Why Nuclear Power's Failure in the Marketplace Is Irreversible (Fortunately for Nonproliferation and Climate Protection)

AMORY B. LOVINS

> *AP: Would the introduction of more nuclear power plants -- something the vice president has said the country needs to meet future electricity demand -- weaken Enron's natural gas trading business?*
> *Jeff Skilling (former CEO of Enron): I will personally eat every new nuclear power plant built in this country for the next 100 years. I don't think we are going to see any new plants built. We've just got a fundamental problem in that nuclear plants make a lot of waste and there is no solution to that problem right now. So they can talk all they want about nuclear power. I don't believe it.*
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> *Associated Press Interview – August 14, 2001*

Nuclear power has suffered the greatest collapse of any enterprise in the industrial history of the world. The twentieth century ended with installed nuclear capacity less than 10%, and an ordering rate less than 1%, of the lowest IAEA forecasts made a quarter-century ago. No vendor has made money by selling reactors, though some have made it up on repairs. Worldwide, nuclear power is stuck at 11% of total generating capacity, providing 6.3% of 1998 primary energy output, *vs*. 8.8% for renewables without, or about 20.3% with, traditional biofuels. In the U.S., nuclear investments exceeding a trillion dollars are delivering little more energy than biofuels; nuclear power's primary energy output and installed capacity are roughly the same as renewables', though its electric output is about four-fifths higher due to nuclear plants' recently improved capacity factors.

The basic reason for this market disappointment is not public concern but unfavorable economics. As *The Economist*'s 19 May 2001 cover story concludes, nuclear power has gone from too cheap to meter to too costly to matter, especially in an increasingly competitive marketplace. A nuclear plant with zero capital cost is now cheaper to write off (and give away equivalent electricity-saving equipment instead) than to operate. Nuclear power's unpleasant capital- and repair-cost escalation and technical surprises are worldwide phenomena, independent of politics. Even France's nuclear program was outpaced twofold by energy efficiency, bankrupted its operator in all but name, and is unlikely to be replaced by more reactors. During 1990–99, global capacity growth averaged only 1%/y for nuclear power (to 354 GW), *vs*. 17%/y for photovoltaics (PVs) and 24%/y for windpower. That's no longer simply rapid growth from a tiny base: in the 1990s, nuclear power averaged global additions of 3.1 GW/y, yet in 2000–01, windpower is adding 3.5–5 GW/y, and by the end of 2001 should reach 22 GW.

Nuclear power's main if not sole competitor was originally presumed to be giant coal plants. These are now equally obsolete on the margin: many competitors work better and cost less than either. That's why central thermal plants are seldom ordered nowadays except by a handful of centrally planned energy systems. Nuclear salesmen scour the world for a single order, while vendors of combined-cycle gas plants, microturbines, wind turbines, PVs, and energy efficiency strive to meet bulging order books.

If no existing nuclear plant suffers an accidental or malicious radioactive release serious enough to compel their early shutdown, they'll probably operate until they're too costly to maintain. In theory, they must also compete in economic dispatch (lowest short-run marginal cost of operation), but in fact, many U.S. reactors have won "must-run" status entitling them to run whenever available even if uneconomic, which ~20–25% of them already are against market-clearing prices. (In Sweden, Sydkraft unsuccessfully sought compensation for *not* continuing to lose money by running Barsebäck at an operating cost roughly twice the price of imported power.) The U.S. short-run marginal cost of nuclear electricity at the busbar is typically reckoned at ~$0.015–0.039/kWh; the average in 2000, under the industry's restrictive definition of costs, was about $0.018. (This article uses constant year-2000 U.S. dollars throughout. Net capital additions—major repairs that are really hidden operating costs—increase the industry's declared operating costs, as would fully internalized waste, decommissioning, and major-accident costs, now typically socialized.)

In any event, the cost of *delivering* the power to the customer must also be added for fair comparison with onsite options that require no delivery. Delivering the average U.S. kWh costs roughly $0.025/kWh for the capital and operating costs and the losses embedded in the existing grid; residential delivery costs, or costs of marginal delivery capacity (new transmission and distribution capacity), are often several-fold higher, but let's use the historic average figure as a conservatism. Nuclear power's typical short-run marginal cost, delivered to the customer, is then about $0.045/kWh using the industry's narrow cost definition. But its long-run marginal delivered cost (including *building* a new nuclear plant) is at least $0.10–0.15/kWh. (Enthusiasts claim that building and running a hypothetical South African pebble-bed design might cost perhaps $0.05/kWh delivered, but given historic experience with paper *vs*. real reactors, twice that would be more plausible.) Existing coal plants often run at or below $0.02 and hence deliver at about $0.045/kWh for existing plants; cleaner new ones would raise that to roughly $0.06–0.08/kWh, almost certainly cheaper than new nuclear plants. What else costs less to build and run than nuclear power?

The most potent competitor, many-fold cheaper than just *running* existing nuclear plants anywhere in the world, is end-use efficiency—a resource that's also many-fold larger. Its average historic U.S. cost, including many poorly designed and chiefly residential programs, is only $0.02 per saved kW-h, already delivered to the customer's premises. Well-designed retrofits, however, can save most of the electricity now used at empirical costs typically ~$0.005/kWh in the business sectors (a 16-month payback at a 5-cent tariff)—even less than zero in new buildings and factories. (My own 90% saving in household electricity had a 10-month payback in 1984; today's technologies are far better and cheaper.) Saved energy is currently the United States' largest single source of energy services, delivering two-fifths of their total. Reduced primary energy intensity during 1975–2000 is now an energy "source" over five times as big as domestic oil output, over twice total U.S. oil imports, over 12 times Persian Gulf imports, and 7.7 times primary nuclear energy output. Oil productivity has indeed doubled since 1975.

Electrical productivity is far less mature, having improved only 8% during 1975–2000—partly because electricity has been heavily subsidized and promoted, has typically been priced at average cost rather than on the margin, and is distributed by utilities that in 49 states are rewarded for selling more energy and penalized for cutting customers' bills. Nonetheless, electrical productivity since 1997 has sustained its steadiest gains in history, averaging 1.6% per year—half as fast as the aggregate drop in primary energy intensity. One-fourth of the national electrical saving has come from California, even after its demand-side efforts were derailed in the mid-1990s. California has held its per-capita use of electricity nearly flat for the past quarter-century, saving 25 average GW compared with the intensity prevailing in the rest of the U.S., and boosting its economic output by investing more productively the billions of dollars thereby saved. Analogously, the Electric Power Research Institute, at its 2001 summer seminar, presented an "enhanced productivity" scenario envisaging 3%/y gains in electrical productivity (a 45% drop in intensity) during 2000–20.

EPRI's 1991 conventional wisdom was that over half of U.S. electricity could be saved at an average cost around $0.03/kWh. RMI's far more detailed analyses in the late 1980s, using empirical cost and performance data for more than 1,000 technologies, found potential retrofittable savings around 75% at an average cost around $0.0085/kWh. The potential today is undoubtedly larger and cheaper, because better technologies and delivery methods have more than kept pace with "depletion" of the efficiency resource. Indeed, new integrative design methods (www.natcap.org) can often make very large energy savings cost *less* than small or no savings—"tunneling through the cost barrier." Moreover, ancillary improvements in service quality, such as a ~6–16% gain in labor productivity in efficient offices, are often an order of magnitude more valuable than the saved energy. Proven methods (www.rmi.org/images/other/C-ClimateMSMM.pdf) can also convert the scores of implementation obstacles into lucrative business opportunities. "Negawatts" can be marketed so quickly that during 1983–85, the ten million people served by Southern California Edison company cut the ten-years-ahead forecast of peak demand by more than 8% *per year*, at about 1% the cost of new supply. And in developing countries, efficiency investments can cut marginal capital needs by four orders of magnitude, making the power sector—now a black hole for one-fourth of development capital—a net exporter of capital to fund other development needs.

After end-use efficiency, typically the next cheapest competitors are three kinds of new generators:

- combined-cycle gas turbines (often ~$0.05–0.06 per delivered kWh at 1999 prices, including 30-year fixed-price gas contracts, or about a penny more at 2001 prices due to temporary turbine and gas shortages),
- some renewables (notably, well-sited windpower costs ~$0.055–0.06 per delivered kWh and will soon drop to or below $0.05, minus a $0.015 subsidy in the U.S.), and
- onsite and hence requiring no delivery, industrial and commercial co- and trigeneration from larger units or from microturbines, again using 30-year constant-price gas contracts (~$0.005–0.05, often ~$0.01–0.02, per delivered kWh net of thermal credit).

In short, *any* of three abundant and readily purchasable resources—efficient end-use, efficiently used gas (especially when thermally integrated), and windpower—can easily beat new and can even beat most old nuclear plants on private internal cost. Any one of these three competitive resources would make nuclear power unnecessary and uneconomic. Two of them are climate-safe, and the third has very low climate impact. Even though cogeneration is typically gas-fired, full practical and profitable conversion to it would cut U.S. CO_2 emissions by about 23%.

These three formidable competitors to nuclear power are being joined by another that's just entering volume production. A winning dark horse, ~60%-efficient proton-exchange-membrane fuel cells, is poised to capture most of the power market in buildings, which use two-thirds of U.S. electricity. Its ~$800/kW initial cost will drop rapidly, ultimately to <$50/kW. The transition to a climatically benign hydrogen economy, profitably at each step starting now (www.rmi.org/images/other/HC-StrategyHCTrans.pdf), is starting to be rapidly implemented by major firms. One of its consequences—wellhead reforming of natural gas with CO_2 reinjection—would make the world's two centuries' worth of known gas profitably usable without climatic harm. (Contrary to the impression of some nonexperts on natural gas, this is a rather ubiquitous and abundant resource, which is partly why the Department of Energy projects U.S. combined-cycle gas capacity to surpass nuclear capacity later in this decade: 126 GW in 2010, *vs.* 97 GW for nuclear power in 2000.) Professor R.H. Williams at Princeton University even makes a plausible case that hydrogen may ultimately be more cheaply made from coal than from natural gas, with carbon sequestration in both cases.

As IIASA first showed for inefficient solar trough systems two decades ago, renewable power generation is no more land-intensive than the full nuclear or coal fuel cycle. Denmark, now 16% wind-powered, is on target for 50% by 2030, without issues of land-use or intermittence (an old canard long since resolved by wind diversity on a mesoscale). A fifth of U.S. electricity could be made by modern wind turbines occupying 5% of four Montana counties, or 0.6% of the Lower 48 states; or all of U.S.

annual electricity could come from ordinary PVs occupying half of a square 160 km on a side (though one would actually site them in distributed fashion, chiefly on buildings). In either case, the land-use can be shared, much as farmers and ranchers do now, earning valuable revenues from the wind that blows above their herds and crops. Modern renewable sources repay their energy investments in months to a few years: illustrating their materials-frugality, 1 kg of silicon in thin-film PVs can produce more electricity than 1 kg of uranium in a pressurized-water reactor. Further PV breakthroughs continue (*e.g.*, *Science* **293**:1119–1122 (2001)).

Meanwhile, the next revolution—distributed utilities—is gaining momentum. As *The Economist* remarked (17 May 2001, online ed.), "In fact, the trend since the mid-1970s has been towards smaller plants. It is micropower, not megapower, that the market favours, thanks to the far smaller financial risk involved." My forthcoming book *Small Is Profitable: The Hidden Economic Benefits of Making Electrical Resources the Right Size* shows how roughly 125 "distributed benefits" of decentralized electricity sources can typically increase their economic value by roughly tenfold, making even PVs cost-effective today in most applications. Even more valuable than familiar electrical engineering attributes—lower grid costs and losses, higher reliability and power quality, dispatchable reactive power, near-infinite ramp rates, etc.—are the lower financial risks of small, short-lead-time modules. For example, a 10-kW resource installable overnight could cost 2.7 times as much per kW as a 50-MW resource installable in two years, yet yield identical financial performance. In the new arena now emerging, discount rates are project-specific and risk-adjusted, new market actors understand financial economics, and competition increasingly embraces all options. Continuing nuclear ownership consolidation may improve operations more than it concentrates risks, but the firesale prices realized at used-reactor sales in the late 1990s confirm a market perception of low or even negative long-run asset value.

Nuclear waste accumulates, and neutron fluence raises decommissioning costs, proportionally to nuclear power generation. Moreover, nuclear power's having died of an incurable attack of market forces—plus the end of the Cold War—offers a unique opportunity to inhibit proliferation as fissile materials, skills, and equipment become no longer ordinary items of commerce (except for minor and readily safeguarded medical and industrial uses). This would make such bomb-kit ingredients harder to get, more conspicuous to try to get, and politically far costlier to be caught trying to get or supply, because for the first time, the reason for wanting them would be unambiguously military. This exposure of illicit transactions—now hidden in and rationalized by a vast flow of supposedly innocent civilian nuclear commerce—would not make nuclear bomb proliferation impossible, but would make it far more difficult, and would focus its resource flows into narrower, more readily monitored channels. This potential for an internally consistent nonproliferation policy was summarized in *Foreign Affairs* in Summer 1980 and in the 1979 book *Energy/War: Breaking the Nuclear Link*; today, its preconditions, somewhat visionary at that time, have been realized, and the logic is as tight as ever.

A word about California's current electricity crisis may be necessary because so many myths have been propagated about its causes (www.rmi.org/URLTOCOME). The published official data clearly show that California did not suffer soaring electricity demand, least of all from the Internet; that the state added in the 1990s more new generating capacity than its 4.3-GW nuclear capacity (but the additions were distributed and nonutility, therefore seemingly invisible); and that the state was not short of oil, which anyhow generates <1% of its electricity. The actual causes were many and complex. Fundamentally, the most important cause was botched restructuring and concentrated market power: seven firms control two-thirds of the bidding space, so each can move the market. Each therefore earned far more profit by selling less electricity at a higher price rather than more at a lower price. Until June 2001, 10–15 GW was apparently being withheld from the market, not all legitimately; that's why the same system that met a 53-GW peak load in summer 1999 suffered rolling blackouts at 29 GW in January 2001. It's not obvious that new capacity built by the same firms that already exercise excessive market power will solve this problem, since those firms will then have even more capacity to withhold and no less incentive to do so.

Nuclear power is unrelated to this problem save in the fundamental sense that its high "stranded asset" costs helped trigger the dreadful restructuring, and in the minor sense that a 1.1-GW outage at San Onofre contributed to the problem. More nuclear power certainly wouldn't help timely (or economically) even it could be financed and sited. In fact, as *Barron's* 6 August 2001 cover story noted, the U.S. is already building more power plants than it might plausibly need. Such overshoot, last seen in the mid-1980s, occurs when slow-to-build central power plants collide head-on with quickly captured efficiency. In the first six months of 2001, for example, even before price hikes hit, Californians' electric savings undid the previous 5–10 years' demand growth, helping to stabilize the market and frustrate the ticket-scalpers' ambitions.

Some advocates hope an oil shock will restore nuclear power's market credibility. Oil shocks may well recur, though the world is far better prepared for them—the Gulf War triggered no oil shortages. Yet the rational response would be not the slowest, costliest option—and the one whose output, electricity, is least fungible for oil—but rather efficiency, distributed thermal and thermoelectric systems, natural gas, and biofuels. Anyhow, oil problems will fade away as superefficient cars (www.hypercar.com) save as much oil as OPEC now sells, helping to make oil uncompetitive even at low prices before it becomes unavailable even at high prices. Moreover, each fuel-cell Hypercar^{SM} will be a 20–40-kW$_e$ mobile power plant. When parked, ~96% of the time, it can be plugged into the hydrogen appliance in a nearby building and into the grid, electricity sales to which should repay up to half the car's lease cost. Such a fleet will ultimately have ~6–12 times as much generating capacity as all power companies now own—yet another nail in the nuclear coffin.

Nuclear advocates' last hope is that climate concerns will revitalize their option. Alas, they've overlooked opportunity cost—the impossibility of spending the same money on two different things at the same time. If saving a kW-h cost (pessimistically) as much as three cents, while delivering a kW-h of new nuclear electricity cost (very optimistically) as little as six cents, then the six cents spent for each new nuclear kW-h could instead have bought *two* kW-h worth of efficiency. The nuclear purchase therefore displaced one *less* kW-h of coal-fired electricity than the same money could have done by buying the cheaper (efficiency) option instead. That's why the order of economic priority must also be the order of environmental priority; why it's irrelevant whether nuclear power can beat coal power as long as any other option costs still less; and why nuclear power makes global warming worse.

Nuclear power is a future technology whose time has passed. Its economic problems are so ineluctable that it would still fail even if it had no political, environmental, safety, or security problems. And as the retirement of the older, higher-quality nuclear pioneers continues the worrisome trend predicted by Nobel physicist Hannes Alfvén—that the enterprise will "pass into ever less competent hands"—each dollar spent to address the unsolved problems will buy ever less solution.

Looking after nuclear power's legacy will be a business with a long future; but the operation of today's nuclear fleet will not. Despite immense investments, devoted efforts, and dedicated careers, those plants will long stand as a monument to what happens when a technology avoids market and political accountability for long enough to make really big mistakes, and when its advocates develop a reputation for mendacity. Its epitaph could be: "Here lies a technology that failed because it did not take its discipline from the marketplace, its values from its customers, and its design from nature." Its seemingly great promise was betrayed by tragic flaws.

Nuclear power has been called "a fit technology for a wise, farseeing, and incorruptible people." A pity we haven't more of them. But its best legacy would be not to make the same mistake again; and the best way to do that is to take economics seriously. The Bush Administration's claims that nuclear power is safe, but needs an extension of its unique statutory cap on liability for major accidents, and is economic, but needs another $1.5 billion in tax breaks, is perplexing to advocates of free markets, and hardly seems a propitious start at acknowledging and respecting market outcomes.

Shorn of distracting details, the nuclear power issue is simple. The technology has failed in the marketplace—a tragic misallocation of talent, work, hope, and investment that deserved better and that continues to distort public choices. However, accepting the verdict of the marketplace will yield the right energy policy conclusion and will also simplify the politics of finding the least unsatisfactory place to put nuclear waste. An orderly terminal phase should be designed for this unfortunate mistake—but can't be, so long as nuclear theology dominates policy. If recognized, however, the commercial collapse of nuclear power, and the rise of better energy alternatives, could be turned into the long-awaited missing step toward effective nonproliferation.

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Amory Lovins, a MacArthur Fellow and originally a consultant experimental physicist, is a frequent advisor to utilities and other industries, and is cofounder and co-CEO of the independent nonprofit applied research center Rocky Mountain Institute (www.rmi.org). Published in 27 books and hundreds of papers, his work has been recognized by the "Alternative Nobel," Onassis, Nissan, Shingo, and Mitchell Prizes, the Happold Medal, and the Heinz, Lindbergh, Hero for the Planet, and World Technology Awards. Portions of this article are adapted from one invited for the November 1999 British newsletter Power Economics*, and from the opening address to the Nuclear Control Institute's 9 April 2001 symposium "Nuclear Power and Nuclear Weapons: Can We Have One Without the Other?" (www.nci.org/conf/lovins/index.htm).*

Amory B. Lovins,
CEO (Research), Rocky Mountain Institute
ablovins@rmi.org
www.rmi.org