain controlled nuclear fission, balancing between extinguishment and uncontrolled criticality. Present nuclear power stations use a combination of passive design and active control systems to maintain this balance. Nuclear power stations may contain a year or more supply of highly radioactive fuel; the consequences of any error can be significant. Table 2 presents the current global mix of different nuclear power plant technologies. First-generation civilian power stations are particularly problematic—for example, the U.K. Magnox and Russian VVER 440-230s. The G8 and European Union (EU) have decided that the latter units cannot be economically raised to sufficient safety levels and that those in Europe will have to be shut down. Second-generation units comprise the vast majority of the world's nuclear fleet and also have safety concerns. Finally, around 75% of nuclear plants are now over 20 years old.

The safety of operating nuclear power stations can be enhanced via technical progress in monitoring and control systems. However, the aging of these units and plans for lifetime extensions may have adverse safety impacts. The new third-generation plants now being built have far greater inherent, that is, passive, safety. However, they are unlikely to achieve "walk away" safety levels. The excellent safety

figure 2. The international nuclear fuel cycle. (Courtesy of Uranium Information Centre; http://www.uic.com.au.)

table 2. The number and total electrical capacity of the different types of nuclear power plants currently in commercial operation (Courtesy of the Uranium Information Centre: *The Nuclear Engineering International Handbook 2005*).

Reactor Type	Main Countries	Number	GWe	Fuel	Coolant	Moderator
Pressurized water reactor (PWR)	United States, France Japan, Russia	268	249	Enriched UO_2	Water	Water
Boiling water reactor	United States, Japan, Sweden	94	85	Enriched UO_2	Water	Water
Gas-cooled reactor (Magnox & AGR)	United Kingdom	23	12	Natural U (metal), enriched UO_2	CO_2	Graphite
Pressurized heavy water reactor	Canada	40	22	Natural UO_2	Heavy water	Heavy water
Light water graphite reactor (RBMK)	Russia	12	12	Enriched UO_2	Water	Graphite
Fast neutron reactor (FBR)	Japan, France, Russia	4	1	PuO_2 and UO_2	Liquid Sodium	None
Total		441	381			

records of many operating nuclear power stations highlight what can be achieved. However, best practice isn't necessarily standard practice, and even highly industrialized countries can get this wrong. Many of the nuclear facility accidents to date seem to have been as much about sloppy management as technology, reflecting the difficulties in managing low probability but high consequence events. Continuing with nuclear power must involve a far greater commitment to failsafe management and organizational design than has characterized the industry to date.

The risk of malevolent actions against nuclear plants is also receiving increased attention now. Nations or terrorists can create a crude form of nuclear weapon by destroying a nuclear power station in a target country. Such a nuclear power station, provided by the attacked country, may hold an order of magnitude more radioactivity than a nuclear weapon.

Energy security has social accessibility and acceptability aspects. The oil crises of the 1970s illustrated potential risks to fossil fuel supplies and drove considerable nuclear development in countries such as France and Japan. It is not difficult to maintain a store of five or more years of fuel supply for a nuclear power station.

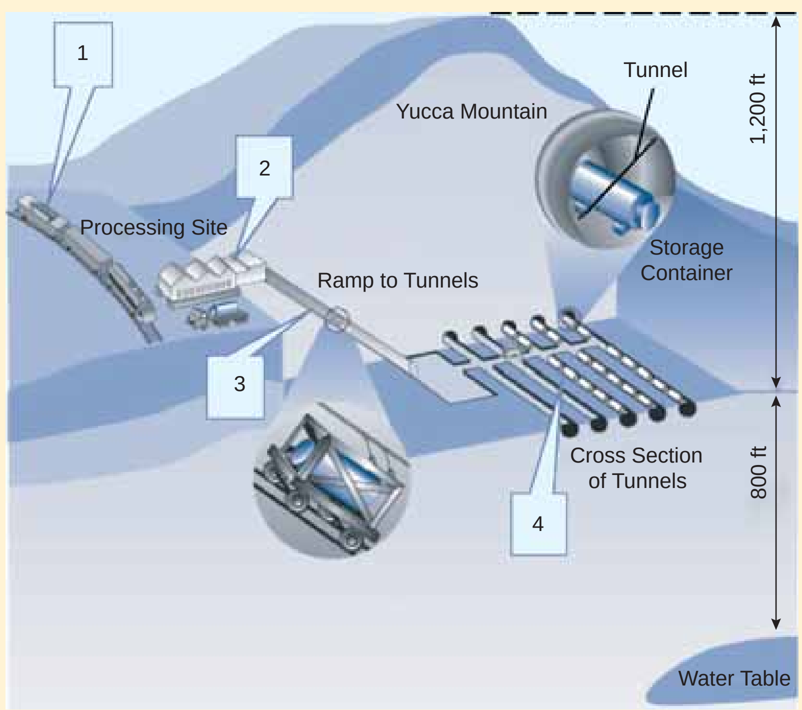

figure 3. The conceptual design of Yucca Mountain Disposal Plan. (Courtesy of the U.S. Nuclear Regulatory Commission).

Deep geological disposal may offer a reasonable compromise between safety, security, economics, and possible future opportunities to treat or even reuse some of the nuclear materials.

The OECD estimates that over 40 countries have potentially economic uranium resources. Nevertheless, Canada and South Africa are among the few countries with nuclear power programs that are currently self-sufficient in uranium. Almost half of nuclear power station fuel currently comes from military stockpiles diluted for this purpose—one of the benefits of the intimate connection between civilian and military nuclear materials.

There are now growing concerns about supply constraints on oil and, to a lesser extent, natural gas production. Geopolitical factors are coming into play, from increasing natural gas prices in the United States to concerns about Russian control over much of Europe's natural gas supply and the Middle East's growing role in meeting oil demand.

The prospect of expanded nuclear power generation and the rundown of military supplies have raised questions about both short-term and longer-term uranium availability. Much of the longer-term concern hinges on the nebulous concept of resources versus reserves and the impact that market demand (and increasing prices) has on this. It is not just nuclear power opponents who raise questions of available reserves; the U.S. Department of Energy (DOE) argues the need for closed-fuel cycles in fourth-generation plants on this basis. However, other observers argue that there is ample uranium to support an expanded nuclear power program running on a once-through fuel cycle well into the second half of this century. The increasing prices for uranium now being experienced should help answer this question over time as production efforts ramp up. Moreover, thorium may prove to be a suitable reactor fuel in the future.

The economics of nuclear power have availability and social acceptability implications. There is no doubt that some countries with a significant commitment to nuclear power have affordable, if not low cost, electricity by international standards. However, it is difficult to establish the unsubsidized costs. The true costs are concealed by very significant public funding (around half of all publicly funded energy R&D in IEA countries over the last 30 years), the blurring of military and civilian budgets for nuclear materials and technologies, investment by monopoly utilities with captive end users, rate-of-return cost structures, and state-underwritten insurance against potential accident liabilities in some countries.

Nuclear power stations have high capital but low operating costs, a similar characteristic to a number of forms of renewable energy generation. Low operating costs mean that once a nuclear power station is built, it will often be competitive in operating costs with other power station technologies. However, societies should compare technologies on the basis of full life-cycle costs including externalities. Some countries impose levies on nuclear power stations to cover waste disposal, which assists transparency.

The debate on nuclear power costs has recently been reignited with different studies placing nuclear power costs below, equivalent to, or well above those of other generation options. The electricity industry restructuring processes seen in much of the world might help to illuminate this debate because nuclear then has to compete against a range of other options in an, at least partially, commercial framework. So far, private players in restructured electricity industries appear lukewarm on nuclear investments for a number of reasons, including high capital costs, long build times, risks of public opposition, and uncertain waste management arrangements.

This is not the end of the issue however. Current energy markets do not generally reflect important environmental externalities such as climate-change emissions and can struggle to reflect other important issues such as longer-term energy security. They may also struggle to drive major energy system transformation, such as that required to meet the burgeoning energy demands of newly industrializing nations like China and India. There may still be a case for strategic government support for nuclear power.

The debate about the role of nuclear power in environmental protection has been an important recent development in the broader nuclear debate. Beyond the special nature of the radioactive environmental pollutants of nuclear power noted earlier, nuclear power has far lower emissions of some traditional local and regional air pollutants (for example, heavy metals, SOx, and NOx) than fossil fuel generation. For nuclear power plants themselves, radioactive material releases are only a small fraction of natural background radiation, and they are usually lower than radioactive material releases from fossil fuel use. Uranium mining and spent fuel reprocessing may have far more significant impacts, but in well-managed facilities, these appear to be reasonable, barring accidents. The risk of accidents (or terrorism) in nuclear facilities with consequent major radiation release, however, still makes nuclear power unique.

Growing concerns about climate change have added a new dimension to decision making in the energy sector, including consideration of the nuclear power option. The latest climate science is alarming, both in terms of the projected adverse impacts of even moderate global warming and the large and immediate reductions in climate-change emissions required to avoid these impacts. Recent work presented at a U.K. conference on avoiding dangerous climate change suggests a daunting task: global emissions might have to peak within the next two decades and then fall by as much as 50% (compared to 1990 levels) by 2050. Given the legitimate aspirations of the developing world, meeting this target would require developed nations to begin reducing their emissions immediately. There is certainly no time for delay—if action to reduce emissions is delayed by 20 years, rates of emission reduction may need to be 3–7 times greater to meet the same temperature target. Furthermore, most of these reductions will have to come from a reduced reliance on fossil fuels.

Such action on climate change would involve many hard and unpleasant choices. The IPCC suggests that the most important actions involve energy conservation and end-use energy efficiency. On the supply side, key issues for our available energy options are their life-cycle climate-change emissions, potential for rapid deployment, and costs.

No energy technologies have zero emissions over their entire life cycle—even renewable resources such as wind energy require energy to be invested in building the wind turbines. There is considerable debate over whether nuclear power is a low-carbon technology, which hinges on the energy used in constructing, maintaining, and eventually decommissioning the power stations. The energy used to provide the uranium fuel and manage wastes is also relevant.

In the view of the U.K. Sustainable Development Commission, "nuclear power can currently be considered a low- carbon technology but...a number of concerns remain over its long-term energy requirements from 'back-end' liabilities and the potential impact of increasing the use of low-grade uranium ores." Interestingly, the same can be said to apply to fossil fuel generation with carbon capture and storage (CCS) and as we move to lower-quality fossil fuel resources that require more energy to extract.

The potential rate of deployment of our different supply options is also relevant. We are undoubtedly capable of building large amounts of conventional fossil fuel generation each year. However, CCS is not yet a proven technology at scale within the power sector and it seems likely that it would take some decades to demonstrate, commercialize, and then deploy it on a large scale. The nuclear power industry has only contributed around 2% of new capacity over the last five years and would take time to ramp up its activities. Major technology providers such as Westinghouse have not built a plant for some 25 years, while reactor builders in the United States have not been awarded a single new contract since 1973 in which the nuclear power station was actually completed.

European-based Areva has only one plant under construction and spoke recently of the need to hire 1,000 engineers. The exception is, of course, Asia and the former Eastern Bloc. Nevertheless, there are only 28 plants currently listed as under construction, and almost half of these projects have been underway for 18 years or more. The ambitious expansion plans of China hadn't actually seen the contracts signed for four new international reactors at the time of writing (early 2006). Even when they do proceed, these plants still represent only a very modest proportion of planned new generation build in China, most of which is expected to be coal fired.

Most of the third-generation nuclear power station designs now proposed have yet to be built, and it will take some years of operation to determine their reliability and costs. Fourth generation nuclear power station designs are even further away, with the U.S. DOE-led International Forum having the goal of developing innovative nuclear power station designs for commercial readiness around 2030.

The primary objective of climate-change policy must be to drive near-term reductions in developed country emission, while setting developing countries on an emissions trajectory that peaks within two decades or so. Nuclear power can only make a limited contribution in this time frame. Moreover, it must now compete against other emerging abatement options that are seeing rapid technical development. For example, some 12 GW of new wind capacity was installed in 2005, considerably exceeding new nuclear build in that year.

Despite the daunting emissions reduction target, some observers still question whether expanded nuclear power programs are *necessary* to protect the climate, and they would certainly not be *sufficient* alone. Expanded nuclear power is, instead, a choice to consider along with other options. Certainly, serious action on climate change will improve nuclear power's competitiveness against conventional fossil fuel technologies, especially coal-fired plant. Still, it is vital that policy makers are not distracted from those energy efficiency opportunities that hold the promise of large, quick, and low-cost abatement.

Nuclear weapon proliferation is a key issue for the societal acceptability of nuclear power. Nuclear weapons have undoubted attractions to countries operating in an uncertain, changing, and increasingly competitive world. They offer a right of veto on military action and a ticket to international standing and influence in foreign policy. The five permanent members of the UN Security Council were drawn from the victors of World War II but were also the original members of the nuclear club.

Civilian and nuclear programs share in large part nuclear materials, technologies, and know-how. Thus, a civilian program offers some of the foreign policy benefits of a military program. The International Atomic Energy Agency (IAEA) has the motto "Atoms for Peace" but a seemingly conflicted mandate: to assist the supply of material and equipment to non-nuclear weapon states, train nuclear scientists, and foster the exchange of information, while also ensuring these states don't develop nuclear weapons. High-risk elements of the civilian nuclear fuel cycle include uranium enrichment, plants capable of producing plutonium, and reprocessing facilities for extracting this plutonium.

Over the past 50 years, many countries excluded from the original nuclear club have been suspected of having nuclear weapon ambitions. These countries were suspected of diverting resources from what were described as civilian or research nuclear power programs. The international response to this revolved around the Non-Proliferation Treaty (NPT) originally negotiated in 1968. The pillars of the NPT are non-proliferation, disarmament, and the right to peacefully use nuclear technology. It has been signed by all but three nations, India, Israel, and Pakistan, who have all developed nuclear weapons. North Korea withdrew from the NPT in 2003 and has since proclaimed that it too has nuclear weapons.

By some measures, the IAEA and nuclear NPT have been successful. Only four nations have definitely acquired nuclear weapons since it was signed, and one of these, South Africa, dismantled its weapons as part of joining the NPT. There were projections in the 1960s that more than 30 nations would have weapons by the present time. No state is known to have successfully constructed a nuclear weapon in secret while subjected to NPT inspection, although Iraq's advanced program uncovered after the first Gulf war did cause considerable disquiet. Part of the NPT's success in unstable regions of the world has been the reassurance it provides nations that their neighbors have not acquired weapons, and they, therefore, do not have to do so themselves.

Now, however, nuclear proliferation tensions are growing again with North Korea and Iran. Furthermore, the nuclear genie is well out of the bottle. The IAEA itself estimates that some 35–40 nonweapon states now possess the technical know-how to build a bomb. Increased geopolitical tensions might see the nuclear club expand rapidly—a UN panel recently noted that "we are approaching a point at which the erosion of the nonproliferation regime could become irreversible and result in a cascade of proliferation."

Some argue that nonweapon states have a reasonable case for pursuing weapons programs because the declared nuclear powers within the NPT are not meeting their obligations to "pursue negotiations in good faith on general and complete disarmament." Regardless, it is concerning but hardly surprising that countries such as Iran might be contemplating the advantages of joining the nuclear club.

Another emerging issue is that of nonstate actors. Nonstate parties, by definition, operate outside national and international regulations and political control. Even if they are unable to build or steal nuclear weapons, they may pursue radiological or so-called dirty bombs, which use conventional explosives to spread radioactive material.

Another key issue will be the choice between closed and open fuel cycles. Closed fuel cycles involve reprocessing of spent fuels from nuclear plants to extract plutonium that can be mixed down with depleted uranium to create mixed-oxide (MOX) fuel for reuse. This cycle might also include fast-breeder reactors that are "optimized" to produce plutonium for such reprocessing. A number of fast-breeder programs have been undertaken, but the technology to date has proven expensive and very technically challenging. A Massachusetts Institute of Technology study on nuclear power recommended pursuit of an open or once-through cycle, largely because of proliferation risks but also for safety and economic reasons. In 1977, the United States suspended commercial reprocessing, at least in part because of proliferation concerns with the technology. Not all countries, however, did the same. The current U.S. administration is taking a very different direction. The Global Nuclear Energy Partnership (GNEP), announced in February 2006, is a plan to form an international partnership to reprocess nuclear fuel in a way that renders the plutonium in it usable for nuclear power stations but not for nuclear weapons. It remains to be seen if this is actually possible.

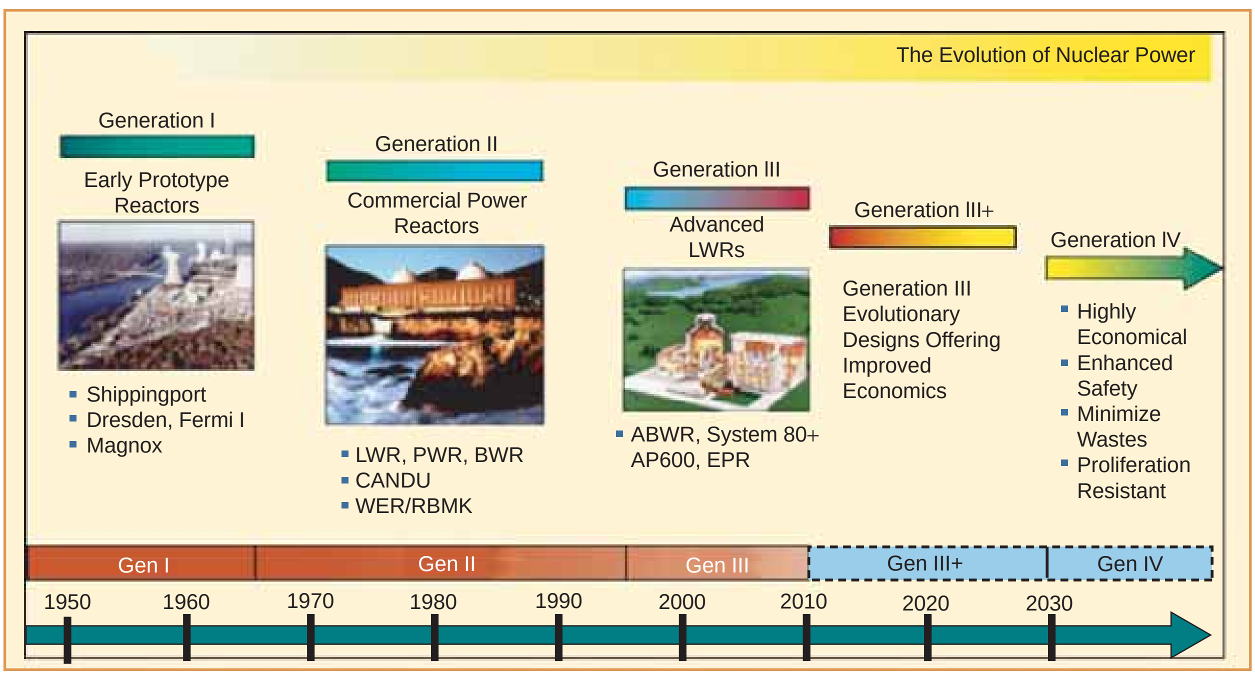

figure 4. The historical and possible future evolution of nuclear power plant technologies. (Courtesy of the U.S. Department of Energy, http://www.ne.doe.gov.)

> The challenge is that nuclear power stations must maintain controlled nuclear fission, balancing between extinguishment and uncontrolled criticality.

Possible Futures for Nuclear Power

Nuclear power's future will be the outcome of numerous complex and challenging choices taken by individual countries and groups of countries. Hence, it is unknowable at this time.

Key uncertainties include the ability to form an international consensus on undertaking serious action on climate change, the evolving geopolitics of military force and nuclear proliferation, and the possibility of peak oil or at least a tightening in the supply of some fossil fuel supplies. National and international institutions and electricity industry governance will also play key roles.

Major technical questions for nuclear power include the choice between closed or open fuel cycles, the development of new power station technologies, the management of nuclear materials, and know-how that might contribute to managing proliferation and waste. Figure 4 highlights the possible evolution of nuclear power generation to advanced third-generation and eventually fourth-generation plant designs. We now briefly consider three general scenarios of how nuclear power might develop over the coming decades and their differing implications.

The first scenario is that nuclear power's fractional contribution to the world electricity supply might decline significantly over time, gracefully or otherwise. Possible causes include loss of community acceptance, for example, after a series of major accidents or terrorist attacks. Such a decline might take many years given the present 30 countries involved, the considerable investments sunk, and the challenge of decommissioning existing power stations. It might be accompanied by reinforced international commitment to reducing nuclear weapon stockpiles. However, for reasons discussed earlier, it seems unlikely that the world will completely reject the nuclear option.

The second scenario is that the industry may continue with business as usual, more or less. In this scenario, there would be a modest increase in global installed nuclear power station capacity, mostly in Asia. For example, current OECD projections correspond to a net growth in installed nuclear capacity of around 600 MW per year to 2030. Given the age profile of existing power stations and likely retirements, this may correspond to perhaps 4–5 GW per year of new plant. Alternatively, it might involve considerable lifetime extension of existing plant. This scenario might be called the path of least resistance for the industry.

There are obvious weapon proliferation risks in the second scenario. The waste management problem for countries that already have significant nuclear power generation would not change markedly. However, those countries with expanding nuclear power station fleets would face significant additional challenges. Lifetime extension may have safety implications, particularly with some of the early designs.

The third scenario envisages a nuclear renaissance, with rapidly expanding nuclear power programs in countries that already have programs and in additional countries. One example is the nuclear climate stabilization wedge, which would see an additional 700 GW of nuclear generation by 2050. This would require around 25 GW per year of new generation capacity over several decades, including ambitious expansion plans for China and India. This scenario has major risks and would put great pressure on the nuclear industry as well as on national and international governance to ensure acceptable outcomes.

Deciding the Future of Nuclear Power

Investment decision making in the stationary energy sector has significant societal implications, can be difficult to reverse, involves significant externalities and now takes place in a context of great uncertainty. Every person and all countries are stakeholders and decision making of this scale qualifies, in engineering ethics terms, as social experimentation requiring informed consent. Future populations are stakeholders too, and should be at the table as well. Thus investment decision making in the stationary energy sector, and in the electricity industry in particular, has become much more complex than had been the case.

Restructured electricity industries aim to devolve investment decision making to individual industry participants. Such commercialized, decentralized, decision making is driven largely by assessed self-interest subject to assigned (legal) accountability. The challenge with nuclear power is our inability to achieve adequate accountability in such a framework—the critical high-impact risks must be underwritten by the state, distorting a decentralized comparison of options. This inevitably politicizes the decision making involving nuclear power.

Thus, centralized decision-making approaches that acknowledge the political dimension may have to be used. Examples include direct political and judicial decision-making procedures. The former involves deal making and political compromise to achieve a sufficient coalition, while the latter, being evidence-based, may tend to side with the status quo and struggle to deal with emerging technologies that do not have established track records. The perceived foreign policy status of nuclear power may distort decision making at the national level, while military decision-making is taken according to a "might makes right" philosophy, which is all too plausible in the context of nuclear power.

Thus, it is not clear that we have adequate frameworks to ensure wise decision making about issues with long-term consequences of global scale, such as nuclear power and climate change. The best we may be able to hope for is a "muddle through" approach based on inertia and a tactical response to issues as they arise. In that context, it is important to note that the nuclear power option remains a choice for many countries; at a global scale, it does not appear to be essential for solving environmental or energy security concerns.

Societal acceptability will clearly be important to nuclear power's prospects in individual countries. A recent international survey of public opinion by the IAEA reported that one-third of respondents wanted existing nuclear power stations to continue running as long as no new ones were built, nearly one-third supported greater use of nuclear power, and one-quarter believed all plants should be closed. Respondents in South Korea, the United States, and India gave the highest support for nuclear power, while less than a quarter of respondents supported construction of new plants in France, Germany, Russia, and Japan.

Culturally, nuclear power is back on the agenda. Part of the explanation might be the declining status of other options, including coal-fired generation and large hydro. While history suggests that public opinion will not determine the future of nuclear power overall, it may still influence the industry's future in many countries and certainly in Europe and the United States.

The imperative, therefore, is to frame decision making in order to best manage the challenges nuclear power presents. These include its politicization and the numerous links between civil and military nuclear applications, which may preclude openness and transparency regarding objectives and potential consequences. Many observers of the nuclear industry have highlighted early problems with the creation of an "engineering priesthood" that took decision making upon itself.

For societal decisions such as the future of nuclear power, the technical expert's role should be to advise. This includes making an informed contribution to public debate that enhances public understanding of the issues. Moreover, engineering expertise will be vital in safely managing the issues and momentum from decisions that have already been taken. We also need new technologies and approaches that expand society's options for improving the sustainability of the stationary energy sector.

To summarize, the deeply ethical and fundamentally value-laden character of such problems requires that the insights of conventional expertise and other authorities must be complemented by those of other legitimate stakeholders, most notably broader civic society.

While this may sound idealistic, it is notable that the lack of such consultation has bedeviled attempts to build repositories for high-level nuclear wastes, exemplified by the stop/go character of the U.S. Yucca Mountain project and yet is the mark of successful programs such as that in Sweden. Other countries have trialed such processes in various ways and the U.K. Citizen Jury on Nuclear Waste Management is a well-known example.

This will not ensure wise decision-making on the future of nuclear power—no individual, profession, or country can do that alone. It will, however, improve the chances that we do the right thing. And the time to properly engage in this process is now—dangerous climate change, energy poverty, energy security, and nuclear proliferation all continue to grow in importance—avoiding difficult decisions may be the worst possible decision.

For Further Reading

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