Nuclear power: economics and climate-protection potential

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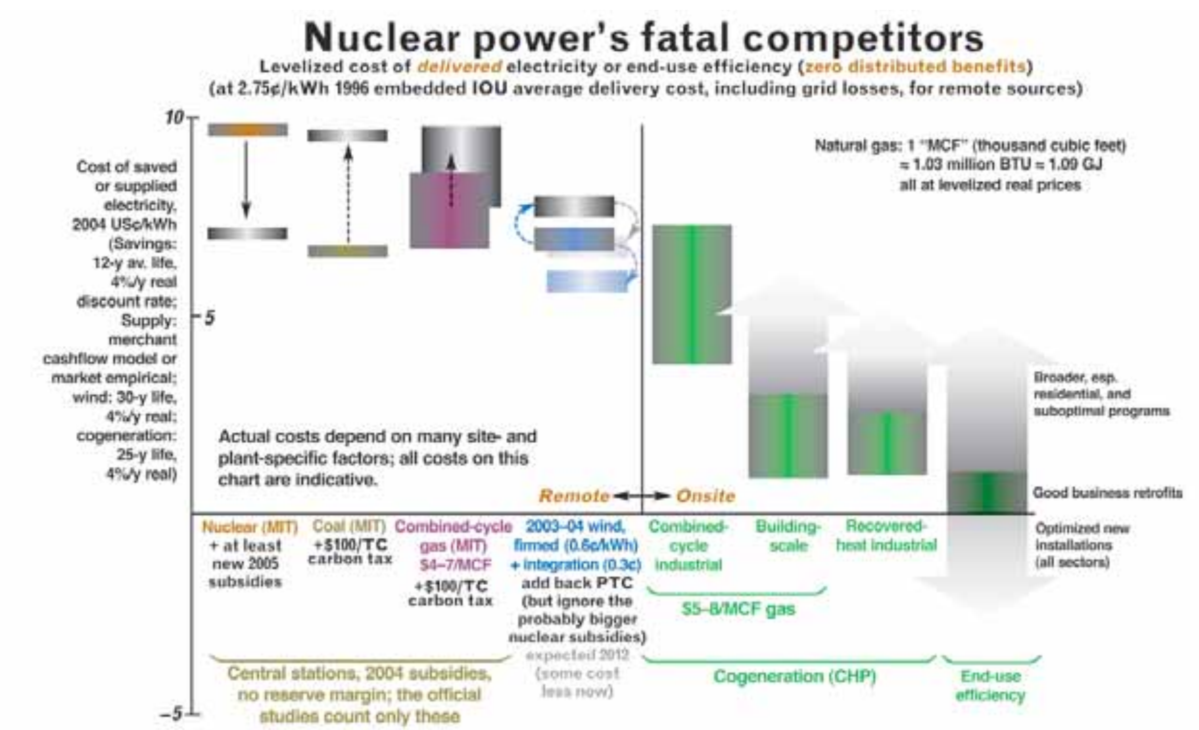
Abstract

Nuclear power is often described as a big, fast, and vital energy option—the only practical and proven source big and fast enough to do much to abate climate change. Yet industry and government data tell the opposite story. Nuclear power worldwide has less installed capacity and generates less electricity than its decentralized no- and low-carbon competitors—one-third renewables (excluding big hydroelectric dams), two-thirds fossil-fueled combined-heat-and power. In 2004, these rivals added nearly three times as much output and six times as much capacity as nuclear power added; by 2010, industry forecasts this sixfold ratio to widen to 136–184 as nuclear orders fade, then nuclear capacity gradually disappears as aging reactors retire. These comparisons don't count more efficient use of electricity, which isn't being tracked, but efficiency gains *plus* decentralized sources now add at least ten times as much capacity per year as nuclear power.

All the meager nuclear orders nowadays come from centrally planned electricity systems, because despite strong official support and greatly increased U.S. subsidies, nuclear power's bad economics make it unfinanceable in the private capital market. Official studies compare new nuclear plants only with coal- or gas-fired central stations. But all three kinds of central stations are uncompetitive with windpower and some other renewables, combined-heat-and power (cogeneration), and efficient use of electricity, all compared on a consistent accounting basis:



Efforts to make nuclear plants appear competitive with central coal or gas plants by enlarging nuclear subsidies or taxing carbon dioxide (CO_2) emissions are futile, because windpower and some other renewables, cogeneration, and technologies for wringing more work from each kilowatt-hour will still win in the marketplace—by margins far too great for new reactor technologies or further-streamlined siting and regulation to overcome, even in principle.

Empirical data also confirm that these competing technologies not only are being deployed an order of magnitude faster than nuclear power, but ultimately can become far bigger. In the U.S., for example, full deployment of these very cost-effective competitors (conservatively excluding all renewables except windpower, and all cogeneration that uses fresh fuel rather than recovered waste heat) could provide ~13–15 times nuclear power's current 20% share of electric generation—all without significant land-use, reliability, or other constraints. The claim that "we need all energy options" has no analytic basis and is clearly not true; nor can we afford all options. In practice, keeping nuclear power alive means diverting private and public investment from the cheaper market winners—cogeneration, renewables, and efficiency—to the costlier market loser.

Nuclear power is an inherently limited way to protect the climate, because it makes electricity, whose generation releases only two-fifths of U.S. CO_2 emissions; it must run steadily rather than varying widely with loads as many power plants must; and its units are too big for many smaller countries or rural users. But nuclear power is a still less helpful climate solution because it's about the slowest option to deploy (in capacity or annual output added per year)—as observed market behavior confirms—and the most costly. Its higher cost than competitors, per unit of net CO_2 displaced, means that every dollar invested in nuclear expansion will *worsen* climate change by buying less solution per dollar. Specifically, every $0.10 spent to buy a single new nuclear kilowatt-hour (roughly its delivered cost, including its 2004 subsidies, according to the authoritative 2003 MIT study's findings expressed in 2004 $) could instead have bought 1.2 to 1.7 kWh of windpower ("firmed" to be available whenever desired), 0.9 to 1.7+ kWh of gas-fired industrial or ~2.2–6.5+ kWh of building-scale cogeneration (adjusted for their CO_2 emissions), 2.4–8.9 kWh of waste-heat cogeneration burning no incremental fuel (more if credited for burning less fuel), or from several to 10+ kWh of electrical savings from more efficient use. In this sense of "opportunity cost"—any investment foregoes other outcomes that could have been bought with the same money—nuclear power is far *more* carbon-intensive than a coal plant.

For these reasons, expanding nuclear power would both reduce and retard the desired decrease in CO_2 emissions. Claims that more nuclear plants are needed to protect Earth's climate cannot withstand documented analysis nor be reconciled with actual market choices. If you worry about climate change, it is essential to buy the fastest and most effective climate solutions. Nuclear power is just the opposite. Claimed broad "green" support for nuclear expansion, if real (which it's not), would therefore be unsound and counterproductive. And efforts to "revive" this moribund technology, already killed by market competition, can only waste time and money.

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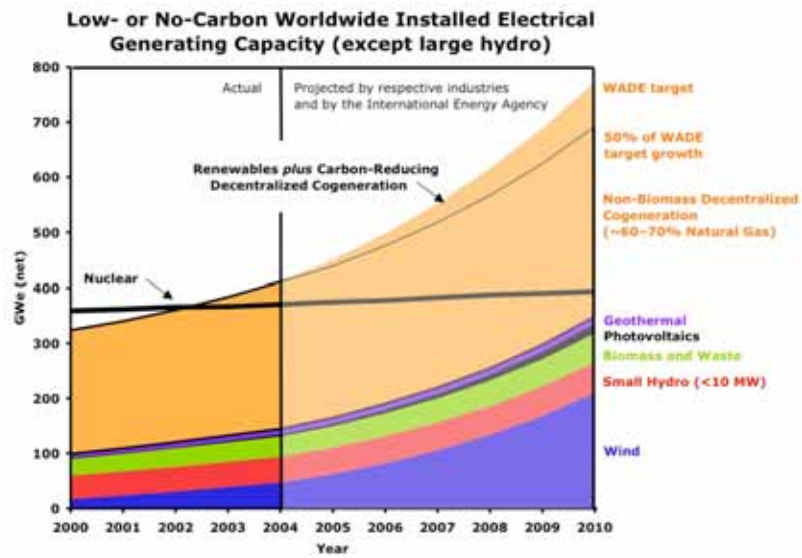
The race is to the fleet

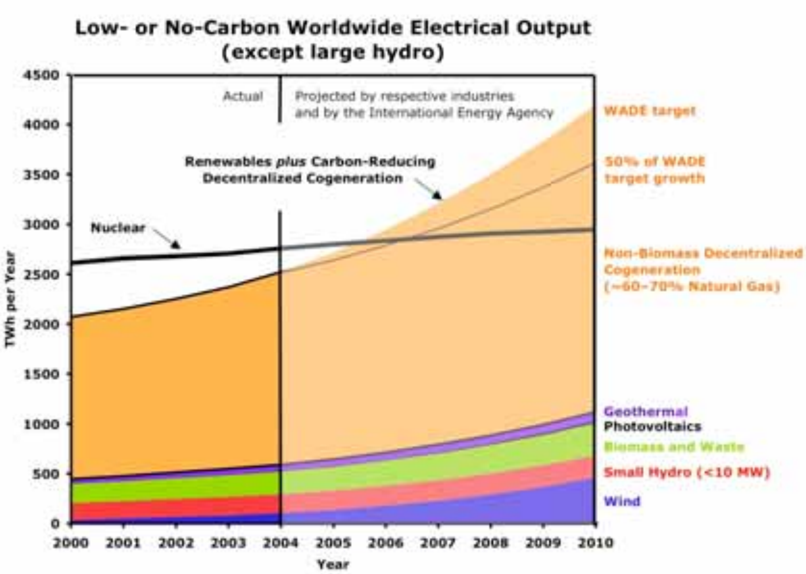
National energy policy currently rests on and reinforces an illusion. Ingenious advocates conjure up a vision of a vibrant nuclear power industry poised for rapid growth, with no serious rivals in sight, and with a supposedly vital role in mitigating the threat of climate change.[2] A credulous press accepts this supposed new reality and creates an echo-box to amplify it. Some politicians and opinion leaders endorse it. Yet industry data reveal the opposite: a once significant but now dying industry already fading from the marketplace (Figs. 1–2, pp. 2–3), overtaken and humbled by swifter rivals. In 2004 alone, Spain and Germany each added as much wind capacity—two billion watts (GW)—as nuclear power is adding worldwide in each year of this decade.[3] Around 2005–2006, nuclear construction starts may add less capacity than solar cells. And in the year 2010, nuclear power is projected by the International Atomic Energy Agency to add 136–184× less net capacity than the decentralized electricity industries project their technologies will add.[4]

That astonishing ratio will increase further, not only because micropower is growing so fast from a base that's already bigger than nuclear power, but also because the aging of nuclear plants is about to send global installed nuclear capacity into a long decline. Mycle Schneider and Antony Froggatt[5] have shown that the world's average reactor is 21 years old, as is the average of the 107 units already permanently retired. Their analysis of reactor demographics found that if the reactors now operating run for 40 years (32 under German law), then during the next decade, 80 more will retire than are planned to start up; in the following decade, 197; in the following, 106; and so on until they're all gone around 2050. Even if China built 30 GW of nuclear plants by 2020, it'd replace only a tenth of the overall worldwide retirements. No other nation contemplates anywhere such an ambitious effort, and even China seems unlikely to complete that proposed addition as its power market becomes more competitive and its polity more transparent: nuclear power today is a Treasury-financed state monopoly whose power sales are guaranteed.

[1] This paper is adapted, slightly updated, and reorganized from the author's "Nuclear power: economic fundamentals and potential role in climate change mitigation," submitted 31 August 2005 to the California Energy Commission in support of the author's 16 Aug. 2005 invited testimony to CEC's Committee Workshop on Issues Concerning Nuclear Power (Integrated Policy Report 2005, docket 04-IEP-1J): www.rmi.org/sitepages/pid171.php#E05-09.
[2] For least-cost solutions, see A.B. Lovins, "More Profit With Less Carbon," *Sci. Amer*. **293**(III):74–83 (Sept. 2005), www.sciam.com/media/pdf/Lovinsforweb.pdf and www.rmi.org/sitepages/pid173.php#C05-05. A broader list, equating nominal nuclear growth with modest efficiency gains, is S. Pacala & R Socolow, "Stabilization Wedges: Solving the Climate Problem for the Next 50 Years with Current Technologies," *Science* **305**:968–972 (2004).
[3] The Spanish government just raised its wind target from 13 GW in 2010 to 20 GW in 2011 (15% of total capacity).
[4] RMI analysis graphed in Figs. 1–2 (p. 2) and documented in a methodological note, spreadsheet, and references at www.rmi.org/sitepages/pid171.php#E05-04. Dr. Eric Martinot (ex-LBNL, now at Tsinghua University) has independently reached similar conclusions: *Renewables 2005: Global Status Report*, Nov. 2005, www.ren21.net.
[5] M. Schneider & A. Froggatt, "On the Way Out," *Nucl. Eng. Intl.*, June 2005, pp. 36–38; *The World Nuclear Industry Status Report 2004*, www.greens-efa.org/pdf/documents/greensefa_documents_106_en.pdf, Dec. 2004.

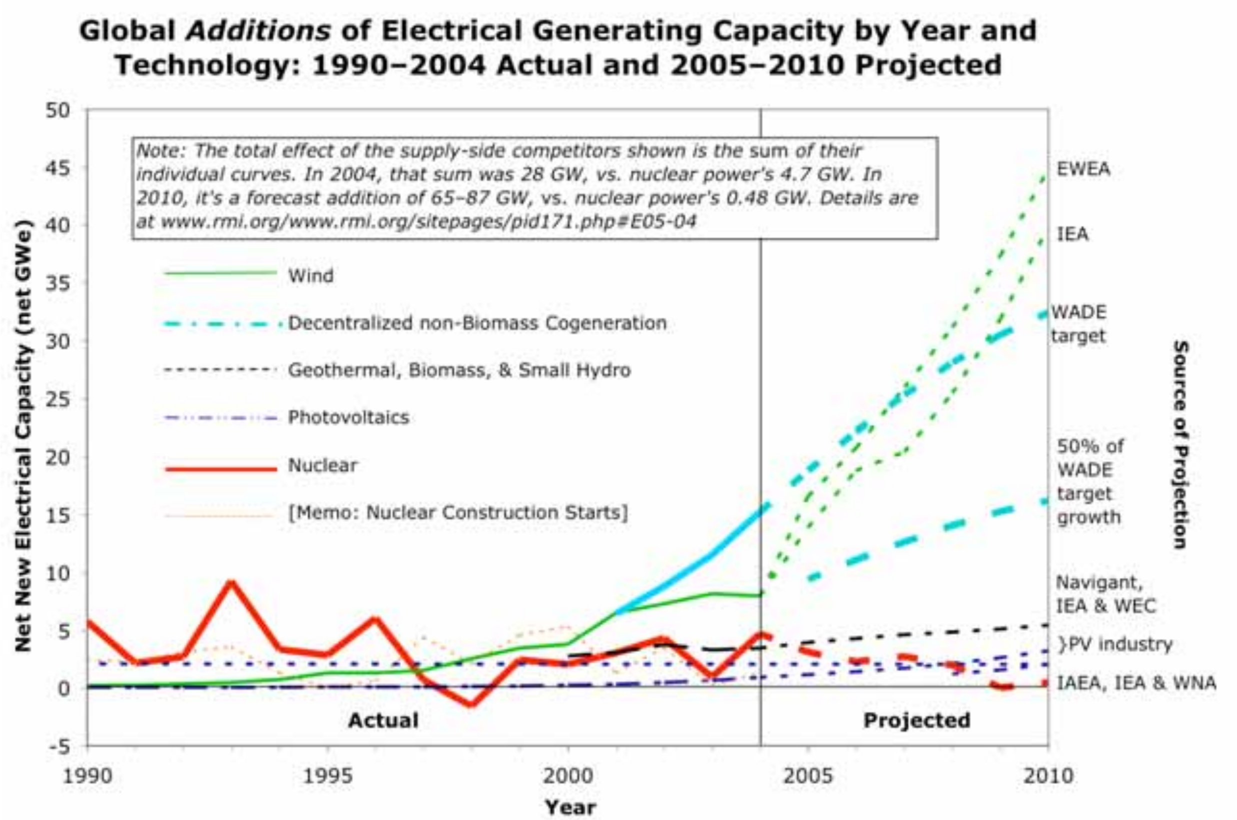
Fig. 1. Worldwide, low- and no-carbon decentralized sources of electricity surpassed nuclear power in capacity in 2002 and in annual output in 2005. In 2004, they added 5.9× as much capacity and 2.9× as much annual output as nuclear power added. (Output lags capacity by 3 y because nuclear plants typically run more hours per year than windpower and solar power — though other renewables, like the fossil-fueled cogeneration shown, have high average capacity factors. Large hydro, over 10 MWe, isn't shown in these graphs nor included in this paper's analysis.) The post-2004 forecasts or projections shown are industry's, and are imprecise but qualitatively clear. The E.U. aims to get 12% of its energy and ~21% of electricity from renewables by 2010, when the European Wind Energy Association projects 75 GW of installed European windpower. China targets decentralized renewables to grow from 37 GW in 2004 to 60 GW, a tenth of total capacity, in 2010. Two-thirds of the decentralized non-nuclear capacity shown is fossil-fueled co- or trigeneration (making power + heat + cooling); its total appears to be conservatively low (e.g.*, no steam turbines outside China), and it is ~60–70% gas-fired, so its overall carbon intensity is probably less than half that of the separate power stations and boilers (or furnaces) that it has displaced; the normal range would be ~30–80% less carbon.*





Thus the global nuclear enterprise has been definitively eclipsed by its decentralized competitors, even though they received 24× smaller U.S. federal subsidies per kWh in FY1984[6] and are often barred from linking fairly with the grid. The runaway nature of the competitors' market victory is evident from Fig. 2 (the first derivative of the upper graph in Fig. 1), showing global *additions* of electric generating capacity by year and by technology, all derived from the same industry data.

Fig. 2. Nuclear power's allegedly "small, slow" decentralized low- and no-carbon supply-side competitors are growing far faster, and are taking off rapidly while nuclear additions fade. Note also the light dotted line of nuclear construction starts, a leading indicator. (It stops in 2004 because future plans are uncertain; due to lead times, this won't affect 2010 completions.)



Moreover, these striking graphs show only the supply side. Electric end-use efficiency may well have *saved* even more electricity and carbon. Most countries don't track it, so it can't be rigorously plotted on the same graph, but clearly it's a large and expanding resource. As one rough indication, the 1.98% drop in U.S. electric intensity in 2003 (whatever its causes) would correspond, at constant load factor, to saving 13.8 GW_p—6.3× U.S. utilities' declared 2.2 GW_p from demand-side management—and the 2004 intensity drop of 2.30% would have saved >16 GW_p (plus 1 GW_p/y from utility load management actually exercised). The U.S. uses only one-fourth of the world's electricity, so it's hard to imagine that global savings don't rival or exceed global

[6] See the detailed analysis in RMI Publications #CS85-7 and –22 (hard copy orderable from www.rmi.org). FY1984 federal energy subsidies exceeded $50b/y. Per unit of energy or savings delivered, they varied by nearly 200-fold between more and less favored technologies. Electricity got 65%—48× as much per kWh as efficiency. Subsidies may be larger and more lopsided today, especially after the 2005 Energy Policy Act. See Doug Koplow's invaluable http://earthtrack.net/earthtrack/index.asp?page_id=177&catid=66 and his new Nov. 2005 estimate (note 63 below).

additions of distributed generating capacity (24 GW in 2003, 28 GW in 2004).[7] Thus these *total* global additions must exceed annual nuclear capacity growth by upwards of tenfold.

Together, then, *the low- or no-carbon supply- and demand-side resource deployments actually occurring in the global marketplace are already bigger than nuclear power and are growing an order of magnitude faster. This is no accident. It simply reflects nuclear power's fundamental uncompetitiveness*—the attribute that, more than any other, makes new nuclear plants unfinanceable in the private capital market.[8] Indeed, the trickle of orders observed worldwide all come from centrally planned electricity systems: nuclear plants aren't bid into auctions nor chosen by an open decision process.[9] But the key question is…uncompetitive compared to what?

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[7] The focus of nearly all EIA data (probably >99%) on the supply side—which provided only 22% of the increase in U.S. energy services during 1996–2005—creates a dangerous "blind spot" that helps make U.S. energy policy in 2005 eerily similar to that of the early 1980s. President Reagan then sought, with modest success, to boost centralized supply expansions with subsidies and siting preëmption. But thanks to Ford/Carter policies, reinforced by the 1979 second oil price shock, the market was quietly producing a gusher of efficiency. For a time, these two trains, one using less energy and the other producing more, sped down the same track in opposite directions. In 1984–85, they met head-on. That almighty trainwreck glutted supplies, crashed prices, and bankrupted suppliers. Efficiency was among the victims too: attention wandered, and Americans, having spent twenty years learning how to save energy, spent the next twenty years forgetting. Soon we may see this very bad movie all over again. Persistently high and jittery oil prices are eliciting major vehicle and biofuel innovations. Micropower is booming. Primary-energy and electric intensities have respectively been falling 2.3 and 1.5%/y since 1996, providing 78% of the increase in delivered energy services. The statistical invisibility of that 78% of the action to policymakers and investors risks repeating, on a larger scale, the ~$100b of losses recently incurred by merchant combined-cycle-plant construction to meet imaginary demand (inferred from a misinterpretation of California's 2000–01 power crisis—see www.rmi.org/images/other/Energy/E01-20_CwealthClub.pdf—plus the Western Fuels Association-funded lie, spread then and now by Mark Mills and Peter Huber, that information technology is a huge and rapidly growing electricity-guzzler; *cf.* http://enduse.lbl.gov/Projects/InfoTech.html). Most of those merchant builders are now deservedly bankrupt. Yet the basic lessons of this episode, like the broader mid-1980s energy-market crash, remain seemingly unlearned. Markets do work. Demand does respond to price. Supply and demand do equilibrate. Small, fast technologies—mass-produced modules with inherently short lead times, deployable by diverse market actors without specialized institutions—can reach customers before big, slow ones can, grabbing revenue streams from energy suppliers. In the early 1980s, efficiency won the race for revenue; today, it's efficiency plus micropower—both far cheaper, more attractive, and with more mature market channels than in the early 1980s. Then, federal policy drove efficiency gains; today, the drivers are smart corporate decisions and state policies. Different details can yield nearly identical results, because these powerful forces continue to operate whether we perceive them or not. In this decade as in the 1980s, those who believe they are helping the nuclear, coal, and hydrocarbon industries may prove to be their worst enemies, while those whom some in those industries might consider their foes may turn out to have done the most to try to save them from federally sponsored disaster. The main hope of averting a mid-1980s-like crash lies in investors' prudence and in the more balanced data, policies, and investment habits fostered by states with policy frameworks based on market processes, not desired outcomes.

[8] S. Kidd (Head of Strategy & Research, World Nuclear Association), "How can new nuclear power plants be financed?," *Nucl. Eng. Intl.* News, 1 Sept. 2005, www.neimagazine.com/story.asp?storyCode=2030770, concludes that despite strong support from the U.S. and other national governments, "financing new nuclear build in the financial markets will prove very challenging." This is due as much to painful experience as to prospective analysis: as Mark Twain put it, "A cat which sits on a hot stove lid will not do so again, but neither will it sit on a cold one."

[9] P. Bradford, "Nuclear Power's Prospects in the Power Markets of the 21st Century," 2005, Nonproliferation Education Center, www.npec-web.org/projects/Essay050131NPTBradfordNuclearPowersProspects.pdf. The Finnish Parliament's recent choice of a nuclear plant doesn't contradict this claim—the secretively handled supporting study used favorable assumptions (*e.g.* 5%/y real discount rate, €1,794/kW capital cost including interest during construction); modern decentralized supply- and demand-side competitors weren't seriously considered; the buyer was a tax-exempt TVA-like nonprofit entity with captive customers, economically equivalent to a long-term power-purchase contract, with no private capital at risk; the plant was mainly financed by 2.6%/y loans provided under unprecedent-

Comparing nuclear power with all *its main competitors—not just the costliest ones*

Standard studies compare a new nuclear plant only with a central power plant burning coal or natural gas. They conclude that new nuclear plants' marked disadvantage in total cost might be overcome if their construction became far cheaper, or if construction and operation were even more heavily subsidized, or if carbon were heavily taxed, or if (as nuclear advocates prefer) all of these changes occurred. *But those central thermal power plants are all the wrong competitors. None* of them can compete with windpower (and some other renewables), let alone with two far cheaper resources: cogeneration of heat and power, and efficient use of electricity. The MIT study (note 57), like every other widely quoted study of nuclear economics, *simply didn't examine these competitors*[10] on the grounds of insufficient time and funding. Thus the distinguished authors' "judgment" that nuclear power merits continued subsidy and support, because we'll supposedly need all energy options, is only their personal opinion unsupported by analysis. The author has verified this widely overlooked interpretation with three of the MIT study's leaders.

To illuminate why the standard studies' consistent omission of non-central-plant alternatives matters, Fig. 3 summarizes the findings of a fair, conservative, simple, and transparent analysis comparing new nuclear plants with an expanded range of widely and abundantly available competitors, all expressed on the same accounting basis—real levelized[11] cost (over a lifetime appropriate for each technology) per *delivered* kilowatt-hour. The methodology and assumptions are in the Appendix on pp. 18–25. Like Fig. 1–2's industry projections for various technologies, one can quibble about many details of the numbers, but their qualitative import is incontrovertible: as the Italian proverb says, *L'aritmetica non è opinione* (arithmetic is not an opinion).

The left side of Fig. 3 first shows the MIT study's nuclear results and its potential "unproven but plausible" nuclear cost reductions under "optimistic" assumptions. Those cost reductions would be a very ambitious outcome for the levels of subsidy and compliant regulation added by the federal Energy Policy Act of 2005. On the contrary, Standard & Poor's has concluded[12] that the Act's nuclear provisions probably won't much reduce nuclear developers' market cost of capital, because most of the key nuclear risks that concern the capital market remain unaddressed. (The bleak competitive prospects for nuclear power revealed by the rest of the graph should deter investment even more, but S&P probably didn't consider that.)

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ed arrangements by German and French parastatals to support those nations' vendors Siemens and Areva (a deal now under legal challenge before the European Commission as an illegal subsidy); and the plant itself, a reported ~€1,875–2,000/kW turnkey bid in 2003 (then worth ~$2,500/kWe in 2004 $), is clearly a loss-leader bid by desperate vendors: an identical unit proposed for France is reportedly expected to cost at least 25% more. Finland's Dec. 2005 energy policy omits nuclear (www.neimagazine.com/story.asp?sectionCode=132&storyCode=2032999).

[10] The MIT study's Executive Summary states: "We did not analyze other [*i.e.*, non-central-plant] options for reducing carbon emissions—renewable energy sources, carbon sequestration, and increased energy efficiency—and therefore reach no conclusions about priorities among these efforts and nuclear power." However, the study's authors drew such a conclusion in the very next sentence: "In our judgment, it would be a mistake to exclude any of these four options at this time." The key issue, of course, is what "exclude" means in practice. Hardly anyone is suggesting that nuclear power not be allowed, on principle, to be offered in the marketplace. Rather, the question is whether it should be given further subsidies and other advantages (as Congress just did) to try to keep it alive despite its manifest inability to compete unaided. Such assistance inevitably comes at competitors' expense.

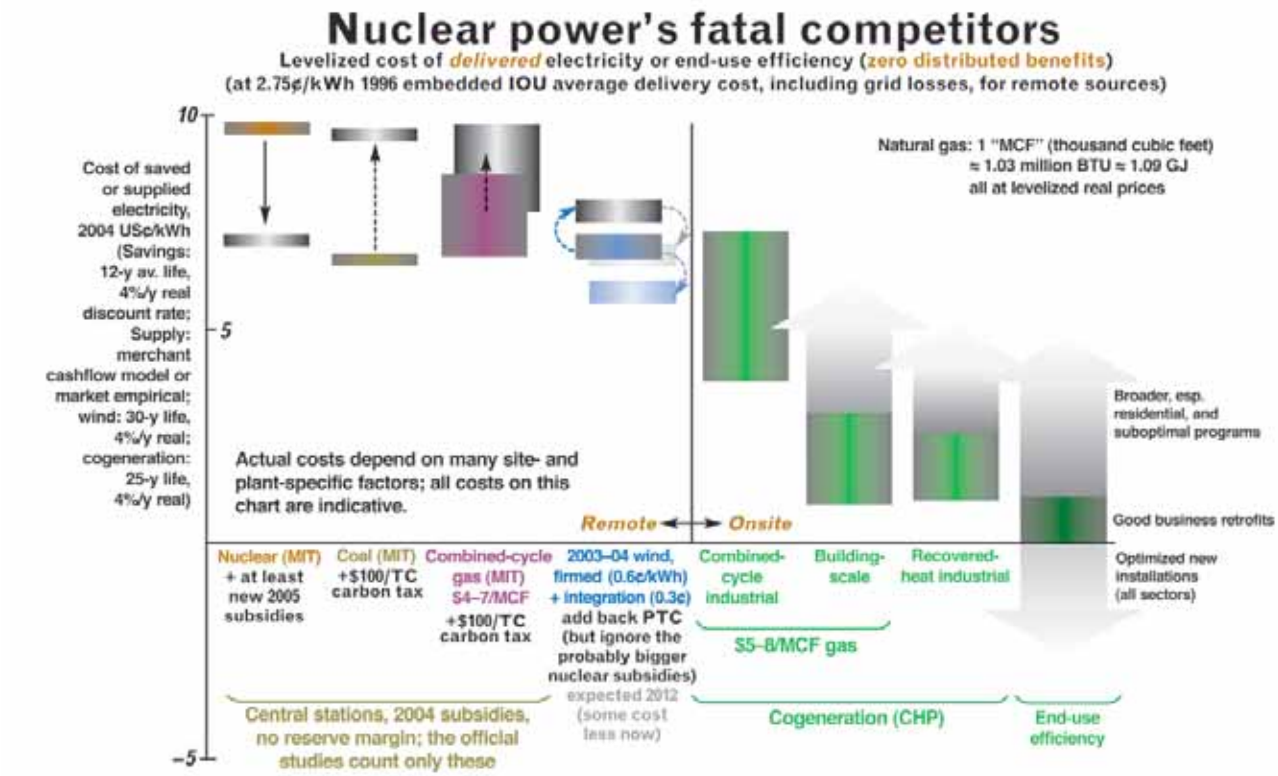
[11] A stream of annual levelized costs has the same present value as an actual time-varying stream of costs.

[12] *Nucl. Eng. Intl.* News, "Energy Policy Act 2005 has limited credit implications: S&P," 18 August 2005, www.neimagazine.com/story.asp?sc=2030540&ac=7969460. See also Kidd, note 8.

Next from the left, Fig. 3 shows the MIT study's conclusions about central coal and gas plants. Heavy carbon taxes ($100 per tonne of carbon) could raise new-coal-electric costs nearly to current new-nuclear costs, based on the 2004 levels of subsidies baked into the numbers shown for both. Alternatively, a very generous interpretation of the effects of the new nuclear support legislation could help new nuclear plants to approach the current market prices of coal-fired electricity. Gas combined-cycle plants would be less affected by carbon taxes, due to their higher thermal efficiency and gas's lower carbon content, but are likelier to see higher fuel prices.

The intended effect of the 2005 Energy Policy Act provisions favoring nuclear construction, plus a very high carbon tax, would be to try to reverse nuclear power's current market disadvantage *vs.* its central-plant competitors. But the rest of Fig. 3 suggests that the immense lobbying efforts that have gone and will continue to go into trying to interchange the relative costs of these three central-plant options will prove futile, because *all three are grossly uneconomic* compared with decentralized supply-side and demand-side competitors, shown on a consistent accounting basis.

Fig. 3. The canonical 2003 MIT study, whose results continue to look conservative, says a new nuclear plant would produce electricity for about 7.0¢/kWh (2004 $). Adding the cost of delivery to the customers (at least 2.75¢/kWh) raises this busbar cost to 9.8¢ per delivered *kWh. The decentralized competitors' delivered costs shown are typically observed for well-executed U.S. marketplace projects. The analysis, detailed on pp. 18–25, systematically favors nuclear power.*



This comparison is conservative in many ways, including:

- The large pre-2005 subsidies to nuclear power and other central stations are baked into the costs graphed, but the Production Tax Credit for windpower (in 2004 $, 1.84¢/kWh for ten years—see note 64 below) is optionally backed out. Most independent students estimate nuclear subsidies' value at well above wind's PTC (see p. 20).[13] Indeed, that PTC was meant to offset the larger permanent subsidies to central-plant competitors. Now that nuclear power has been given its own PTC, this effort to level at least part of the playing-field has again been re-tilted.

- Windpower is assumed to incur a 0.9¢/kWh firming and integration cost (generally well above actual), but no corresponding reserve-margin or spinning-reserve cost is counted for nuclear or other central plants, although their large unit size makes them tend to fail in larger chunks and their forced outages often last longer. *Every* source of electricity is intermittent, differing only in why they fail, how often, how long, and how predictably.
- Marginal costs of delivering power from all the remote sources are understated by using nine-year-old average embedded historic costs—and for investor-owned utilities (IOUs), which generally have denser loads than the quarter of U.S. demand that they don't serve.
- Other than heat recovery by cogeneration, *none* of the 207 "distributed benefits" documented in RMI's *Economist* 2002 book of the year *Small Is Profitable* is counted—yet they typically increase the economic value of distributed resources (supply- *and* demand-side) by an order of magnitude, swamping all the cost differences shown.[14]
- The case made by the static cost comparisons shown—with short-term projections only for nuclear and windpower—becomes far stronger when one considers cost *trends*. For fundamental and durable reasons, as discussed on pp. 20–22 for windpower, efficiency and renewables are getting rapidly cheaper.[15] (Page 21 also notes that some wind projects *today* have half the lowest cost assumed here.) The end-use efficiency potential, too, gets ever bigger and cheaper as new and improved technologies, offshore and high-volume manufacturing, competition, streamlined delivery, and (above all) integrative design outpace the depletion of potential savings.[16] The speed of and further scope for all these competitors' improvements far exceeds any plausible improvements for nuclear power.

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[13] "Energy Subsidies in the European Union: A brief overview," European Environment Agency (Copenhagen), 2004, http://reports.eea.eu.int/technical_report_2004_1/en/Energy_FINAL_web.pdf, notes that during the first 15 years' industrial development, the U.S. subsidized nuclear power ~30× as heavily as windpower per kWh produced. UNDP estimates that only ~8% of the past 30 years' world energy R&D subsidies went to *all* renewables combined.

[14] A.B. Lovins *et al.*, *Small Is Profitable*, RMI, 2002, www.smallisprofitable.org, fully documents these "distributed benefits." The biggest come from financial economics—lower risk with small fast modules, avoided fuel-price volatility risk (worth ~1–2¢/kWh for windpower), etc.—and the next biggest from electrical engineering.

[15] See slides 9–10 in the .PPT at www.rmi.org/sitepages/pid171.php#E05-09. Some argue that onshore wind has very limited potential because of siting conflicts (in the U.K., a leading nuclear advocate, Sir Bernard Inghams, reportedly boasted he had fomented two-thirds of these: P. Toynbee, *Guardian*, 23 Aug. 2003). Yet this objection seems unsound because most lower-48-states onshore wind resources are on very low-value land whose few residents are generally eager for such projects: Native American Reservations just in the Dakotas have ~300 GW of high-class windpower potential, and nearly all High Plains farmers and ranchers welcome the royalties. People who think onshore sites will be very limited then extrapolate from odd cases like the Cape Cod windpower controversy to argue that offshore wind is equally likely to be blocked by siting conflicts. It seems more plausible that offshore siting issues—coastal visibility, navigation and fishing compatibility, cable and structural cost, marine engineering —will be offset by free land and by stronger, steadier wind regimes (less surface roughness, hence lower gustiness).

[16] For example, Jim Rogers PE notes that in *nominal* dollars, compact fluorescent lamps cost >$20 in 1983, $2–5 in 2003 (with ~1b/y volume); electronic T-8 lighting ballasts, >$80 in 1990, <$20 in 2003 (while producing 30% more light per watt); industrial variable-speed drives, ~60–70% cheaper since 1990; window air conditioners, 54% cheaper and 13% more efficient than in 1993; low-emissivity window coatings, ~75% cheaper than five years ago; and direct/indirect luminaires have gone from a premium to the cheapest option. Meanwhile, the biggest New England lighting retrofitter has halved the normal contractor price through more streamlined delivery. EPRI's VP Clark Gellings agrees the "negawatt" resource is becoming cheaper and bigger (personal comm., 4 July 2005).

Fig. 3 shows a huge gap between the cost of delivered electricity from new central plants and the cost of delivered or saved electricity from just the three categories of decentralized resources included—not counting the many other renewables now succeeding in the market (Figs. 1–2).[17] That gap is so big that *nothing can save nuclear power from its dismal economics.* Not regulatory change: the U.S. industry has already enjoyed a regulatory system of its own design for a quarter-century with zero orders. Not new kinds of reactors: if the nuclear steam supply system were *free*, the rest of the plant would still cost too much. Not carbon taxes: they'd help efficiency and renewables equally and cogeneration at least half as much. Not hydrogen: nuclear energy is a hopelessly costly way to split water.[18] And not the roughly $13 billion of new nuclear subsidies just added: history teaches us that markets ultimately prevail. Indeed, history also suggests that whenever a President makes nuclear power the centerpiece of energy policy and tries to smooth its way, the resulting relaxation of market discipline ultimately harms its prospects.[19]

Comparative speed

Although nuclear power is clearly the costliest resource in Fig. 3, might it have other advantages that from a public policy perspective could justify paying a premium for it? Clearly freedom from carbon emissions[20] isn't sufficient, because renewables and end-use efficiency provide the same attribute at much lower cost, and cogeneration does so partially; a fossil-fueled cogenerator that saves, for example, half as much carbon per kWh and costs half as much per kWh as a zero-carbon resource thereby saves carbon at the same cost per ton. But might the comparative *speed*

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[17] This slate seems bound to expand, probably dramatically, as basic innovation accelerates—*e.g.*, cheap 65%-efficient quantum-dot photovoltaics, cheap PV concentrators (www.sunengy.com), or using ultralight fuel-cell cars as plug-in power plants when parked. The latter option (typically using hydrogen reformed from natural gas), which the author proposed in the early 1990s, would give the U.S. light-vehicle fleet an order of magnitude more generating capacity than is now on the grid: A.B. Lovins & D.R. Cramer, "Hypercars®, Hydrogen, and the Automotive Transition," *Intl. J. Veh. Design* **35(1/2)**:50–85 (2004), www.rmi.org/images/other/Trans/T05-01_HypercarH2AutoTrans.pdf, and note 18.

[18] This is as true of nuclear heat for thermolysis of water as of nuclear electricity for electrolysis: A.B. Lovins, "Twenty Hydrogen Myths," 2003, www.rmi.org/images/other/Energy/E03-05_20HydrogenMyths.pdf.

[19] Bradford, note 9.

[20] Neither nuclear power nor any other electrical resource is wholly carbon-free when embodied energy is counted, though most end-use efficiency comes very close. Nuclear plants' cement and steel intensity, plus uranium enrichment energy, actually make the net-energy issue worth exploring. Dr. John Price and the author did so with the best literature available in 1977 (*Non-Nuclear Futures*, Ballinger [Cambridge MA], Part Two), and concluded that nuclear plants using high-grade uranium ore and low-energy methods of decommissioning and waste management have an order-of-magnitude favorable net energy yield individually. However, that analysis also showed, by a closed-form analytic solution, that the rapid nuclear growth forecast then (and proposed now by advocates of nuclear solutions to climate change) would cause a negative net energy balance *for the collective nuclear enterprise* until the growth leveled off. This thesis has recently been revived and the individual-plant analysis updated by J.W.S. van Leeuwen & P. Smith, www.oprit.rug.nl/deenen/Chap_2_Energy_Production_and_Fuel_costs_rev6.PDF, 6 Aug. 2005 (see also www.world-nuclear.org/info/inf11.htm). Pending review, the author expresses no opinion of their work, but notes that the results will be quite sensitive to the ore-grade, enrichment-technology, and end-of-life assumptions. It would also be useful to follow up on another potential climate impact of nuclear power—concerns that ^{85}Kr released by reprocessing could ionize the atmosphere (W.L. Boeck, D.T. Shaw, & B. Vonnegut, *Bull. Am. Meterol. Soc.* **56**:527 (1975); R.G. Harrison & H.M. ApSimon, *Atmos. Electr*. **28**(4):637–648 (1994)), or possibly help to form ultrafine aerosols (R.H. Harrison & K.S. Carslaw, *Revs. Geophys.* **41**(3):1012 (2003); K.S. Carslaw, R.G. Harrison, & J. Kirkby, *Science* **298**:1732–1737 (2002)), enough to affect nimbus rainfall (such as the Asian monsoon) or other important processes. Collapsing nuclear growth has moderated this concern, but it persists, and direct observational tests seem difficult due to uncontrolled variables.

of deploying these various resources at scale, and the total scale that they can ultimately achieve, offer nuclear power such an advantage?

Figs. 1–2 (pp. 2–3) show that in 2004, when U.S. windpower additions were artificially depressed, decentralized low- and no-carbon generation worldwide nonetheless outpaced nuclear power by nearly sixfold in annual capacity additions and nearly threefold in annual output additions, and was pulling away rapidly. This occurred at a substantial scale, four times that of U.S. nuclear power—adding 28 GW to the 2003 global decentralized-generation base of ~383 GW—and was achieved despite nuclear power's generally higher subsidies per kWh (with modest exceptions, notably in Germany) and its far easier access to the grid. This speed disparity, probably more than doubled by efficient use (pp. 3–4), reflects the decentralized competitors' basic advantages, such as short lead times, modularity, economies of mass production, usually mild siting issues (excepting such pathological cases as Cape Cod wind), and the inherently greater speed of technologies that are deployable by many and diverse market actors without needing complex regulatory processes, challengingly large enterprises, or unique institutions. As either nuclear power or its decentralized supply- and demand-side competitors grow, it's hard to imagine how this balance of speed could ever shift in favor of nuclear power—the quintessentially big, long-lead-time, delay-prone, lumpy, complex, and contentious technology, and one that a single major accident or terrorist attack could scuttle virtually everywhere.

Of course *every* technology has its own hassles, obstacles, barriers, and hence risk of slow or no ultimate implementation at scale. Peter Schwartz says that bizarre local rules let a neighbor's objections block his installing photovoltaics on his roof. Efficiency has numerous obstacles—~60–80 market failures, each convertible to a business opportunity[21]—that leave most of it not yet bought. But efficiency's obstacles are being overcome sufficiently to have sustained an unprecedented 1.5%/y average decline in U.S. electric intensity since 1996, even though electricity is the form of energy most heavily subsidized and most prone to split incentives, is seldom priced on the margin, and is sold by distributors which in 48 states are rewarded for selling more kWh and penalized for selling fewer kWh. (The overall U.S. rate of decrease in primary energy intensity was 2.3%/y during 1996–2004, most of it believed to be due to more efficient use.) Such firms as DuPont, IBM, and STMicroelectronics routinely cut their energy intensity by 6%/y, and word of the resulting juicy profits is spreading.[22] In contrast, nuclear power, despite every form of advantage an enthusiastic federal government can provide, has fulfilled no U.S. orders since 1973, and now has a tenth the capacity that was then officially forecast. The key question about "dry hole risk" thus seems to be whether nuclear power, or the diverse portfolio of competing options already far outstripping it in the global marketplace, has the greater risk of badly underfulfilling expectations at scale. Based on actual market behavior and fundamental technological attributes, no *analytic* basis is evident on which nuclear power could satisfy this concern. (The contrary is claimed—by those who also erroneously claim that the decentralized competitors, though necessary and desirable, are *currently* far smaller and slower than nuclear.) An illuminating illustration of the speed of a diverse portfolio of short-lead-time technologies installed by diverse actors in an open market occurred in California during 1982–85, when

[21] This taxonomy is at pp. 11–20 of A.B. & L.H. Lovins, *Climate: Making Sense* and *Making Money*, RMI, 1997, www.rmi.org/images/other/Climate/C97-13_ClimateMSMM.pdf.

[22] *E.g.*, www.pewclimate.org/companies_leading_the_way_belc/company_profiles/index.cfm, www.cool-companies.org/homepage.cfm, and sporadic reports in *RMI Solutions* newsletter, www.rmi.org.

resource acquisitions were fairly across-the-board and the playing field was (by historical standards) relatively level as between supply- and demand-side investments. In those few years, with none of the climate or supply-adequacy concerns that motivate many actors today, the three investor-owned utilities' solicitations elicited (compared with a 37-GW peak load in 1984):

- 23 GW (62% of load) of contracted-for electric end-use efficiency to be installed over the following decade
- 13 GW (35%) of contracted-for new generating capacity, mostly renewable
- 8 GW (22%) of additional new generating capacity on firm offer, plus
- a further 9 GW (25%) of new generating offers arriving *each year*

These contracts and offers totaled 144% of the 1984 peak load, exceeding forecast load growth through the end of the implementation period. Had bidding not been suspended in April 1985 because of the resulting power glut, another year or so of acquisitions at that pace could have displaced every thermal station in California—which in hindsight could have been valuable.[23] This examples suggests that the big risk of creating a level playing-field is not a dangerous paucity but rather an awkward surplus of decentralized alternatives.

Comparative size of the practically and economically exploitable resource base

How about the ultimate potential *size* of the competing resources? Is it true, as nuclear advocates often claim, that only nuclear power is big enough to take on such gigantic tasks as powering an advanced industrial economy and displacing carbon emissions? Clearly not.[24] Just add these up:

- At less than the delivered cost of just *running* a nuclear plant, even if building it cost nothing, potential U.S. electricity savings range from 2–3× (EPRI) to 4× (RMI) nuclear power's 20% U.S. electricity-market share (2004), according to the bottom-up assessments summarized in those organizations' joint *Scientific American* article (note 74).

[23] Similarly, during 1979–85, the U.S. ordered more new capacity from small hydro and windpower than from coal and nuclear plants, excluding their cancellations, which totaled more than 100 GW—despite nuclear's ~24× greater FY1984 subsidy per kWh and far greater interconnection obstacles as mentioned on p. 7 above and in note 13.

[24] A favorite tactic of nuclear advocates (*e.g.*, M. Hoffert *et al.*, "Advanced Technology Paths to Global Climate Stability: Energy for a Greenhouse Planet," *Science* **298**:981 (2002)) is to dismiss end-use efficiency (as desirable but small) without analysis, reject each supply alternative separately as impractical at an enormous scale, and never add up the diverse portfolio of competitors—which *together,* using each to do what it does best, could stabilize climate and support ambitious global development goals (see note 35). Hoffert *et al.* present not a reasoned strategy or portfolio analysis but a wish-list of technologies they do or don't like, with no economics and no totals. But comparing ¢/kWh would reveal nuclear power's huge opportunity costs, as noted on pp. 14–15 below. Hoffert *et al.* would reject as inadequate all of the climate-safe, profitable, market-winning energy options whose R&D succeeded, and substitute the speculative, uneconomic, failed technologies that 30 years' experience has winnowed out. Such time-travel would take us back 30-odd years, to just before the first oil shock, when nuclear fusion (on earth, not appropriately sited 150 million km away), pie-in-the-sky (solar power satellites whose assumed cheap photovoltaics would deliver cheaper power from your rooftop), and fast breeder reactors (which proved proliferative, uneconomic, sterile, and probably unsafe) were widely touted. But despite vast public investments, these all failed investors' economic giggle test. Reviving the 1970s' cramped logic is a public disservice. Hoffert *et al.*'s seductive polemic masquerading as analysis seeks to divert attention and funding from winners to losers. If it misled non-expert policymakers, then more decades of tragically misallocated time and R&D resources (J.P. Holdren *et al.*, *Energy Research and Development for the Challenges of the Twenty-First Century*, PCAST, Washington DC, 1997, www.ostp.gov/Energy/index.html; D.M. Kammen & G.F. Nemot, "Real Numbers," *Issues in Sci. & Technol.*, pp. 84–88, Fall 2005) would probably make the climate problem truly insoluble.

- Cogeneration potential in industry and buildings is very large if regulators allow it. Lawrence Berkeley National Laboratory[25] preliminarily found waste-heat cogeneration alone to have a technical potential nearly as large as today’s U.S. nuclear capacity, though cost and feasibility are very site-specific.
- Windpower’s U.S. potential on readily available rural land—equivalent to a few of the larger Dakota counties—is at least twice national electrical usage.[26] China’s Meteorological Administration similarly found 2 TW of practical windpower potential, more than China’s total electricity usage.[27] European experience confirms that windpower’s intermittence even at penetrations of at least ~14% for Germany[28] or 30% for West Denmark[29] would be manageable at modest cost if renewables are properly dispersed, diversified, forecasted, and integrated with the existing grid and demand response.[30] LBL-58450 notes that 2014 resource plans include 20% wind for SDG&E and 15% for Nevada Power—neither near a limiting value. Intermittence does require attention and proper engineering, but it’s neither a serious issue nor unique to renewables: the grid is already designed for sudden loss of big blocks of capacity, *e.g.* from transmission or even

[25] O. Bailey & E. Worrell, “Clean Energy Technologies: A Preliminary Inventory of the Potential for Electricity Generation,” LBNL-57451, April 2005, http://repositories.cdlib.org/lbnl/LBNL-57451/; ~2.5 GW has been installed.
[26] D.L. Elliott, L.L. Wendell, & G.L. Gower, *An Assessment of the Available Windy Land Area and Wind Energy Potential in the Contiguous United States*, PNL-7789, Pacific Northwest Laboratory (Richland WA), Aug. 1991, www.nrel.gov/wind/wind_potential.html, estimated the Dakotas’ Class III+ wind potential, net of environmental and land-use exclusions (50% of forest area, 30% of agricultural and 10% of range lands, 20% of mixed ag/range lands, 10% of barren lands, and 100% of urban, wetlands, and parks and wilderness areas), at 2,240 TWh/y, equivalent to 58% of total U.S. 2002 net generation. But they assumed 750-kW turbines with 50-m hub height, 25% efficiency, and 25% losses. Today’s 2–5 MW turbines have hub heights up to 100 m, efficiencies are up to the mid-40s of percent and rising, and losses have been at least halved. These turbine improvements, and improved wind prospecting and measurement, combine with the unexpectedly improved wind regime lately found at greater hub heights: C.L. Archer & M.Z. Jacobson, “Spatial and Temporal Distribution of U.S. Winds and Wind Power at 80 m Derived from Measurements,” *J. Geophys. Res.* **108**(D9):4289–4309 (2003). Together, these factors appear to have increased the U.S. wind potential assessed in 1991 by a factor of at least two, including for windy lands in the Dakotas; yet NREL doesn’t yet seem to have published an updated wind resource assessment comparable to the 14-year-old PNL-7789.
[27] CREIA reports the industry belief that China’s 20-GW 2020 windpower target could be exceeded by twofold (thereby surpassing its ambitious 32-plant nuclear-additions goal): “China has potential to be world’s biggest wind energy market by 2020,” 6 Nov. 2005, www.ewea.org/documents/051106WF12Chinalaunchrelease.pdf. In Nov. 2005, China’s leaders set a goal to raise total renewables from 2004’s 7% (half big hydro) to 15% of all energy, and in Dec. 2005, they’re expected to raise the 2020 windpower goal to 30 GW (E. Martinot, pers. comm., 4 Dec. 2005). Most observers would consider it more plausible that China will add 30 GW of wind than 32 nuclear plants by 2020.
[28] See European Wind Energy Association brief of 10 May 2005, “German Energy Agency Dena study demonstrates that large scale integration of wind energy in the electricity system is technically and economically feasible,” www.ewea.org/documents/0510_EWEA_BWE_VDMA_dena_briefing.pdf. Collaborators on this study included the major German grid operators E.ON Netz, RWE Netz, and Vattenfall Transmission.
[29] European Wind Energy Association, “Wind Power Technology: Operation, Commercial Developments, Wind Projects, and Distribution,” ~2004, www.ewea.org/documents/factsheet_technology2.pdf.
[30] Windpower today, in an average wind year, generates the equivalent of 19–20% of Denmark’s electricity use and 25–30% of that of three German *Länder* (>50% in some whole months in Schleswig-Holstein), and on windy days with light loads, over 100% of the load in certain regions, particularly in West Denmark, North Germany, and northern Spain. For more detailed treatments of integrating intermittent resources into the grid, see *Small Is Profitable*, note 14, pp. 193–200, and J. C. Smith, E.A. DeMeo, B. Parsons, & M. Milligan, “Wind Power Impacts on Electric Power System Operating Costs: Summary and Perspective on Work to Date,” NREL CP-500-35946, www.nrel.gov/docs/fy04osti/35946.pdf. Loadshape correlation matters: U.K. wind capacity factors average higher in the high-load than the low-load quarters (G. Sinden, “Wind Power and the he UK Wind Resource,” www.eci.ox.ac.uk/renewables/ukwind**)**, and highest—~2/3—at peak load (www.bwea.com/ref/stop.html).

nuclear-plant[31] outages. Whenever renewable penetration levels of supposed concern have been approached in practice, they've faded over the hazy theoretical horizon—which also continues to recede as distributed intelligence gradually permeates the grid.

- Other renewable sources of electricity are also collectively very large indeed—small hydro, biomass power (especially cogen), geothermal, ocean waves, currents, solar-thermal, and photovoltaics (which NREL's Dr. Garry Rumbles expects will get to or below ~5¢/kWh delivered, within at most a few nuclear-plant lead times). These sources and windpower also tend to be statistically complementary, working well under different weather conditions. All renewables collectively, plus solar technologies that indirectly displace electric loads (daylighting, solar water heating, passive heating and cooling), clearly have a practical economic potential many times U.S. electricity consumption, *i.e.* at least an order of magnitude greater than nuclear power provides today.
- Even at such a scale, land-use concerns are unfounded for a diversified renewable portfolio. For example, a rather inefficient PV array covering half of a sunny area 100×100 miles could meet all annual U.S. electricity needs.[32] In practice, of course, PVs would be building-integrated, rooftop-retrofitted, and built into parking-lot shades, alongside highways, etc. to avoid marginal land-use and to make the power near the load.[33] Specious claims persist comparing (say) the footprint of a nuclear reactor or power station with the [generally miscalculated] land area of which some fraction—from about half for PVs to a few percent for wind turbines—is physically occupied by renewable energy and infrastructure. But ever since the International Institute for Applied Systems Analysis's 1977 *Energy in a Finite World*, it's been well known that *properly including the relevant fuel cycles*, land intensity is quite similar for solar, coal, and nuclear power. An update might even show a modest land advantage to solar.
- A sizeable literature shows that old canards about poor net energy yield from wind and PV technologies are invalid; they generally use very old (or originally grossly erroneous) data on materials intensity. Even some more careful recent papers, such as Prof. Per Peterson's, show materials intensities for windpower far above those found by a detailed lifecycle assessment based on actual projects[34] reflecting recent technological refinement.
- Renewables have a very large potential on a global scale. Even under restrictive solar power assumptions, the International Energy Agency's *World Energy Outlook 2004* (pp. 229–232) foresees a potential of ~30,000 TWh/y in 2030—roughly 2030 world demand.
- Most importantly, a cost-effective *combination* of efficient use with decentralized (or even just decentralized renewable) supply is ample to achieve strong climate-stabilization and global development goals, even using technologies quite inferior to today's.[35]

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[31] As of 15 Nov. 2005, the latest completed *major* outage (≥12 days at zero power)—planned or forced—among U.S. operating nuclear units averaged 36 days and occurred an average of 17 months after the previous such event: www.nei.org/documents/NuclearPerformanceMonthly.pdf, downloaded 2 Dec. 2005. See also note 49 below.
[32] J.A. Turner, "A Realizable Renewable Energy Future," *Science* **285**:687 (1999).
[33] U.S. rooftops in 2025 could accommodate up to 710 GW_p of PVs, net of orientation, HVAC equipment, and shading: Navigant Consulting, Sept. 2004, www.ef.org/documents/EF-Final-Final2.pdf.
[34] Danish Wind Turbine Mfrs. Assn. "The Energy Balance of Modern Wind Turbines," *Wind Power Note*, No. 16, Dec. 1997, www.windpower.org/media(444,1033)/The_energy_balance_of_modern_wind_turbines%2C_1997.pdf. R.H. Williams (Princeton) and the author have separately calculated that a gram of silicon in thin-film photovoltaics can produce more energy over the normal operating life than can a gram of uranium in a light-water reactor.
[35] A.B. & L.H. Lovins, F. Krause, & W. Bach, *Least-Cost Energy: Solving the CO_2 Problem*, Brick House (Andover MA), 1981; A.B. Lovins, "Least-Cost Climatic Stabilization," *Ann. Rev. En.* **16**:433–531 (1991); F. Krause, *Energy*

For all these reasons, a portfolio of least-cost investments in efficient use and in decentralized generation will beat nuclear power in cost *and* speed *and* size by a large and rising margin. This isn't hypothetical; it's what today's marketplace is proving decisively. To be sure, all technologies have a nonzero non-completion risk (at a given site and over all sites); all have implementation hassles. But observed market behavior proves that this risk has been far smaller so far for the competitive portfolio than for nuclear power. Why should this reverse at larger scale?

Indeed, there is good historical reason to believe that nuclear power's perceived problems and actual capital costs tend to increase as it expands. At the height of U.S. nuclear growth, the more coal or (especially) nuclear plants were built or being built, the more they cost in constant steam-plant $/kW. (Later costs closely tracked the coal curve but far overshot the nuclear curve.) Statistical testing[36] suggested a causality that's bad news for nuclear power.[37] It could be even more troublesome at the scale that the nuclear enterprise would need to achieve to make much of a dent in climate change. Dr. Tom Cochran has estimated[38] that adding 700 nuclear GWe worldwide—roughly twice today's nuclear capacity—and running it for 2050–2100 would:

- add ~1,200 nuclear plants (if they lasted 40 years);
- require 15 new enrichment plants (each 8 million SWU/y);
- create 0.97 million tonnes of spent fuel, requiring 14 Yucca Mountains, and containing ~1 million kg—hundreds of thousands of bombs' worth—of plutonium…or

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Policy in the Greenhouse, Intl. Project for Sustainable Energy Paths, 1989– , www.ipsep.org; D.W. Aitken, "Transitioning to a Renewable Energy Future," International Solar Energy Society, 2003, http://whitepaper.ises.org.

[36] The hypothesis was proposed by I.C. Bupp, J.-C. Derian, M.-P. Donsimoni, & R. Treitel, "The Economics of Nuclear Power," *Technol. Rev.* **77**(4):15–25 (1975); refined by W.E. Mooz, *A Second Cost Analysis of Light Water Reactor Power Plants*, RAND (Santa Monica), R-2504-RC, 1979; and confirmed, in collaboration with Vince Taylor, by C. Komanoff, *Power Plant Cost Escalation: Nuclear and Coal Capital Costs, Regulations, and Economics*, Komanoff Energy Associates (NY), 1981, whose regression results are graphed as a supply curve in slide 30 at www.rmi.org/sitepages/pid171php#E05-09. For the original version of that graph, plus further discussion and historical perspective, see A.B. Lovins, "The Origins of the Nuclear Power Fiasco," pp. 7–34 in J. Byrne & D. Rich, eds., *The Politics of Energy Research and Development* (*Energy Policy Studies*, Vol. 3), Transaction Books (New Brunswick, USA, & Oxford, UK), 1986, RMI Publ. #E86-29; also Krause (ref. 35), Vol. II, Part 3E, 1994.

[37] Normally if people think an activity is hazardous, the market tends to signal that perception through insurance premia, tort liability, and regulatory internalization of societal costs. This used to work fairly well for coal plants, chiefly through the Clean Air Act. But for nuclear plants, unique liability-limiting laws and an unresponsive regulatory system largely suppress these signals. Moreover, the more plants there are, the more pollution or other perceived hazard they'll cause, and the more probably they'll have an incident you'll hear and care about. As rising public concerns work through the political and regulatory processes, they increase pressure for each plant to become cleaner and safer so that their collective burden doesn't increase. Meanwhile, returns to investment in plants' cleanliness and safety tend to diminish. One would therefore expect the real cost of each plant to rise geometrically with the number of plants built. That is precisely what we observe, explaining 93% of real cost escalation for U.S. nuclear and 68% for coal plants commissioned during 1971–78; no other explanation better fitting the data has been proposed. This inferred causality would hurt nuclear power. For a coal plant, the perceived irritation is real and directly sensible: you can see it, smell it, and wipe it off the windowsill. But for a nuclear plant, the perceived hazard is insensible and ineffably abstract. If someone, even someone you consider highly credible, announces that the risk of a meltdown or a successful terrorist attack has just been greatly reduced, you can still feel that it's too big and you don't like it: you may care more about big consequences than allegedly small probabilities. Thus the investments that this societal process can require of a coal plant are reasonably bounded, while for a nuclear plant they are unpredictable and nearly open-ended. Efforts to dismiss or suppress such concerns don't make them go away, but only make them pop out elsewhere, like squeezing a balloon. And this is not a uniquely U.S. phenomenon. Similar real cost escalation has occurred across all major nuclear-power countries: see the graphs in Lovins (1986), note 36.

[38] At the 22 June 2005 Board meeting of Natural Resources Defense Council (personal comm., 30 June 2005).

- require 50 new reprocessing plants (each 800 TSF/y with a 40-y operating life) to extract that plutonium under, one hopes, stringent international safeguards;
- require ~$1–2 trillion of investment; and yet
- cut the global average temperature rise by just 0.2˚C.

Similarly daunting numbers were published in 1988 by RMI researchers Dr. Bill Keepin and Greg Kats.[39] They showed that under the demand-growth assumptions then popular, building a 1-GW reactor every 1–3 days through 2025 couldn't reverse CO_2 growth, so nuclear power "cannot significantly contribute to abating greenhouse warming, except possibly in scenarios of low energy growth for which the problem is already largely ameliorated by efficiency improvement." Since 1988, the economic and logistical logic of non-nuclear investments has become far more compelling; Dr. Cochran has simply reminded us of the impracticality of relying on one dominant and slow option rather than on a diverse and well-balanced portfolio of quicker options.

Implications for climate protection

Does this mean that abating climate change (to the major extent it's caused by fossil-fuel CO_2) is hopeless because of the sheer scale of the carbon substitution required? No; rather, it means that:

- much, indeed most, of the carbon displacement should come from end-use efficiency, because that's both profitable—cheaper than the energy it saves—and fast to deploy;
- end-use efficiency should save not just coal but also oil—especially in transportation[40], which in the U.S. in 2003 emitted 82% as much CO_2 as power generation: indeed, since power generation emits only 39% of U.S. and 40% of world CO_2[41], *across-the-board energy efficiency addresses 2.5 times as much CO_2 emission as an electricity-only focus*;
- supply-side carbon displacements should come from a diverse portfolio[42] of short-lead-time, mass-producible, widely applicable, benign, readily sited resources that can be adopted by many actors without complex institutions or cumbersome procedures; and
- the total portfolio of carbon displacements should be both *fast* in collective deployment (MW/y—or, more precisely, TWh/y per y) and *effective* (carbon displaced per dollar).

This last point highlights perhaps the most troublesome unheralded drawback of nuclear power. Buying a costlier option, like nuclear power, instead of a cheaper one, like the competitors

[39] "Greenhouse warming: Comparative analysis of nuclear and efficiency abatement strategies," *En. Pol.* **16**(6):538–561 (Dec. 1988).

[40] The displacement of oil-fired power stations has already been done and can't be done again. In the U.S., <3% of electricity is oil-fired (and only a tenth of that oil is distillate—nine-tenths is gooey bottom-of-the-barrel residual oil), while <2% of oil makes electricity. Worldwide, these figures are only around 7%. The only consistent U.S. holdout, Hawai'i, is shifting markedly toward renewable acquisitions now that its main utility has figured out how advantageous they can be. Moreover, outside such rare condensing-plant situations, most oil-fired power plants are relatively small, run variably or intermittently, and on small grids—not a suitable target for displacement by nuclear plants, which both for technical and for economic reasons must run as steadily as possible. Fortunately, *all* U.S. oil use can be saved or displaced at much lower cost than buying it—even at half today's oil price, and even if its externalities are all worth zero—via the business-led strategy detailed by RMI's Pentagon-cosponsored 2004 study *Winning the Oil Endgame* (www.oilendgame.com). Its implementation is now beginning and shows much promise.

[41] USEIA, *Ann. En. Rev. 2004*, p. 341, data for 2003 (the most recent available), www.eia.doe.gov.

[42] The strategic advantages of a diversified portfolio are unquestioned. This does not mean, however, that every option merits a place in the portfolio purely for the sake of diversity, any more than a financial portfolio should include bad investments just because they're on the market. Diversification is good, but it must be intelligent.

shown in Fig. 3, *displaces less carbon per dollar spent*. This opportunity cost is an unavoidable consequence of not following the least-cost investment sequence: the order of *economic* priority is also the order of *environmental* priority. For example, based on the indicative costs in Fig. 3, and neglecting the energy embodied in manufacturing and supporting the technologies (or, equivalently, assuming that they all have similar embodied energy intensity per dollar[43]), we could displace coal-fired electricity's carbon emissions by spending ten cents to deliver roughly:

- 1.0 kWh of nuclear electricity at 2004 subsidy levels and costs, or
- 1.2–1.7 kWh of dispatchable windpower at no to 2004 subsidies and 2004–2012 costs, or
- 0.9–1.7+ kWh of gas-fired industrial cogeneration or ~2.2–6.5+ kWh of building-scale cogeneration (both adjusted for their carbon emissions[44]), or
- 2.4–8.9 kWh of waste-heat cogeneration burning no incremental fuel (more if credited for burning less fuel), or
- from several to 10+ kWh of end-use efficiency.

The ratio of net carbon savings per dollar to that of nuclear power—the reciprocal of their relative costs of saved or supplied energy—is their ratio of effectiveness in climate protection per dollar. This comparison reveals that *nuclear power saves as little as half as much carbon per dollar as windpower and traditional cogeneration, half to a ninth as much as innovative cogeneration, and as little as a tenth as much carbon per dollar as end-use efficiency*. Or as Keepin and Kats arrestingly put it, based on their reasonable 1988 estimate that efficiency would save ~7× as much carbon per dollar as nuclear power, "*every $100 invested in nuclear power would effecttively release an additional tonne of carbon into the atmosphere*"—so, counting this opportunity cost, "the effective carbon intensity of nuclear power is nearly six times *greater* than the direct carbon intensity of coal fired power." Whatever the exact ratio, this finding is qualitatively robust even if nuclear power becomes as cheap as its advocates claim it can, but its competitors don't. Recall also that this paper has used assumptions systematically favoring nuclear power, and didn't count nuclear power's old and new U.S. subsidies—preliminarily estimated[45] to total ~4.2–8.2¢/kWh, or roughly two-thirds of new plants' apparent total marginal busbar cost.

Alongside the economic priority of carbon displaced per dollar, one must consider physical speed of deployment: if nuclear investments are also inherently *slower* to deploy, as we discussed on pp. 8–10 above, then they don't only *reduce* but also *retard* carbon displacement. Thus **if climate matters, then we must buy the most solution per dollar and per year spent. Empirically, on the criteria of both cost *and* speed, nuclear power seems about the least**

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[43] This is a valid first-order assumption because energy markets are in reasonable equilibrium. The only reason net energy analysis received much attention—around 1975 when the author helped to write its "generally accepted accounting practice"—was that severe disequilibria then made it possible, though not common, for a project to make money but lose energy. That is no longer true. However, any technology with very high materials or process-energy intensity merits a corresponding degree of suspicion about its net energy balance. Modern corn ethanol, which has a modestly favorable net energy yield but unimpressive economics without subsidy, is a case in point.

[44] The reciprocal of the delivered cost of 3.78–7.28¢/kWh (for a range of 28–64 MWe unit size and $5–8/MCF gas price) yields a gross 1.4–2.6 kWh/$0.10. However, this technology does emit fossil carbon in its operation. If, as a conservative approximation, the carbon emission is 3× less per kWh than for the coal-fired power plant and the fossil-fueled boiler displaced (4× is often achievable and is not an upper limit), then the carbon-reducing effect of a gas-fired CCGT cogeneration kWh is only about two-thirds as big as windpower's, or ~0.9–1.7 kWh/$0.10.

[45] Koplow, note 63 below, as of 8 November 2005. Further study seems more likely to raise than lower these figures.

effective climate-stabilizing option on offer. The case for new nuclear build as a method of climate protection is therefore purely rhetorical and cannot withstand analytic scrutiny.

Conclusions

This widening gap between market reality and nuclear theology raises some pointed policy questions. Why divert further public resources from market winners to the market loser?[46] Why pay a premium to incur nuclear power's uniquely disagreeable problems? (No other energy technology spreads do-it-yourself-kits and innocent disguises for making weapons of mass destruction[47], nor creates terrorist targets[48] or potential for mishaps that can devastate a region, nor creates wastes so hazardous, nor is unable to restart for days after an unexpected shut-down.[49]) Why incur the opportunity cost of buying a costlier option that both saves less carbon per dollar and is slower per megawatt to deploy? And if, unsupported by analysis, you think "we need everything," how will you avoid acting like a Chinese-restaurant diner who orders one item from each section of the menu because it all sounds tasty, spends his money on a small bowl of shark's-fin soup and other delicacies, can't afford rice, and goes away hungry?

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[46] Nuclear plant vendors probably got far less 2004 revenue than renewable power equipment vendors' ~$30b.

[47] A.B. & L.H. Lovins & L. Ross, "Nuclear Power and Nuclear Bombs," *Foreign Affairs*, Summer 1980, www.foreignaffairs.org/19800601faessay8147/amory-b-lovins-l-hunter-lovins-leonard-ross/nuclear-power-and-nuclear-bombs.html; A.B. Lovins, "Nuclear Weapons and Power-Reactor Plutonium," *Nature* **283**:817–823, 28 Feb. 1980, www.rmi.org/images/other/Security/S80-01_NucWeaponsAndPluto.pdf; V. Gilinsky, H.W. Hubbard, & M. Miller, "A Fresh Examination of the Proliferation Dangers of Light Water Reactors," 2004, www.npec-web.org/projects/NPECLWRREPORTFINALII10-22-2004.pdf. Note also that the higher enrichment of pebble-bed reactor fuel (>90% of the way to highly enriched bomb-grade uranium in terms of separative work) makes this type of reactor particularly proliferative by encouraging the wide development and deployment of cheaper enrichment technologies like centrifuges. The combination of centrifuges' concealability and modularity with ^{235}U bombs' simplicity and lack of need for prior testing (thus defeating the "timely warning" criterion fundamental to nonproliferation strategy) makes this an especially dangerous development. That's quite aside from the other daunting issues described in J. Harding's 2004 ESKOM paper at www.rmi.org/sitepages/pid171php#E05-10 and the dismal economic picture now starting to emerge (www.neimagazine.com/story.asp?storyCode=2030985; S. Thomas, "The Economic Impact of the Proposed Demonstration Plant for the Pebble Bed Modular Reactor Design," Aug. 2005, www.psiru.org/reports/2005-09-E-PBMR.pdf; www.noseweek.co.za, Dec. 2005).

[48] *E.g.*, F.N. von Hippel, "Revisiting Nuclear Power Plant Safety," *Science* **291**:201 (2003); A.B. & L.H. Lovins, *Brittle Power: Energy Strategy for National Security*, Brick House (Andover MA), 1981, out of print but reposted at www.rmi.org/sitepages/pid1011.php. Crashing a large airplane at high speed into a reactor, though it has been threatened, is likely but not necessary to breach its containment, and is not even the most plausible threat. Neither is a concerted paramilitary attack aimed at taking over the control room. Rather, using readily available and inconspicuously portable standoff weapons, often from outside the security perimeter, a small group or even an individual could cause many an existing light-water reactor to melt down uncontrollably if the attack were properly designed by a technically trained person (analogous to the structural engineer(s) who planned the 9/11 airplane attack on the World Trade Center) using publicly available information.

[49] After the Northeast blackout on the afternoon of 14 August 2003, the nine scrammed U.S. nuclear units achieved 0% output on the 15th, 0.3% on the 16th, 5.8% on the 17th, 38.4% on the 18th, 55.2% on the 19th, and 66.8% on the 20th. That's two and a half days to restore 6% power, five-plus days to half-power, and two-thirds power after six and a half days. The units lost an average of 97.5% of their capacity for the first 3 days, 82% for 5, 59% for 7, and 54% for 12 days (www.nrc.gov/reading-rm/doc-collections/event-status/reactor-status/2003/index.html)—hardly a reliable resource. Such an inability to restart promptly after a major grid outage (and hence not just nucleate restart but restore the gross supply/demand balance to permit restart altogether) makes nuclear plants least available when they are most needed—a sort of "anti-peaker" attribute. This present security issue, like nuclear plants' potential for national- or world-scale shutdown in case of a serious accident or attack, has received curiously little notice; yet milder windpower failures, confined to a relatively small region, are claimed to be an insurmountable problem.

A popular euphemism holds that we must "keep nuclear energy on the table." What exactly does this mean? Continued massive R&D investments for a "mature" technology that has taken the lion's share of energy R&D for decades (39% in OECD during 1991–2001, and 59% in the United States during 1948–98)? Ever bigger taxpayer subsidies to divert investment away from the successful competitors?[50] Heroic life-support measures? Where will such efforts stop? We've been trying to make nuclear power cost-effective for a half-century. Are we there yet? When will we be? How will we know? And would nuclear advocates simply agree to desubsidize the entire energy sector, so all options can compete on a level playing field?

The Energy Policy Act of 2005 is festooned with lavish subsidies and regulatory shortcuts for favored technologies that can't compete unaided.[51] Nuclear expansion, for example, gets ~$13 billion in new gifts from the taxpayer:[52] 80% loan guarantees (if appropriated), ~$3 billion in dubious "R&D," 50% licensing-cost subsidies, $2 billion of public insurance against any legal or regulatory delays, a 1.8¢/kWh increase in operating subsidies for the first 8 y and 6 GW (equivalent to a capital subsidy of ~$842/kW—roughly two-fifths of likely capital cost)[53], a new $1.3-billion tax break for decommissioning funds, and liability for mishaps capped at $10.9 billion (and largely evadable through shell companies). The industry already enjoyed Treasury payments to operators as a penalty for late acceptance of nuclear waste (which there's no place to put nor obvious prospect of one), free offsite security, and almost no substantive public participation in or judicial review of licensing.[54] The total new subsidies approximate the entire capital cost of six big new nuclear plants. Taxpayers have assumed nearly all the costs and risks they didn't already bear; the promoters will pocket any upside, yet are unwilling to risk any material amount of their own capita, despite ~$569 billion of FY2004 revenue and $694 billion of market capitalization (if they were a country, they'd rank as the world's #13 economy).[55] Yes, this boost may yield slight twitches from the moribund nuclear industry—but no authentic revival.

Lord Keynes said, "If a thing is not worth doing, it is not worth doing well." Nuclear power has already died of an incurable attack of market forces, with no credible prospect of revival. Current efforts to deny this reality will only waste money, further distort markets, and reduce and retard carbon dioxide displacement. Cheaper, faster, abundant decentralized alternatives are now empirically larger, are being bought an order of magnitude faster in GW/y, and offer far greater

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[50] C. Komanoff's 1992 study *Fiscal Fission*, www.earthtrack.net/documents.asp?docUrl=FiscalFission.pdf, found that during 1950–90, the U.S. put ≥$0.5 trillion into nuclear power, which produced electricity for at least 9¢/kWh, twice the contemporaneous cost of equivalent fossil-fueled electricity.

[51] Nuclear power isn't the only beneficiary of this latest burst of Congressional largesse. Coal gasification, for example, is also richly aided even though a large-scale program, worthy of the defunct Synfuels Corporation, would yield 8–10 times less gas than efficient use could save, and would cost 4–5 times as much per unit (*WTOE*, note 40).

[52] This estimate by Public Citizen, in undiscounted nominal dollars, rests on specific assumptions, chiefly about loan guarantees not yet appropriated. However, it may also be low, partly because Congress "scores" tax expenditures only over the next ten years, while many subsidies last longer. Koplow (note 63 below) implies far higher figures.

[53] Assuming a 4%/y real discount rate, ignoring ramp-up, and discounting back to the first year of full-power operation. The 2005 present value is ~$640/kW. *Cf.* EIA's earlier "Analysis of Five Selected Tax Provisions of the Conference Energy Bill of 2003," Feb. 2004, http://tonto.eia.doe.gov/FTPROOT/service/sroiaf(2004)01.pdf.

[54] The NRC, which shows every sign of capture by the industry it is supposed to regulate, has made clear its unwillingness to consider the most serious outstanding issues, including credible terrorist attacks, even though in nearly half of tests, guards have proven unable to repel small groups of mock attackers whose capabilities and tactics were severely constrained (www.nci.org/nci-ht.htm).

[55] D. Koplow, "NuSubsidies Nuclear Consortium," www.earthtrack.net/documents.asp?docUrl=NNC_Overview.ppt.

ultimate potential. Since nuclear power is therefore unnecessary and uneconomic, we needn't debate whether it's safe. And the more concerned you are about climate change, the more vital it is to invest judiciously, not indiscriminately—best buys first, not the more the merrier.

A state government committed to market-based, least-cost energy policies could do much to correct the distortions introduced by misguided federal policies. State energy taxes might even be designed to offset federal energy subsidies, technology-by-technology, to create a "subsidy-free zone."[56] This should have a salutary effect on energy cost, security, environmental impacts, and broad economic benefits. Just talking seriously about it and analyzing its consequences could help to focus attention on the differences between current federal energy policy and sound free-market principles. Such a state could become the first jurisdiction in the world to allow all ways to save or produce energy to compete fairly and at honest prices, regardless of which kind they are, what technology they use, how big they are, or who owns them. Who could be against that?

Appendix: Analysis Underlying Fig. 3 (p. 6)

Fig. 3 (p. 6) graphs the following levelized costs in 2004 US$, documented next. All have only about one significant figure, not the three shown here for calculational clarity. In summary:

- Nuclear (see p. 19): 7.02¢/kWh busbar cost (MIT study at 40 y, 0.85 capacity factor) + 2.75¢/kWh delivery cost = 9.77¢/kWh; successive sensitivity tests for cost reductions: MIT study's 5.76¢/kWh for –25% construction cost, 5.55¢/kWh for 5→4 y construction time, 5.34¢/kWh for reducing O&M cost to 1.36¢/kWh, and 4.40¢/kWh for zero risk premium *vs.* coal and gas plants, all + 2.75¢/kWh delivery cost = combined minimum delivered cost 7.15¢/kWh, *i.e.*, ~2.6¢/kWh "cheaper" than expected for a 2003 order
- Coal (p. 21): MIT study's 4.40¢/kWh busbar cost (at $1.26/million BTU coal) + 2.75¢ delivery cost = 7.15¢/kWh; $100/tonne carbon tax or equivalent would raise this, per MIT study, to 6.91 + 2.75 = 9.66¢/kWh (p. 22)
- Combined-cycle gas (p. 21): MIT study's 3.98–5.86¢/kWh at levelized real gas prices of $3.95– $7.04 per thousand cubic feet ["MCF"], + 2.75¢/kWh delivery cost = 6.73–8.61¢/kWh; illustrative $100/tonne carbon tax or equivalent raises this (p. 22) to 7.78–9.77¢/kWh
- Wind (pp. 21–22): 3.0–3.5¢/kWh busbar + 0.6¢/kWh firming + 0.3¢/kWh integration + 2.75¢/kWh delivery cost = 6.65–7.15¢/kWh; optionally add back levelized after-tax Production Tax Credit (0.86¢/kWh, note 64) = 7.51–8.01¢/kWh; optionally subtract 1.0¢/kWh for cost reduction that DOE and industry expect by 2012 (already surpassed by some projects) = 6.51–7.01¢/kWh without or 5.65–6.15¢/kWh with PTC
- Cogeneration (p. 22) at levelized real gas prices of $5–8/MCF: combined-cycle industrial 3.78–7.28¢/kWh at 28–64 MWe; recovered-heat industrial 1.1–2.6, perhaps up to 4, ¢/kWh; building-scale ~1–3¢/kWh well-optimized, or up to ~7¢/kWh with standard design

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[56] One might at first suppose that federal preëmption could prevent this, but states' powers to devise and enforce their own tax regimes for their own purposes should trump the notion that only the federal government can use fiscal instruments to influence energy choices. For example, states now have widely differing levels and structures of automobile and gasoline taxes, yet aren't preëmpted by the federal authority to set car efficiency standards.

- End-use efficiency (societal cost, see pp. 23–25): ~0–1¢/kWh for well-designed and -executed retrofits in commercial/industrial sectors; <0 for optimized new installations in all sectors; up to ~5¢/kWh for suboptimal business programs or broad all-sectors programs

General methodology: All costs are in 2004 US$ unless otherwise stated. For central plants, we use the 2003 MIT nuclear study's merchant cashflow model with its ~5%/y implicit real discount rate and all its other assumptions[57]; the MIT analysis uses engineering economics with no risk adjustment, a conventional approach that favors nuclear power. For decentralized competitors, such as windpower (mainly in Class V–VI sites, levelized at 4%/y over 30 y), we use observed costs or higher. Similarly, for gas-fired industrial cogeneration, the basis is a set of proprietary empirical data for five commercial projects that a leading developer considers typical and amply profitable; for building-based cogeneration and trigeneration (coproduction of electricity with useful heating and cooling), we draw on a wider range of anecdotal in-house and reported experience, reflecting costs' sensitivity to site-specific design details. All cogeneration costs are levelized at 4%/y real over 25 y. Costs of electric end-use efficiency are drawn from a wide range of data (pp. 23–25), converted as fully as possible to a conservatively assumed 12-y average service life and levelized at a 4%/y real discount rate. Fig. 3 shows the potential for lower nuclear costs and for the expected reduction in windpower costs by 2012 (one nuclear lead time away), but doesn't otherwise reflect future costs, which tend to favor non-nuclear options.

Location: To compare resources fairly, regardless of their scale and their distance from the retail customer, the levelized busbar costs of remote resources (central nuclear, coal, and gas plants plus windpower) is converted into *delivered* costs at the retail meter by adding a uniform nominal delivery cost. Absent a recent national assessment of marginal delivery cost, reflecting the costs and losses of new transmission and distribution capacity, we adopt as a conservatively low benchmark the 1996 embedded-average-historic real delivery cost of U.S. investor-owned utilities in 1996, namely 2.75¢/kWh, derived from their published financials (in the USEIA *Electricity Annual*) in RMI calculations published in 2002.[58] A realistic marginal cost for delivery would be site-specific but generally higher: *e.g.*, *Small Is Profitable* (p. 219) notes that PG&E's average grid cost some years ago was ~8% above the national average but that this large utility's maximum marginal grid cost was 5.5× the national average. The delivery-cost adder does not apply to resources that are already onsite, namely cogeneration and end-use efficiency.

New nuclear plant: We adopt the analysis of the 2003 MIT study *The Future of Nuclear Power* for a nominal light-water reactor of the various advanced types now on offer. For a 40-y life and 0.85 average capacity factor, that study found a levelized busbar cost of 6.7¢/kWh (2002 $), which we convert to 7.0¢/kWh in 2004 $ using the 1.0471 GDP implicit price deflator. The MIT study makes a strong case that its assumed overnight cost of $2,000/kW (2002 $) or $2,094/kW (2004 $) is realistic and may well be conservative. (For example, it's less than the ~$2,200/kW apparent overnight turnkey cost of the new Finnish plant, which shows every sign of being built at a substantial loss, especially at today's higher commodity prices.) The weaker analytic basis of the University of Chicago 2004 study, which adopted overnight costs of $1,232 to $1,847/kW,

[57] J. Deutsch & E.J. Moniz (Co-Chairs), *The Future of Nuclear Power*, MIT, 2003, http://web.mit.edu/nuclearpower/.
[58] A.B. Lovins *et al.*, *Small Is Profitable: The Hidden Economic Benefits of Making Electrical Resources the Right Size*, Rocky Mountain Institute, 2002, www.smallisprofitable.org, at pp. 217–219.

reflects industry hopes but not global experience. The World Nuclear Association's "authoritative" compilation of others' estimates of nuclear cost[59] adds no new reason to believe its vigorous claim of $1,000–1,400/kW "achievable now." That's because all its sources simply recycle industry estimates—except the independent MIT team, whose closely reasoned $2,000/kW base case WNA rejects (while nonetheless citing the MIT study as authority for its own contrary findings). WNA understandably prefers to assume cheap money equivalent to public financing of nuclear plants, but within an increasingly privatized sector in a largely market-based global economy, that's clearly inconsistent with market principles and realities.

Capacity factors averaging 0.9 have lately and commendably been achieved by the U.S. reactor fleet, but the MIT study notes this is unrepresentative of experience with mature programs in other industrial countries (the global average is ~0.75) and doesn't seem realistic over 40 y; we use the MIT study's 0.85. Our 40-y lifetime, the MIT study's upper bound, is also unsupported by convincing experience and may well prove overly generous.[60] Neither of these assumptions, though, is important to the outcome, which depends largely on nuclear plants' capital cost and cost of money. Those who wish to bet that the MIT study's capital costs are 40-odd to 100% too high should put their money where their mouths are. They're conspicuously failing to do so, and if they did, their financial ratings could reasonably be expected to suffer.

New coal and gas central plants: We similarly adopt the MIT study's busbar costs of 4.4¢/kWh for pulverized-coal plants and 4.0–5.9¢/kWh for combined-cycle gas plants (both in 2004 $), using a utility natural-gas price levelized at $4–7/MCF.[61]

Windpower: Windpower's empirical busbar costs vary widely: wind energy varies as the cube of windspeed, so a 10% stronger wind contains 33% more energy.[62] It is not generally true, as economic theorists might suppose, that the best sites have been exploited first; rather, siting tends to be determined substantially by local utility policies, buyback prices, and transmission capacity. For example, the Dakotas' world-class wind sites stand virtually unexploited because lignite-plant operators bar transmission access and FERC has not yet intervened to promote competition.

For windpower's busbar costs, this paper conservatively adopts a range of 3.0–3.5¢/kWh, conventionally assuming 30-y operating life, and including the Production Tax Credit (PTC), which Fig. 3 offers the option of adding back (but without adding back nuclear power's probably larger

[59] World Nuclear Association, "The New Economics of Nuclear Power," www.world-nuclear.org/economics.htm, 1 Dec. 2005. The best rebuttal to this redux's claim of robustly competitive new nuclear plants is the industry's insistence on more subsidies and its unwillingness to bid turnkey projects at anywhere near the claimed costs.
[60] Higher figures, such as the 60-y life implied by some recent NRC license extensions, seem unlikely to be empirically validated, but if they were, that wouldn't materially alter this paper's conclusions.
[61] Henry Hub front-month prices were around $6–8/MCF from November 2004 through July 2005; at the end of August 2005, as Henry Hub reopened after Hurricane Katrina, its June 2007 contracts were priced at $8.55/MCF in nominal dollars. EIA's *Annual Energy Outlook 2005* (Jan. 2005) forecasted that power plants will pay in 2025 an average of $5.58/million BTU for gas (2004 $, *not* levelized), nearly one-fourth below $7/MCF. One needn't guess at the long-term gas price; constant-price forward gas can be bought today in the futures and options markets.
[62] In 2000, NREL noted a 1.8¢/kWh lower production cost for a Class VI than for a Class IV site, but expected better designs to shrink this difference to 0.6¢/kWh by 2010: "Technology Profile for Wind," www.nrel.gov/analysis/power_databook/docs/pdf/db_chapter02_wind.pdf.

2004 subsidies[63]). This cost range exceeds the lowest wind energy contract price in 2003, FPL's 2.9¢/kWh including PTC. The 3.0–3.5¢/kWh range also brackets the historic capacity-weighted average cost of 3.37¢/kWh (2004 $) observed for >2.7 GW of U.S. wind projects commissioned in 1999–2005; the lowest observed cost is only 1.5¢/kWh, and the highest, excluding one outlier, 5.8¢/kWh.[64] Further confirming reasonableness, LBNL-58540 (*id.*) found that Western utilities' resource plans use levelized costs as low as 2.3¢/kWh in a good site, also including PTC.

In 2005, nominal wind-turbine costs spiked from ~$1,000/kW to ~$1,250/kW for three reasons: a weaker dollar (the erratic PTC long ago made the U.S. cede wind-turbine manufacturing dominance to Europe), higher steel prices, and a spot shortage of turbines (the world's major makers are booked over a year ahead). That shortage was due to the U.S. installation bust in 2004 and resurgence in 2005–6, both caused by the perennial unpredictability of Congress's brief PTC renewals; the latest of its three expirations, from December 2003 to October 2004, delayed ~1 GW of projects. However, these factors do not appear to reflect equilibrium market behavior—the PTC was just renewed for three years, bringing some short-term stability to market development—and the first two causes, especially steel prices, would also raise nuclear costs.

The 2005 wind-turbine price spike occurs against a background of downward-trending real costs due to production volume, big players like GE, installation and operating experience, and improving technology. Windpower's real capital costs have historically fallen by 12–18% per doubling of installed capacity, which worldwide averaged 28%/y growth (a 2.5-y doubling time) in 1999–2004. Rising hub heights increase wind capture more than had been expected (thus expanding the whole wind resource and its competitiveness); have markedly increased efficiencies; have boosted typical capacity factors to ~0.30–0.35 (again very sensitive to site); and can achieve CF ~0.45 in many good offshore sites. R&D is also yielding turbines optimized for lower-windspeed sites, which are much more widespread and often closer to load centers. Availability varies by model and manufacturer but is typically ~0.95–0.98 and rising. The combination of these factors led DOE to project in 2001 that nominal windpower costs in Class VI to Class IV sites will respectively fall from 2.4–3.0¢/kWh in 2010 to 2.2–2.7¢/kWh in 2020.[65] As the new LBL empirical data confirm, some of this progress has already occurred. The ~1¢/kWh cost decrease that DOE and the industry currently expect from ~2003 to ~2012 is approximately shown as a sensitivity test in Fig. 3 (p. 6), but its result still exceeds likely long-term windpower costs. Indeed, LBNL's database of actual projects shows some *already* costing less than DOE's lowest expectation for 2010, which is sooner than a nuclear plant ordered today can be built.

For dispatchability comparable to central stations', we add to all wind costs a firming cost of 0.6¢/kWh (the BPA wind-firming tariff), and to be extra-conservative (note 30), an additional

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[63] The most authoritative independent U.S. expert estimates pre-2005 federal nuclear subsidies had a levelized 2004-$ value of 0.79–4.2¢/kWh, and preliminarily estimates that the Energy Policy Act of 2005 added another ~3.4–4.0¢/kWh for at least the next 6 GW: D. Koplow, "Nuclear Power in the U.S.: Still Not Viable Without Subsidies," 8 Nov. 2005, www.earthtrack.net/earthtrack/library/NuclearSubsidies2005_NPRI.pdf.

[64] M. Bolinger & R. Wiser, "Balancing Cost and Risk: The Treatment of Renewable Energy in Western Utility Resource Plans," LBNL-58540, Aug. 2005, http://eetd.lbl.gov/ea/ems/reports/58450.pdf, at p. 27. EIA's *Annual Energy Outlook 2005* adopts 4.5–6¢ (2003 $) levelized over 20 y without PTC. On this basis, PTC has a levelized value of ~1.1–1.2¢; we levelize at 4%/y for 30 y, after-tax as LBNL-58540 recommends, to yield a PTC of 0.86¢/kWh in 2004 $. EIA's 4.5–6¢/kWh would be ~2.4–3.5¢/kWh on our accounting basis, *vs*. our 3.0–3.5¢.

[65] Cited at end of "Technology Profile for Wind," note 62.

0.3¢/kWh for integration, which BPA's firming tariff already includes. The generally lower ranges (including a firming and integration cost of roughly zero for hydro-rich California) cited in Table EP-5 of LBL-58450 and in NREL CP-500-35946 (note 30) suggest both these values are excessive, especially in combination. Mature firming markets, even at large scale, should indeed get substantially cheaper, especially with demand-response "virtual peaker" contracts. The extra 0.3¢/kWh might instead pay for adding transmission to some remote sites where coal or lignite developers monopolize transmission capacity that wind could more cheaply utilize. In general, it does not appear that the best lower-48 U.S. windpower resources are more remote from load centers than are suitable sites for big nuclear and coal plants, although historically the major transmission lines have been built to link load centers with the latter, not the former.

Cogeneration: Tom Casten, Chairman and CEO of Primary Energy, LLC (a leading cogeneration developer with ~0.9 GW of operating U.S. projects), has generously shared proprietary data on five projects he considers typical and profitable, assuming 10%/y weighted-average cost of capital (~200 basis points above the utility average he cites) and 25-y amortization.[66] We have parameterized levelized real natural-gas costs as \$5–8/MCF—conservatively assumed to be \$1/MCF higher than central plants' gas cost—so his actual gas-fired combined-cycle cogeneration project costs imply net levelized electricity costs of 3.78–7.28¢/kWh at 28–64 MWe. This credits any avoided capital cost of duplicate boiler facilities and associated O&M, as well as the useful thermal energy produced (*i.e.*, what it would otherwise have cost to produce with a conventional boiler). To protect proprietary data, Casten's recovered-heat ("recycled-energy") data are also for a blend of three actual projects in the 60–160 MWe size range, all using heat that was previously being thrown away. That heat is worth more than the applicable capital and O&M costs, so these projects book an average net annual profit of \$5.8–19.3 million, including return of and on capital, *before* valuing of the 517 GWh/y that the average project generates. Dividing those figures would indicate a notional negative cost of electricity (–2.1 to –4.7¢/kWh), but Fig. 3 instead graphs their actual all-in electricity price (+1.1 to +2.6¢/kWh), with possible variation up to 4¢/kWh in less favorable cases. The building-scale cogeneration costs shown are for very well-designed projects integrated with end-use efficiency and load management, and where appropriate, use very efficient absorption chillers or desiccants or both to replace vapor-compression chillers. More conventional designs, such as those considered in a recent proprietary RMI study of five 4.0–5.5 MWe prospects in California, deliver at a typical net cost around 4.8–5.7¢/kWh, within Fig. 3's shaded upper range of up to 7¢/kWh.

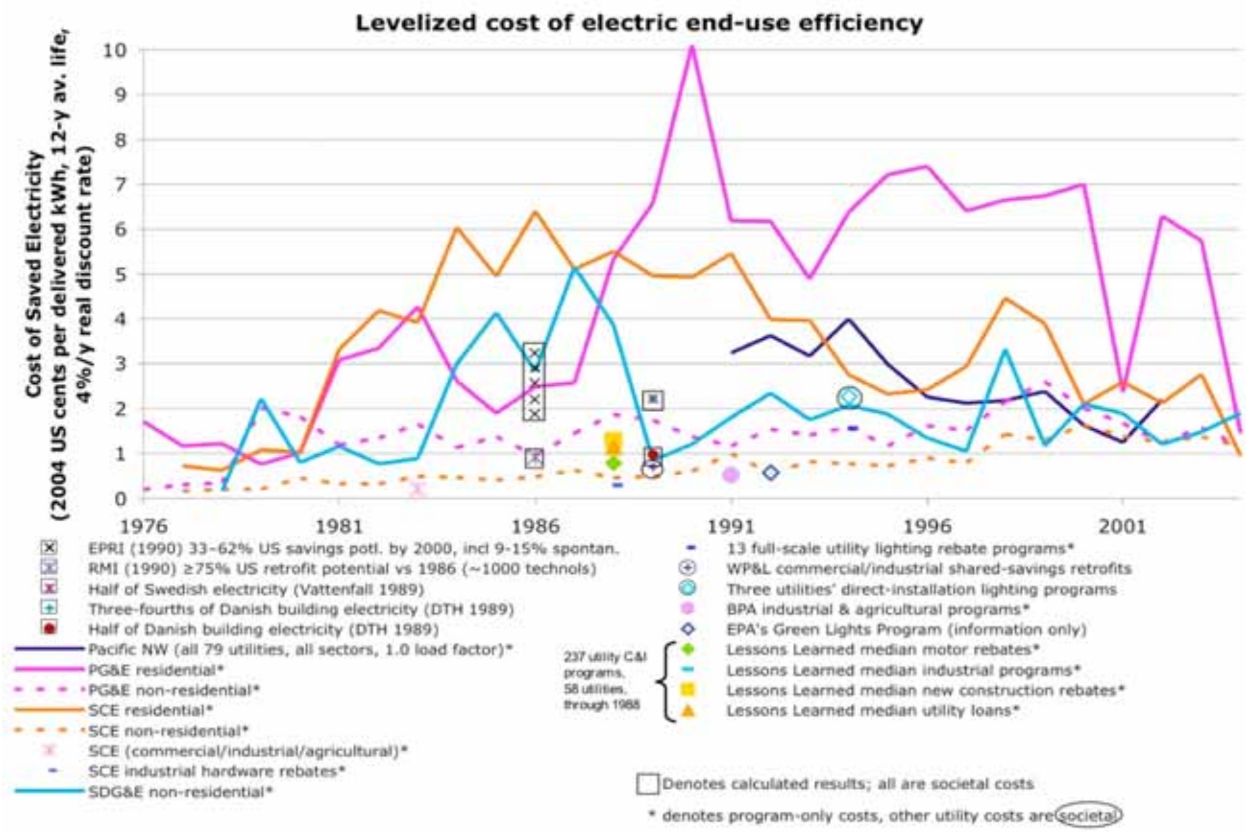
Central-plant sensitivity testing: We adopt the MIT study's conclusion that the nuclear busbar cost of 7.0¢ (2004 \$) could fall to 5.8¢ if nuclear capital cost declined 25%, to 5.6¢ if construction speeded up from the assumed "optimistic" 5 y to 4 y, to 5.3¢/kWh if O&M costs fell to 1.36¢/kWh, and to 4.6¢ if the capital market attached zero risk premium to nuclear *vis-à-vis* other central-station projects. (This is within WNA's claimed range, but still barely matches coal, let alone beats the decentralized competitors.) We also adopt the MIT study's finding that each \$50 of carbon tax, or equivalent trading price, per tonne of carbon (TC) emitted raises the 40-y coal-electricity price by 1.3¢/kWh and the combined-cycle gas-electricity price by 0.5¢/kWh. The MIT study tests for a carbon pricing range of \$50–200/TC. Based on a broader view of the role of end-use efficiency and decentralized supply-side competitors, an equilibrium value of

[66] T. Casten and S. Richards PE (Primary Energy, LLC), personal communications, 12 and 15 August 2005.

even \$100/TC seems implausibly high, and a long-run market-clearing price in a comprehensive and efficient market seems more likely to range from negative to single digits,[67] but for conservatism, Fig. 3 sensitivity-tests an illustrative carbon tax of \$100/TC.

End-use efficiency: A detailed treatment of this complex subject is well beyond the scope of this paper, but Fig. 4 summarizes some key data. This graph compares the levelized cost of saving a kWh (normalized as nearly as possible to a uniform accounting basis) from a variety of utility program evaluation findings and from bottom-up engineering studies of efficiency potential.

Fig. 4. Costs of saved electricity from some evaluated utility programs and some empirically based detailed engineering studies of national end-use efficiency potential.



The main primary or secondary data sources are diverse but representative.[68] Asterisked program-only costs are typically about half of total societal real resource costs (customers pay the rest). The best results shown are existence proofs of what is possible. Key implications include:

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[67] Consistent with a value <\$50/TC, on 7 April 2005 the California PUC adopted the final imputed costs for CO_2 emissions to be used by the utilities as the "greenhouse gas adder" in long-term planning and procurement: a net present value of \$8/2000 lb CO_2, based on a cost of \$5 per ton CO_2 in the near term, \$12.50 by 2008, and \$17.50 by 2013 (CPUC Decision 05-04-024, Conclusion of Law 7). To convert from \$/ton CO_2 to \$/ton C, divide by 0.27.

[68] S. Nadel, *Lessons Learned: A Review of Utility Experience with Conservation and Load Management Programs for Commercial and Industrial Customers*, NYSERDA #90–8 (Albany), American Council for an Energy-Efficient Economy Publ. #U901 (1990), www.aceee.org/store/proddetail.cfm?CFID=237174&CFTOKEN=57381814&ItemID=237&CategoryID=7; A.B. Lovins, "Negawatts: Twelve transitions, eight improvements and one distraction," *En. Pol.* **24**(4):331–343 (1996), RMI Publ. #U96-11, www.rmi.org/images/other/Energy/U96-11_Negawatts12-8-1.pdf; A.B. Lovins, "Apples,

- Program costs tend to decline with experience, as shown by the recent evaluations for the three California investor-owned utilities[69] and the aggregate of the 79 Pacific Northwest utilities evaluated by the Northwest Power Planning Council.[70] California has generally mild climates, high building and appliance efficiency standards, and a long DSM history, so other sites lacking those attributes should tend to have bigger potential at lower costs.
- Broad programs, especially those emphasizing the relatively costlier and higher-transaction-cost measures common in the residential sector (notably home shell retrofits), tend to cost a few ¢/kWh. In striking contrast, many programs targeting commercial and industrial savings cost much less, and the best ones cost less than 1¢/kWh. Potential savings in these sectors are so large that the data support ~1¢/kWh or lower societal cost for savings ~20% of total use, with higher or lower costs plausible depending on assumptions.
- Very detailed bottom-up analyses for Danish buildings[71] and for all electricity uses in Sweden[72] and the United States[73], and EPRI's moderately detailed estimate of U.S. potential savings[74], show very large technical-potential savings (~40–75+%) at total soci-

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Oranges, and Horned Toads," *El. J.* **7**(4):29–49 (1994), available through www.sciencedirect/com or as RMI Publ. #U94-16; A.B. Lovins. "Letter to Professor Paul. L. Joskow, Department of Economics, MIT," 12 Jan. 1992, RMI Publ. #U93-2; A.B. Lovins. "Report to Minister for Industry and Economic Planning on matters pertaining to Victorian Energy Policy" [Australia], 30 Nov. 1990, RMI Publ. #U91-5.

[69] C. Rogers, M. Messenger, & S. Bender, *Funding And Savings For Energy Efficiency Programs For Program Years 2000 Through 2004.* Staff report for California Energy Commission, July 2005, www.fypower.org/pdf/CEC_Trends2000-04.pdf, updated 1976–2004, M. Messenger & C. Rogers (CEC), pers. comms., Nov.–Dec. 2005. Evaluation protocols have evolved over the period graphed, but have been modern and stable since the mid-'90s; earlier evaluations may have been self-reported or less conservatively and completely included certain factors.

[70] Northwest Power Planning Council, "Utility Conservation Achievements Reports: 2004 Survey," www.nwcouncil.org/energy/rtf/consreport/2004/Default.asp, and "Utility Conservation Achievements Reports: 2002 Survey," www.nwcouncil.org/energy/rtf/consreport/2002/Default.asp.

[71] J.S. Nørgård, a leading expert at the Danish Technical University (DTH/Lyngby), showed in detail how half the electricity in Danish late-1980s buildings could be saved at an average cost of 0.6¢/kWh, or three-fourths at 1.3¢/kWh (1986 $): *Husholdninger og Energi*, Polyteknisk Forlag, København, 1979, updated and summarized in his "Low Electricity Appliances—Options for the Future," at pp. 125–172 in T.B. Johansson, B. Bodlund, & R.H. Williams, eds., *Electricity: Efficient End Use and New Generation Technologies and Their Planning Implications* (Lund U. Press, 1989).

[72] B. Bodlund *et al.*, "The Challenge of Choices," in Johansson *et al.*, *id.*, 1989, showed for Vattenfall, the Swedish State Power Board, how to save half of Swedish electricity at 78% lower cost than making more (*i.e.*, at an average cost of 1.6¢/kWh in ~1986 $). Sweden, like Denmark, is already quite energy-efficient. Vattenfall's CEO ordered removed from the paper the usual disclaimer saying it didn't represent the organization's official view.

[73] E SOURCE (Boulder CO), *Technology Atlas* series (five volumes and numerous supplements, 1999–), www.esource.com, subscription products by various authors, condensing six volumes by the author's COMPETITEK team at Rocky Mountain Institute, 1986–92. Those encyclopedic works, totaling 2,509 dense pages cited to 5,135 sourcenotes, assessed empirical cost and performance for ~1,000 technologies; showed how to combine them into optimal packages; remain the most detailed assessment to date of the potential for electric end-use efficiency; and found that upwards of three-fourths of U.S. electricity (*vs.* 1986 frozen efficiency) could be saved at an average cost of ~0.6¢/kWh (1986 $). The basic findings are summarized in A.B. Lovins, "Least-Cost Climatic Stabilization," note 35, referencing similar sectoral findings by other analysts. The RMI analyses excluded fuel-switching lifestyle changes, load management, technological progress beyond the late 1980s, and some technical options. How much of the indicated potential actually gets captured is a policy and marketing variable, but some utilities have in fact captured 70–90+% of particular efficiency markets in months to years through skillful marketing, suggesting that most of the national technical potential could actually be captured over a few decades.

[74] EPRI, *Efficient Electricity Use: Estimates of Maximum Energy Savings*, CU-6746, 1990, summarized in A.P. Fickett, C.W. Gellings, & A.B. Lovins, "Efficient Use of Electricity," *Sci. Am.* **263**(3):64–74 (Sept. 1990). EPRI estimated that full application of late-1980s techniques to the expected 2000 U.S. economy could save (almost all cost-effectively) ~24–44% of U.S. electricity, not including a further 8.6% expected to occur spontaneously by then,

etal costs similar to or below today's broad-based utility program costs, although these studies used 1980s technologies that generally cost more and saved less than today's.

- Few if any of the programs shown use truly modern technologies, and probably none uses modern integrative design techniques that typically "tunnel through the cost barrier" to achieve very large industrial, commercial, and residential kWh savings at *negative* marginal cost in most new installations[75] and some retrofits.[76]

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A student of nuclear power since the 1960s, Mr. Lovins has consulted for scores of utilities worldwide, many of them nuclear operators. In 1986–92 he led the world's most detailed examination of electric efficiency potential. He served in 1980–81 on USDOE's senior advisory board and in 1999–2001 on a Defense Science Board panel on the energy efficiency of military platforms. It may be of historic interest that his high-school experimental-physics research received national awards from Westinghouse, General Electric, the American Nuclear Society, and Dr. Glenn T. Seaborg, then Chairman of the U.S. Atomic Energy Commission. At that time, he and Dr. Seaborg both thought nuclear power sounded like a good idea.

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nor a further 6.5% likely to be saved by utilities' planned efficiency programs. The total potential saving found by EPRI was thus ~39–59%. These findings are compared with RMI's (see previous note) by E. Hirst, "Possible Effects of Electric-Utility DSM Programs, 1990 to 2010," ORNL/CON-312, Oak Ridge National Laboratory, Feb. 1991. Hirst's and the author's comparisons, summarized in the 1991 *Ann. Rev. En.* article, note 35, showed that most of the difference came from EPRI's assuming a drivepower saving 3× smaller and 5× costlier than EPRI found in our joint 1990 article (Fickett *et al., op. cit. supra*), and from a simple methodological difference: EPRI excluded, but RMI included, credit for maintenance costs saved by customers, so commercial lighting savings cost 1.2¢/kWh in the EPRI but –1.4¢/kWh in the RMI supply curves. Normalizing for these non-substantive differences makes the two curves nearly identical. The remaining differences—believed to be due to the modernity, thoroughness of characterization, and disaggregation of the measures analyzed—are less important than the EPRI/RMI consensus that cost-effective potential savings are many times larger than utilities, even in California, currently plan to capture. This was further confirmed by PG&E's "ACT^2" experiment, which the author co-founded and co-steered in the 1990s (with A.H. Rosenfeld, Ralph Cavanagh, and Carl Weinberg), but whose striking integrative-design successes are not yet reflected in California's codes or its utilities' programs.

[75] See *e.g.* P.G. Hawken, A.B. Lovins, & L.H. Lovins, *Natural Capitalism*, Little Brown (Boston), 1999, summarized in *Harv. Bus. Rev.*, May–June 1999, pp. 145–158, both free downloads at www.natcap.org; A.B. Lovins, "Energy efficiency—taxonomic overview," *Encyc. of Energy* **2**:382–401, Elsevier, 2004, RMI Publ. #E04-02, www.rmi.org/images/other/Energy/E04-02_EnergyEffTax.pdf; and other sources in the bibliography to the author's paper, ref. 2. A detailed methodological discussion, clarifying common misconceptions about the costs of utility programs and technical efficiency gains, is A.B. Lovins, "Apples, Oranges, and Horned Toads," *El. J.*, n. 68.

[76] For example, A.B. Lovins, "The Super-Efficient Passive Building Frontier," *ASHRAE J.*, June 1995, pp. 79–81, www.rmi.org/images/other/Energy/E95-28_SuperEffBldgFrontier.pdf, describes how to save three-fourths of the electricity used by a ~200,000-ft^2 curtainwall office tower near Chicago, at a retrofit cost slightly below that of the normally required 20-year routine renovation that saves no energy. Comfort and value would also improve greatly.

