The Nuclear Illusion

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A widely heralded view holds that nuclear power is experiencing a dramatic worldwide revival and vibrant growth, because it's competitive, necessary, reliable, secure, and vital for fuel security and climate protection.

That's all false. In fact, nuclear power is continuing its decades-long collapse in the global marketplace because it's grossly uncompetitive, unneeded, and obsolete—so hopelessly uneconomic that one needn't debate whether it's clean and safe; it weakens electric reliability and national security; and it *worsens* climate change compared with devoting the same money and time to more effective options.

Yet the more decisively nuclear power is humbled by swifter and cheaper rivals, the more zealously its advocates claim it has no serious competitors. The web of old fictions[1] ingeniously spun by a coordinated and intensive global campaign is spread by a credulous press and boosted by the nuclear enthusiasts who, probably for the first time ever, now happen to lead nearly all major governments at once. Many people have been misled, including four well-known individuals with long environmental histories[2]—amplified by the industry's echo box into a sham but widely believed claim of broad green endorsement—and some key legislators. As a result, the U.S. Congress in late 2007 voted $18.5 billion, and the industry will soon be back for another $30+ billion, in new loan guarantees for up to 80% of the cost of new U.S. nuclear units. And the long-pronuclear British government, abruptly reversing its well-reasoned 2002 policy, has decided to replace its old nuclear plants with new ones, although, it claims, without public subsidy[3]—a feat no country has yet achieved. Thus policy diverges ever farther from market realities.

To mind the gap between claim and fact, let's review each step in the nuclear catechism. We'll explore the past and future costs of new nuclear plants, what alternatives they must beat,

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[1] Longtime nuclear commentator Walter C. Patterson noted in 2006 that "Those suffering from nuclear amnesia have forgotten why nuclear power faded from the energy scene in the first place, how many times it has failed to deliver, how often it has disappointed its most determined advocates, how extravagantly it has squandered unparalleled, unstinting support from taxpayers around the world, leaving them with burdens that may last for millennia." His thorough demolition of today's generally recycled nuclear arguments is at www.waltpatterson.org.

[2] Professor James Lovelock CH CBE FRS (the venerable 88-year-old ecologist who proposed the Gaia hypothesis), Dr. Patrick Moore (a prominent Greenpeace organizer and officer in the 1970s), Peter Schwartz (once head of Shell Group Planning and a former Trustee of Rocky Mountain Institute), and his Global Business Network cofounder and colleague Stewart Brand (creator of *Whole Earth Catalog* and *CoEvolution Quarterly*). All are good people and the latter two are my longtime friends. Schwartz has been an energy expert. Regrettably, all four seem unaware of, or unable to deal analytically with, the realities described here, and the first two eagerly provide the nuclear industry's green public face. No environmental *group* of any consequence—only industry front groups—shares their views. A brief rebuttal to Dr. Moore's views (www.newsweek.com/id/131753) is at www.newsweek.com/id/137501.

[3] Actually, the Jan 2008 White Paper (http://nuclearpower2007.direct.gov.uk/docs/WhitePaper.pdf), following U.S. and French practice, says the UK Government plans to bar objections in local planning inquiries based on need and economics as having been already settled by the national consultative process (whose similar predecessor failed a court test), and assigns to taxpayers the risks of cost overruns in waste management and decommissioning. The *Daily Telegraph* further reported on 10 Jan 2008 that "The Government will also intervene if the carbon market does not set a price high enough to make carbon-free forms of electricity generation cheaper" (www.telegraph.co.uk/earth/main.jhtml?xml=/earth/2008/01/10/eanuclear110.xml). It's not clear how the latter two policies will square with Labour's, let alone Conservatives' stricter, expressed commitment to no nuclear subsidies.

and the rapidly shifting competitive landscape in which they must contend. We'll compare their market success with that of some surprising new rivals, and contrast those in deployment speed, reliability, and overall adequacy. We'll see how government subsidies approaching or even exceeding 100% of nuclear power's entire cost aren't attracting investors. Capitalists are instead flocking to competitors that offer lower costs and lower financial risks. Most surprisingly, by comparing all these options' ability to protect the climate and enhance energy security, we'll show why nuclear power could never effectively deliver these crucial benefits even if it could find free-market buyers—while its carbon-free rivals do offer those benefits with greater scale, speed, and confidence.

A quick look at the track record

At the end of 2007,[4] the world had 439 operating nuclear stations totaling 372 GW (billion watts) of net generating capacity with an average age of 23 years—a year older than the 117 reactors already shut down. The International Atomic Energy Agency (IAEA) says 31 nuclear units were under construction in 13 countries—eight more than at the end of 2004, but ~20 fewer than in the late 1990s. All but five were in Asia or Eastern Europe; yet the Asian Development Bank has never financed one, and reaffirmed this policy in 2000, nor has the World Bank, with a minor 1959 exception. Much of the reported activity is not new: of the 31 units listed as under construction, 12 have been so for at least 20 years, some were started in the 1970s, and two long-moribund projects have been re-listed.[5]

Turning ambitions into actual investments, firm orders, and operating plants faces fundamental obstacles that are now first and foremost economic, since the political obstacles related to safety, waste, proliferation, etc., can be and in many countries have been bypassed by fiat. The economic evidence below confirms that new nuclear power plants[6] are unfinanceable in the private capital market because of their excessive costs and financial risks and the high uncertainty of both.[7] During the nuclear revival now allegedly underway, no new nuclear project on earth has

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[4] The nuclear data in this paragraph are from Mycle Schneider and Antony Froggatt's authoritative *World Nuclear Industry Status Report 2007* (Jan 2008) published by the Green faction in the European Parliament, www.greens-efa.org/cms/topics/dokbin/206/206749.the_world_nuclear_industry_status_report@en.pdf.
[5] *Id*.: the BN-800 Russian fast-breeder project, begun in 1985 and reportedly now resuming work (www.inspi.ufl.edu/icapp07/program/abstracts/7348.pdf), and the equally autarchic Tennessee Valley Authority's Watts Bar 2 project (begun in 1972, suspended in 1985, and abandoned in 1994, but TVA announced in Oct 2007 that it had chosen Bechtel to complete the plant for $2.5 billion).
[6] We refer here just to conventional types, chiefly light-water reactors. Some advocates of hypothetical new types claim they would be far cheaper. There is no evidence for this. See *e.g.* J. Harding, "Pebble Bed Modular Reactors—Status and Prospects," 2005, RMI Publication #E05-10, www.rmi.org/images/PDFs/Energy/E05-10_PebbleBedReactors.pdf, and 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). (Despite a dismal economic assessment leaked in South Africa (www.neimagazine.com/story.asp?storyCode=2030985, 6 Sept 2005, that government seems to favor huge long-term investments in this technology that would foreclose virtually all other energy R&D options for a decade or more, and is also receiving proposals for at least 20 GW of advanced light-water reactors to bolster its 36-GW grid. Recent steps toward efficiency and distributed generation are tiny in comparison.) New reactor types won't change the conclusions below, because even if the nuclear steam supply system were *free*, the *rest* of the power plant—two-thirds of its capital cost—would still cost far too much to compete with negawatts and with most micropower.
[7] On 1 Sept 2005, S. Kidd, the World Nuclear Association's Head of Strategy and Research, concluded that despite strong U.S. and other governmental support, "financing new nuclear build in the financial markets will prove very

been financed by private risk capital,[8] chosen by an open decision process, nor bid into the world's innumerable power markets and auctions.[9] No old nuclear plant has been resold at a value consistent with a market case for building a new one. And two strong global trends—greater transparency in governmental and energy decision-making, and wider use of competitive power markets—are further dimming nuclear prospects.

The Economist observed in 2001[10] that "Nuclear power, once claimed to be too cheap to meter, is now too costly to matter"—cheap to run but very expensive to build. Since then, it has become severalfold costlier still to build—and in a few years, as old fuel contracts expire, it is also expected to become severalfold costlier to run. As we'll see, its total cost now markedly exceeds that of other common power plants (coal, gas, big wind farms), let alone the even cheaper competitors described below—cogeneration, some further renewables, and efficient end-use of electricity. Higher fossil-fuel prices since 2001 haven't improved nuclear power's economic case, for two reasons: its own costs have risen even more (its actual fossil-fuel competitors don't include oil), and its formidable new competitors use little or no fossil fuel and generally exhibit falling, not rising, prices.

U.S. nuclear operators' impressive success[11] in improving reliability and performance (through experience, better management, ownership consolidation, shut-down lemons, and compliant regulation) have been unable to offset prohibitive *capital* costs. To deemphasize this hurdle, the industry emphasizes its low *operating* costs, often comparing the cost of just *running* plants already built with the *total* costs of *building and* operating other kinds of new plants. The term "generating costs" or "production costs," widely used in such misleading comparisons, refers to bare operating costs without capital costs for construction or (usually) for major repairs.[12]

The nuclear industry has consistently underestimated its capital costs, often by large factors, and then claimed its next low forecasts will be accurate.[13] Of 75 U.S. plants operating in 1986, the U.S. Energy Information Administration found two-year-cohort-average cost overruns of 209–381%.[14] This bankrupted a New Hampshire utility. In the Northwest, the Washington

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challenging" ("How can new nuclear power plants be financed?" *Nucl. Eng. Intl.* News, www.neimagagazine.com/story.asp?storyCode=2030770). Since then it has clearly become more so (*infra*).

[8] Some vendors and prospective buyers, however, have made relatively small internal preconstruction investments in design, licensing, or fees to reserve manufacturing slots for critical components.

[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.

[10] Cover story, 19 May 2001.

[11] Thanks to a market-driven combination of plant- and firm-level reforms and support by the Institute of Nuclear Power Operations. The results are summarized by prominent economist Paul Joskow, "Prospects for Nuclear Power: A U.S. Perspective," U. of Paris—Dauphine, 19 May 2006, http://econ-www.mit.edu/files/1187.

[12] Much of the existing global nuclear fleet has incurred major maintenance costs, *e.g.*, to replace corroded steam generator tubes. A common U.S. practice is to capitalize such "net capital additions" rather than expensing them, so they appear on the owner's balance sheet but are not counted as an operation and maintenance cost as normal repairs are. This can significantly understate operating costs while causing negative depreciation on the balance sheet.

[13] P. Joskow (ref. 11): "Nobody has ever overestimated the construction cost of a nuclear power plant at the pre-construction stage." Joskow also correctly notes that many industry cost estimates exclude certain "owner's costs" such as engineering, land, insurance, spares, training, and licensing/regulation.

[14] USEIA data summarized in www.neimagazine.com/journals/Power/NEI/November_2007/attachments/Table1.jpg, from M. Gielecki and J. Hewlett, *Commercial Nuclear Power in the United States: Problems and Prospects*, USEIA, 1994 (http://tonto.eia.doe.gov/ftproot/features/hewlett1.pdf). These "overnight costs," a common convention, exclude interest during construction or other owner's costs, which can as much as double total construction costs. The authoritative analysis of the initial U.S. reactor program is I.C. Bupp and J.-C. Derian, *Light Water: How the Nuclear Dream Dissolved*, Basic Books (NY), 1978.

Public Power Supply System (WPPSS) fiasco caused the biggest-ever U.S. municipal bond default ($2.25 billion), saddled the Bonneville Power Administration with a $6-billion debt, and raised wholesale electric rates more than 500%. Seasoned investors still bear the scars. As Mark Twain remarked, a cat that sits on a hot stove lid will not do so again, but neither will it sit on a cold one. Yet some widely quoted recent studies claim new-nuclear costs will match or beat the lowest ever observed in the United States[15]—assuming standardization and construction streamlining that so far are not actually occurring.[16]

The U.S. experience with 1970s and 1980s nuclear construction was uniquely dismal—as *Forbes* put it,[17] "the largest managerial disaster in U.S. business history, involving $100 billion in wasted investments and cost overruns, exceeded in magnitude only by the Vietnam War and the then Savings and Loan crisis." That economic failure is the main reason why no U.S. nuclear plant ordered after 1973 was completed, and all orders placed since 1978 and 48% of all 253 U.S. orders ever placed were cancelled. Moreover, no new orders have yet been placed: recent license applications are placeholders in the queue for subsidies, which are largest for early applicants, but are not orders and are not yet financed.

The industry blames its U.S. disappointments chiefly on citizen intervention. Yet most if not all other countries with big nuclear programs but no effective citizen intervention, such as Canada, Britain, Germany, France, Japan, and the Soviet Union, also suffered substantial nuclear-cost escalation, and their nuclear construction forecasts collapsed in similar fashion.[18] Thus whatever the political and regulatory system, new nuclear plants' *costs*, compared with competitors', are the dominant predictor of whether they will be ordered and whether, if built, they can repay their investors. Without confidence of a fair risk-adjusted return on and of their capital, capitalists won't invest.[19] Are they now confident that the causes of past cost overruns have been corrected and that new causes of runaway costs are not emerging?

What would new nuclear plants cost?

Decades-old cost data can be a poor guide to a different future, so in 2003, a prominent MIT team published the first of just two thorough, independent, and evidence-based[20] economic

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[15] J.G. Koomey and N. Hultman, "A Reactor-Level Analysis of Busbar Costs for U.S. Nuclear Plants, 1970–2005," *En. Pol.* **35**(11):5630–5642 (Nov 2007), http://dx.doi.org/10.1016/j.enpol.2007.06.005; N.E. Hultman, J.G. Koomey, and D. Kammen, "What History Can Teach Us About the Future Cost of U.S. Nuclear Power," *Envtl. Sci. & Technol.* pp. 2088–2093, 1 Apr 2007 (American Chemical Society); N.E. Hultman and J.G. Koomey, "The risk of surprise in energy technology costs," *Envtl. Res. Letters* **2**(034002):1–6 (2007).
[16] M. Wald, "Plan to Build Reactors Is Running Into Hurdles," *N.Y. Times*, 5 Dec 2007, www.nytimes.com/2007/12/05/business/05nuke.html. So far, of three firms seeking U.S. licenses to build and run five reactors, one firm wants more than a dozen significant changes to a preapproved design, and two propose designs not yet finally approved. A fourth firm has ordered parts for a plant whose design isn't yet even submitted to regulators. Regulators had hoped for just 2–3 standard designs, but there are already five with more on the way.
[17] J. Cook, "Nuclear follies," 11 Feb 1985.
[18] A.B. Lovins, "The origins of the nuclear power fiasco," pp. 7–34 in J. Byrne and D. Rich, eds., *The Politics of Energy Research and Development*, Energy Policy Studies, Vol. 3 (Transaction Books, New Brunswick / Oxford), 1986, RMI Publ. #E86-29.
[19] Some industry observers emphasize logistical and political constraints that jeopardize any nuclear revival, *e.g.* at the 2007 American Nuclear Society meeting: "Nuclear Renaissance Faces Formidable Challenges," *Power Eng. Intl.*, Aug 2007, http://pepei.pennnet.com/display_article/303716/6/ARTCL/none/none/Nuclear-Renaissance-Faces-Formidable-Challenges/. Those constraints are real, but I think those of economics and financing are more basic.
[20] As distinguished by industry and government projections that just quoted each other's hopes, such as the World Nuclear Association's "authoritative" claim of ~$1,000–1,500/kW twin-unit overnight costs (~2004 $) ("The New

analyses. It found that new nuclear plants could not compete with new central power plants burning coal or natural gas,[21] though the gap might be considerably narrowed by high carbon taxes plus, if effective, huge subsidies (since approved) for the next half-dozen U.S. nuclear units to be built.

In June 2007, a Keystone Center study group[22] sponsored by eleven organizations—nine of which sell, buy, or are allegedly about to buy nuclear plants—raised the MIT study's nuclear cost estimates from 7.7–9.1¢/kWh (kilowatt-hour) to 8.3–11.1¢/kWh (all in 2007 $ at the power plant). This was mainly due to rapidly escalating capital costs, but the Keystone group also raised projected nuclear fuel costs, after current contracts expire in ~2012, by ~2–3× with open or ~2× with closed (reprocessing-based)[23] fuel cycles, due to long-mismanaged uranium and enrichment activities.

At some sponsors' insistence, the Keystone group studied nuclear costs in isolation and didn't compare them with any alternative. Those have escalated too, though by less: in the three years ended 3Q2007, North American nominal construction costs for power plants surged 76%, to 2.31× year-2000 levels for all main types or 1.79× for non-nuclear types.[24] But regardless of how non-nuclear plants fared, the Keystone new-nuclear busbar-cost estimate definitively rebuts 2–3×-lower industry claims: indeed, leading trade journal *Nuclear Engineering International* dryly remarked that the industry's choice "to either focus on other aspects—in particular the 'finding' that nuclear is a viable option for dealing with climate change—or ignore the [Keystone] report altogether" is "anomalous, and suggests a certain amount of discomfort with the findings."[25] For instance, the Nuclear Energy Institute continues deliberately to misrepresent the Keystone findings.[26]

Economics of Nuclear Power," Dec 2005, www.world-nuclear.org/reference/pdf/economics.pdf), or the 2004 University of Chicago study, whose sketchy analysis of observed costs led it to project new-reactor power costs, in favorable regulatory regimes, at or below the lowest ever observed in the United States (Koomey and Hultman, ref. 15).

[21] J. Deutsch and E. Moniz, eds., *The Future of Nuclear Power*, http://web.mit.edu/nuclearpower/. For lack of time and funding, the MIT study explicitly didn't examine the non-central-station competitors compared here, and therefore has no analytic basis for its "judgment" that nuclear power merits continued subsidy and support.

[22] *Nuclear Power Joint Fact-Finding*, June 2007, Keystone Center (Keystone CO), www.keystone.org/spp/documents/FinalReport_NJFF6_12_2007(1).pdf.

[23] A concise summary of why reprocessing complicates waste management and nonproliferation is Gilinsky and Macfarlane's dissent to the National Research Council's *Review of DOE's Nuclear Energy Research and Development Program*, 29 Oct 2007, http://books.nap.edu/catalog.php?record_id=11998.

[24] Cambridge Energy Research Associates' Power Capital Costs Index (PCCI, http://ihsindiexs.com/index.htm) is based on overnight costs for three overseas nuclear plants adjusted to U.S. factor costs, plus ten combined-cycle gas-fired units, nine coal, four gas-fired turbines, and four wind farms. Another estimate, from Table 3.1 in MIT's 2007 study *The Future of Coal*, http://web.mit.edu/coal/, found 2004 busbar costs for new utility coal plants ~5¢/kWh (2007 $) but pegged 2004–07 real capital-cost escalation at ~25–30%. Some estimate 30–50%. Jim Harding's Nov2007 NPEC-Carnegie speech suggests coal busbar costs ≥9¢/kWh, *vs.* ~12–15¢ nuclear, for plants ordered around the end of 2007.

[25] "How much?" *Nuclear Engineering Intl*, 20 Nov. 2007, www.neimagazine.com/storyprint.asp?sc=2047917.

[26] In summer 2007 I corresponded with the NEI's President, retired Vice Admiral Skip Bowman and his VP of Communications, Scott Peterson. I pointed out that NEI's press release's headline falsely claimed that the study "affirms nuclear energy's competitiveness in [a] climate-constrained world," although the study made *no* economic comparison and the NEI press release says nothing about the study's unfavorable cost findings. NEI admitted to me that its claim of competitiveness was only NEI's opinion based on its own analyses—then refused to amend its release, still up at www.nei.org/newsandevents/newsreleases/keystonecenterreportaffirmsnuclearenergyscompetitiveness/.

Since the Keystone findings, new nuclear plants' uniquely rapid capital-cost escalation, far from abating, has accelerated. The same top trade journal summarizes how the latest analyses, including one by Keystone coauthor Jim Harding (former director of strategic planning at Seattle City Light), have found the Keystone report's lower cost range of $3,600/kW "no longer believable" and its upper range of $4,000/kW "probably low."[27] Harding's estimate of total current construction costs (2007 $ including interest during construction) of ~$4,300–4,550/kW matches prospective customer Constellation's published, then redacted, estimate of ~$4,300/kW.[28] That's slightly above Standard & Poor's (S&P's) May 2007[29] and American Electric Power's August 2007 estimates of ~$4,000/kW, but well below Moody's October 2007 estimate[30] of ~$5,000–6,000/kW—which Moody's called admittedly "only marginally better than a guess" but still solid grounds for caution.

By early 2008, industry estimates were creeping even above Moody's dismaying range. In September 2007, Lew Hay, CEO of FPL Group, said the total cost of a new nuclear plant (all in mixed future dollars as-spent) could be ~$5,000–7,000/kW, or "on the order of magnitude of $13 to $14 billion" for a two-unit plant. Yet just five months later, FPL[31] filed formal cost estimates up to nearly twice that high—$12–*24* billion (again in mixed future dollars) for a 2.2–3.04-GW two-unit plant, equivalent to ~$4,200–6,100/kW in 2007 $.[32] And even that cost may

[27] Quoted in *Nucl. Eng. Intl,* ref. **Error! Bookmark not defined.**; J. Harding, "Economics of Nuclear Power and Proliferation Risks in a Carbon-Constrained World," *El. J.* **30**(20):1–12 (Nov. 2007), doi:/10/1016/j.tej2007/10/012, www.energy.ca.gov/2007_energypolicy/documents/2007-06-25+28_workshop/presentations/panel_4/Jim_Harding_Economics_of_Nuclear_Power_and_Proliferation_Risks.pdf; "Seven Myths of the Nuclear Renaissance," Euratom 50th Anniv. Conf., Eur. Parl. (Brussels), 7 Mar 2007, www.nirs.org/nukerelapse/neconomics/jimharding382007.pdf. The Keystone range assumed 0–3.3%/y real escalation and 5–6-year construction. Interest during construction was included. A 7-year construction time would raise the upper estimate to $4,200/kW.

[28] Quoted in *Nucl. Eng. Intl,* ref. **Error! Bookmark not defined.**.

[29] "Which Power Generation Technologies Will Take The Lead In Response To Carbon Controls?" S&P Viewpoint, 11 May 2007.

[30] Moody's Investors Service, "New Nuclear Generation in the United States: Keep Options Open vs. Addressing An Inevitable Necessity," 10 Oct 2007.

[31] Florida and a few other states are the focus of current U.S. nuclear construction interest because recently passed laws allow interest on construction costs to be currently recovered through tariffs as if the plant were already a completed, "used and useful" asset—the "Construction Work in Progress" (CWIP) mechanism that had unpleasant consequences a few decades ago. A similar nuclear project just proposed by Progress Energy Florida (estimating ~$17 billion, apparently in mixed future dollars, for two units in-service 2016/17, including $3 billion for transmission) is expected to raise retail tariffs by an average of 3–4%/y during 2009–18 (www.progress-energy.com/aboutus/news/article.asp?id=18222), implying a total rise of ~30–40+%. Historically, such price increases, besides causing political trouble, may depress demand below levels needed to pay for the project. If for any reason it is abandoned, the full "regulatory IOU" falls due with no offsetting benefits to customers. CWIP collection smoothes the price shock of ratebasing the nuclear plant, but allows price elasticity to start working sooner, giving the "bow wave" of cost more time to depress the demand that was assumed when the project was initiated. CWIP also partly shifts cancellation risk from investors to customers, though investors typically remain at risk (subject to litigation outcomes) for at least most of their principal.

[32] Kindly converted to 2007 $ by J. Harding (personal communication, 27 Apr 2008) using standard methodologies based on the mixed-current-dollars-as-spent cost ranges FPL submitted to the Florida PSC in Feb 2008, which include ~$200–250/kW for transmission: $5,500–8,090/kW for a 2.2-GW design or $5,430– $7,995/kW for a 3.04-GW version. P. Russell, "FPL says cost of new reactors at Turkey Point could top $24 billion," *Nucleonics Week*, p. 3, 21 Feb 2008. FPL's reported overnight cost (2007 $) was $3,108–4,540/kW—about 2–3× the figures still widely claimed by advocates, and ranging from somewhat below to ~$600/kW above the Keystone cost range. In Mar 2008, Constellation's Senior VP Dr. Joe Turnage confirmed to a National Academies committee (the nuclear subgroup of the America's Energy Future panel) that a plausible 2007 $ overnight cost is ~$3,500–4,500/kW; some

be understated, because FPL's implicit real cost escalation rate is only ~1.1–1.5%/y, severalfold slower than recent experience.[33]

Five months earlier, when Mr. Hay thought FPL's plant would cost $10 billion less (in mixed future dollars) than the high end of that range, he warned that even $13–14 billion is "bigger than the total market capitalization of many companies in the U.S. utility industry and 50% or more of the market capitalization of all companies in our industry with the exception of Exelon."[34] In June 2007, the Nuclear Energy Institute told the U.S. Department of Energy (DOE) that this largest U.S. electric company, with a market cap "in the $40-billion range," "would be hard pressed" to finance even a $5–6-billion nuclear plant without Federal loan guarantees.[35] In 2008, any buyer who still projects such low costs appears to be headed for a nasty collision with reality.

Why are nuclear costs rising so rapidly?

Record and still-rising[36] real prices for commodities like steel, copper, and cement are often blamed for nuclear power's uniquely rapid capital-cost escalation, but do not actually appear to be an factor.[37] The dominant cause, rather, is severe manufacturing bottlenecks[38] and scarcities

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other overnight-cost utility estimates in early 2008 reportedly exceeded $5,000/kW (possibly in future-year dollars). By April 2008, some utilities were fighting to block release of their latest cost estimates: J. Murawski, "Cost of nuclear plant fuels battle," 24 Apr 2008, www.newsobserver.com/print/thursday/business/story/1048035.html. And in May 2008, Moody's confirmed that five experienced nuclear utilities' latest cost estimates "have blown by our highest estimate" computed just eight months ago: R. Smith, "New Wave of Nuclear Plants Faces High Costs," *Wall St. J.*, 12 May 2008.

[33] J. Harding (personal communication, 25 Mar 2008) suggests this plausible scenario for such a plant: $3,600/kW overnight cost in 2008 $ (around FPL's Feb 2008 midrange), escalating at 7.8%/y real (AEP's estimate for 2002–07 heavy utility construction) until 2017 commercial operation, with two years' preconstruction starting 2008, then seven years' construction. This implies a ~18¢/kWh busbar cost in 2008 $ and first-year revenue requirements of 30¢/kWh, plus delivery costs to customers. Lest Harding's nine-year project cycle time be thought excessive, FPL's FPSC filing says, "Failure to initiate development of the Project now…would irrevocably foreclose the possibility of adding new nuclear capacity before 2018 [for Unit 1, and 2021 for Unit 2]" (Russell, ref. **Error! Bookmark not defined.**). On 18 Mar 2008, the Florida Public Service Commission certified need for FPL's two units, in-service 2018 and 2020, so the first unit will take at least a year more than Harding assumed. Nuclear construction's long duration is the main reason such projects are uniquely vulnerable to escalating real capital costs.

[34] Quoted in *Nucl. Eng. Intl.*, ref. **Error! Bookmark not defined.**.

[35] R. Myers, testimony to DOE, 15 June 2007, www.lgprogram.energy.gov/061507-TPH.pdf, at p. 82.

[36] For example, the world's leading iron-ore supplier extracted a huge price rise from its main Asian customers from 1 Apr 2008: "Miners Win 65% Jump in Iron-Ore Prices," *Wall St. J.*, p. A2, 19 Feb 2008.

[37] A quick estimate by Prof. Per F. Peterson (Dept. of Nuclear Engineering, University of California/Berkeley, personal communication, 24 Apr 2008), found that the main raw materials in a 1-GW PWR (according to a 1974 study, ORNL-4515), even at the high commodity prices of 20 Mar 2008, add up to only ~$36/kW (2008 $). Recent price increases contributing to this sum are a tiny fraction of overnight costs upwards of $3,000/kW. This conclusion appears to be robust despite the decades-old data on the tonnages required. In contrast, a Sept 2008 utility-industry study (M. Chupka and G. Basheda, "Rising Utility Construction Costs: Sources and Impacts," The Brattle Group, www.edisonfoundation.net/Rising_Utility_Construction_Costs.pdf) devotes six pages to escalation of materials costs, which it lists first among causes of power-plant cost escalation, but doesn't analyze the contribution of these materials to total construction budgets, nor the linkage between raw-materials and finished-products prices. The report's data on shop, fabrication, and engineering capacity (pp. 21–24) are far more convincing. And the report rightly concludes that the U.S. Energy Information Administration's capital-cost estimates are not credible. See also NUKEM's April 2008 market report "Nuclear Renaissance USA: Coping with New NPP Sticker Shock" (Danbury, Connecticut / Alzenau, Germany, www.nukeminc.com/mr_preview.cfm), which extensively discusses commodity costs and other causes of nuclear cost escalation.

of critical engineering, construction, and management skills that have decayed during the industry's long order lull. These bottlenecks and scarcities have put the flagship new-build project—Finland's Olkiluoto-3 reactor—at least 24 months behind schedule[39] after 28 months' construction, at least 50% over budget (losing the fixed-price builders at least €1.5 billion and customers twice that),[40] and harshly criticized by the Finnish nuclear safety regulator.[41] The industry has deftly shifted from describing the project as plain proof of the superiority of advanced reactors to a normal case of the unique challenges of building first-of-a-kind plants. But even competitors are palpably anxious that "If the nuclear industry doesn't deliver this time, there won't be a third time," and that Olkiluoto-3 is already contradicting rosy forecasts and starting to be seen as evidence that "the nuclear industry cannot deliver" on even one new plant.[42]

The construction challenges driving cost escalation are most formidable in the United States, currently the world leader in nuclear-revival rhetoric. U.S. nuclear manufacturing went from ~400 suppliers and 900 certifications in the 1980s to fewer than 80 and 200 today (though partly due to consolidation).[43] The atrophy is so advanced that some major components are avail-

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[38] Notably for specialized ultra-heavy forgings, some of which have one supplier in the world: Y. Takamoto and A. Katz, "Samurai-Sword Maker's Reactor Monopoly May Cool Nuclear Revival," Bloomberg.com, 13 Mar 2008, www.bloomberg.com/apps/news?pid=20601109&sid=aaVMzCTMz3ms&refer=h&sid=aaVMzCTMz3ms&refer=h. The plant can produce 5.5 reactors' worth of forgings per year and plans to expand this to 8.5 in 2010, but that capacity must be shared with users in hydrocarbon and other heavy industries (Squassoni, ref. 215). China may start up capacity to make such forgings, perhaps even in 2008, but buyers will be wary of quality.

[39] The owner, Teollisuuden Voima Oyj (TVO), announced 10 Aug 2007 that delays will stretch to two years (incurring unpublished but reportedly substantial contractual penalties for the builders) due to problems in meeting a requirement reportedly known to the builders since 2001 ("Areva: Plane crash requirements to delay Olkiluoto-3 construction," *Nucleonics Week*, 16 Aug 2007). If the total delay is just two years, it will only bring the plant to the world (chiefly Asian) average construction time of six years, *vs.* the very aggressive original four-year target, which rivals the world's fastest (in Japan).

[40] *Kauppalehti* (Finnish business daily), paraphrased at www.bellona.org/news/Olkiluito_delay, 2007. In addition, *Power Engineering International* reports that the Federation of Finnish Technology Industries expects Finnish industry to have to buy €0.2b/y worth of emissions credits during the delay, or probably ~€0.5b and counting. The builders' contracts also set penalties for late completion, rumored to be 0.2% per week (after 1 May 2009) for 26 weeks, then 0.1% per week, all capped at 10% of the contract value, or ~€0.3b.

[41] Ref 4; A. Katz (Bloomberg News), "Finnish plant demonstrates nuclear power industry's perennial problems," *Intl. Her. Trib.*, 6 Sept. 2007, www.iht.com/bin/print.php?id=7391855; D. Gauthier-Villars, "Trials of Nuclear Rebuilding," *Wall St. J.*, p. A6, 6 Mar 2007. The regulator's "listed quality deviations" now exceed 1,700. This 1.6-GW project isn't a normal free-market transaction. Its tax-exempt, nonprofit, TVA-like buyer TVO issued long-term power-sale contracts to major customers, then financed it with 75% debt, mainly €1.95b at a below-market 2.6%/y from Bayerische Landesbank, sweetened by French and Swedish loan guarantees. Parliament narrowly approved the plant based on an unsound and then-nonpublic study that excluded demand-side and modern decentralized competitors, and assumed a €0.7b-below-bid nuclear cost. The project was a major loss-leader for the Areva-Siemens consortium, which bid its next, identical, plant (Flamanville-3) ~25% higher to Électricité de France and is trying hard, but so far unsuccessfully, to renegotiate its ruinous Finnish fixed-price contract. Areva NP's first-half 2007 financial report even states, "Our position is that, ultimately, a reasonable overall balance on the split of cost overruns can be expected to be found with TVO"—which, however, emphatically denies it will pay anything extra (www.forbes.com/markets/feeds/afx/2007/09/28/afx4165822.html). The Areva/Siemens consortium has come under strain and may be restructured by the leaders of France and Germany, since Areva is ~91% owned by the French state ("Fate of Areva NP, Siemens' nuclear business in hands of state leaders," *Nucleonics Week*, 26 July 2007).

[42] "Rivals warn of risk from Areva's Olkiluoto-3 delays," *Nucleonics Week*, 13 Sept 2007.

[43] "Supply chain could slow the path to construction, officials say," *Nucleonics Week*, 15 Feb 2007.

able from only one or two suppliers in the world, counterfeiters are moving in,[44] and experienced subcontractors are scarce.[45] A U.S. utility executive recently remarked that he couldn't recall any imported components in a nuclear project he ran in the 1980s, while "Now 80%…is going to have to come from offshore."[46] Such imports don't just challenge safety inspectors (akin to recent issues with some imported drugs); they also help to explain especially rapid U.S. reactor cost escalation. That 80% estimate, of course, was neither rigorous nor an estimate of a fraction of total project cost. Yet in the five years through April 2008, the U.S. dollar declined by 27% against the Euro and by 12% against the yen. Had the dollar held its value as well as the Euro, the price of oil would have been under $70/bbl rather than $119/bbl.[47] The cost of reactor components imported by the United States—but not by French/German builders in Finland—reflects the weak dollar.

Nuclear workers are becoming scarce too. Forty percent of those at U.S. plants are eligible for retirement within the next five years, and only 8% are younger than 32. Two-fifths of France's reactor operation and maintenance staff will retire by 2015, and few of the new hires are trained nuclear experts. Meanwhile, nuclear education is dwindling. Since 1980, U.S. nuclear engineering university programs have declined from 65 to ~29 and have trouble attracting talented students; the Nuclear Energy Institute says the U.S. now has 1,900 undergraduates and 1,100 graduate students in nuclear engineering programs, but this remains far smaller than needs to offset retirements and staff proposed growth. In 2002, the UK had no undergraduate course in nuclear engineering.[48] The number of German academic institutions with nuclear courses is expected to drop from 22 in 2000 to 10 in 2005 to 5 in 2010; 46 nuclear diplomas were granted in 1993, zero in 1998, and only two in the five years ended in 2002.[49] As experienced nuclear experts retire, safely running old plants will be hard enough without staffing new ones.

What the *World Nuclear Industry Status Report 2007* calls "rapid loss of [construction and operating] competence and lack of manufacturing infrastructure" isn't the only big obstacle:

> The nuclear industry and utilities face challenges in a radically changed industrial environment. Today the sector has to deal with waste management and decommissioning expenses that far outweigh estimates of the past, it has to compete with a largely modernized gas and coal sector and with new competitors in the new and renewable energy sector.

Further, many countries now expose builders to the risks of free-market competition—both with micropower and with efficient use of electricity—rather than shielding investors via traditional utility rate-basing. For example, as soon as big Tokyo customers could choose their supplier, a third of them fled from costly rate-based nuclear-dominated generation to cheaper industrial cogenerators. Enthusiasm is no guarantee of market success: high-flying U.S. merchant (non-utility) builders of combined-cycle gas-fired plants recently wrote off about $100 billion worth of plants they'd built for which there was no demand.[50] And in the restructured markets

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[44] R. Smith, "Utilities Fret as Reactor-Part Suppliers Shrink," *Wall St. J.*, p. B1, 11 Apr 2008. She quotes the Chairman of the U.S. Nuclear Regulatory Commission: "The global supply chain is stretched, if not to the breaking point, at least to the tipping point."

[45] "Subcontractor inexperience delayed Olkiluoto-3 projects, officials say," *Nucleonics Week*, 14 June 2007.

[46] Smith, ref 44.

[47] *Wall St. J.* editorial, "The Fed's Bender," p. A18, 28 Apr 2008.

[48] For further UK challenges, see I. Catto, "Where are the people?" *Nucl. Eng. Intl.* **512**(637), 29 (Aug 2007).

[49] These human-resources data are from ref. 4.

[50] They were misled by two disinformation campaigns. The first, by the Western Fuels Association and its surrogates like the Greening Earth Society, claimed that the Internet uses an order of magnitude more electricity than it does

now operating in nearly half the U.S. states and for more than half its electricity, developers must build power plants at their own risk or at the risk of a long-term power-purchasing entity. This exposure to competition raises financial risk and hence the cost of capital. This makes it "unlikely that we will see much if any investment in nuclear capacity" in those states.[51]

Nuclear plants worldwide enjoy unique legal exemption from liability for catastrophic accidents.[52] The United States even offers its next half-dozen nuclear plants new federal insurance against regulatory delays,[53] even though meaningful public participation in licensing has already been virtually eliminated. Yet governments cannot so easily quash uncertainties about what nuclear plants will cost and whether, once built, they can remain competitive for decades. These uncertainties deter equity investors and drive developers to high debt ratios that weaken credit ratings. *Nuclear Engineering International*[54] concludes that this means "there aren't many company boards that would give the go-ahead to a new nuclear plant." So far, no U.S. utility's board has done so, despite the extraordinary new subsidies described below.

A further issue arises in states that still rate-base new power plants: financial comparisons between power plants typically use levelized costs, but utility customers would feel sticker shock. A total construction cost ~$5,200/kW, near the low end of Moody's October 2007 estimate, implies a levelized busbar cost of ~16¢/kWh. But this would require a typical regulated utility in 2013 to collect *first-year* project revenue of ~27¢/kWh—three times typical tariffs[55]—*plus* delivery cost to customers. At that rate, even photovoltaics could look like a bargain. A "death spiral" of rising price and falling demand may ensue because customers now have more choices than just buying ever more grid electricity: they can vote with their feet by buying less electricity, more efficiency, and more onsite generation—all now becoming widely available.

What are new nuclear plants' competitors?

The MIT study compared new nuclear power only with other central thermal plants, while the Keystone study made no comparison. All nuclear advocates and most nuclear analysts,

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and will soon account for half of total demand (see Epilogue, pp. 213–219, in J.G. Koomey, *Turning Numbers Into Knowledge*, 2nd edn., 2008, Analytics Press, Oakland, www.analyticspress.com). The second campaign alleged that the lights went off in California in 2000–01 because that state had built no power plants in the 1990s. California actually built >4.5 GW (more than its nuclear capacity) in unnoticed non-utility decentralized capacity averaging ~35 MW/unit; the actual causes of its self-inflicted power fiasco were much simpler and more interesting (A.B. Lovins, "California Electricity: Facts, Myths, and National Lessons," RMI Publ. #U01-02, www.rmi.org/images/PDFs/Energy/U01-02_CalifElectricity.pdf). Meanwhile, the ~200 GW of new U.S. combined-cycle plants was hit by soaring natural-gas prices. Now they run at capacity factors around 0.2.

[51] P. Joskow, "The Future of Nuclear Power in the United States: Economic and Regulatory Challenges," AEI-Brookings Joint Center for Regulatory Studies, Wkg. Paper 06-25, Dec 2006, http://econ-www.mit.edu/files/1192. The main exception is the NRG merchant nuclear project proposed in South Texas based on estimated costs roughly half those found by other utilities in 2008.

[52] This subsidy, via laws like the U.S. Price-Anderson Act, must be valuable because the industry perennially says that despite its safe operations, it cannot operate without such a liability shield. Tellingly, Koplow has shown that single nuclear operator firms buy property insurance for their nuclear plant and business that exceed by an order of magnitude the outdated coverage for their offsite liability, and that their self-coverage exceeds the entire national nuclear industry's liability caps (ref. 186).

[53] The U.S. industry has enjoyed a regulatory system of its own devising for several decades with no new orders. The U.S. Nuclear Regulatory Commission has licensed more reactors than the next four countries combined, and has never failed to approve a power-reactor license application.

[54] Ref. **Error! Bookmark not defined.**.

[55] J. Harding calculation at a 4%/y real discount rate: personal communication, 15 Jan 2008.

including those in the capital markets, assume that the only game in town is coal- or gas-fired central power stations. These have well-known attributes. Coal is abundant but becoming costlier—in 2007 and early 2008, world spot prices tripled and a key U.S. benchmark price doubled.[56] Scarcer gas has lately suffered from high and volatile prices (and, in Europe, political pressures from Russia). Both kinds of power plants, especially coal-fired ones, are also becoming considerably costlier to build. Coal plants emit more conventional air pollution and are less efficient than modern gas plants. Burning coal contributes greatly, gas 2–4× less, to climate change. It's becoming much harder both economically and politically to build new coal plants, especially in the United States,[57] where three leading investment banks no longer finance them without proof that they'll compete even under "potentially stringent" carbon pricing, and will favor energy efficiency and renewables instead.[58] Only a third of announced new U.S. coal plants are actually getting permitted or built.[59] Meanwhile, high and volatile gas prices are making gas-fired plants less attractive. The nuclear industry believes these trends should bring customers back to the atom.

However, focusing on these three kinds of central plants is obsolete. In today's market they're *all* the wrong competitors, because two other diverse classes of electrical resources are walloping *all* central plants in the global marketplace. These new competitors are *negawatts*—electricity saved by more efficient or more thoughtfully timed end-use by customers[60]—and *micropower*—the *Economist* magazine's generic term for two diverse classes of less centralized resources. Micropower comprises two classes of technologies:

1. onsite generation of electricity (at the customer, not at a remote utility plant)—usually *cogeneration* of electricity plus recovered waste heat (outside the U.S. this is usually

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[56] S. Oster and A. Davis, "China Spurs Coal-Price Surge," *Wall St. J.*, p. A1, 12 Feb 2008.

[57] In 2007, for example, TXU's plans for 11 coal-fired plants in Texas were scaled back to three, whose construction remains uncertain, after a leveraged buyout encouraged by major environmental groups. California (SB1368, 2006) and Washington State (SB6001, 2007) have also outlawed long-term utility investment in baseload generation emitting more carbon than a combined-cycle plant; this policy effectively prohibits new coal-fired plants unless they reliably capture at least three-fifths of their CO_2 emissions.

[58] J. Ball, "Wall Street Shows Skepticism Over Coal," *Wall St. J.*, p. A6, 4 Feb 2008. The common assumption that "Carbon Caps May Give Nuclear Power a Lift" (R. Smith, *Wall St. J.*, p. A4, 19 May 2008, www.climateark.org/shared/reader/welcome.aspx?linkid=99837) simply assumes that efficiency and renewables won't be serious competitors, though it does highlight the huge market distortions that could arise if carbon emissions allowances were given to nuclear utilities and not to their nonutility competitors. The Congressional Budget Office's May 2008 report "Nuclear Power's Role in Generating Electricity" concludes that nuclear may undercut coal power with a $45/t carbon tax (www.cbo.gov/ftpdocs/91xx/doc9133/05-02-Nuclear.pdf), but contrary to Smith's summary (*id.*), compares nuclear only with coal and central gas plants, not with "any other form of power generation."

[59] E. Schuster, "Tracking New Coal-Fired Power Plants," NETL, 10 Oct 2007, www.netl.doe.gov/coal/refshelf/ncp.pdf.

[60] Scores of utilities have demonstrated, and implemented at scale, rapid, large, predictable, extremely cheap negawatts. California's per-capita use of electricity has been flat for 30 years while per-capita real income rose 79%—saving more than $100 billion and 65 GW of power-supply investment. Firms like DuPont, Dow, and IBM are saving billions of dollars by cutting their energy intensity, sometimes as fast as 6–8% a year. For general background, see A.B. Lovins, "Energy End-Use Efficiency," RMI Publ. #E05-16, www.rmi.org/images/PDFs/Energy/E05-16_EnergyEndUseEff.pdf (2005); "Negawatts: Twelve Transitions, Eight Improvements, and One Distraction," *En. Pol.* **24**(4):331–343 (Apr 1996), RMI Publ. #U96-11, www.rmi.org/images/PDFs/Energy/U96-11_Negawatts12-8-1.pdf; and five detailed 2007 "Advanced Energy Efficiency" lectures as MAP/Ming Professor in Stanford's School of Engineering, www.rmi.org/stanford.

called CHP—combined-heat-and-power): this is about half gas-fired, and saves at least half the carbon and much of the cost of the separate power plants and boilers it displaces;
2. *distributed renewables*—all renewable power sources except big hydro plants, which are defined here as dams larger than 10 megawatts (MW).

The nuclear industry professes to support both these options, but denies they can offer serious alternatives to nuclear power because they're too costly, too unreliable, too small individually, too slow to build, and too small in total ultimate potential. Let's examine these claims in turn.

How do new competitors' costs compare with nuclear's?

New nuclear power, as noted above, was found by the 2003 MIT study to be uncompetitive with other central plants, and has since suffered greater cost escalation. But big coal- and gas-fired plants are not the only competitors. In 2005–06, one of us (ABL) explored this larger competitive landscape in an independent, conservative, and transparent analysis[61] summarized in *Nuclear Engineering International*.[62] Using the best available 2004 U.S. data, it compared the costs of new nuclear plants with the costs of some of their widely and abundantly available competitors. All costs were expressed on the same accounting basis—real levelized cost (over a lifetime appropriate for each technology) per kilowatt-hour *delivered* to the retail meter. The global nuclear lobby objected strenuously but only rhetorically;[63] substantively the analysis remains uncontroverted, and others have since strongly reinforced its findings. Its methodology and assumptions are updated here to reflect the latest reliable data.[64]

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[61] A.B. Lovins, "Nuclear Power: Economics and Climate-Protection Potential," RMI Publ. #E05-14, 6 Jan 2006, www.rmi.org/images/PDFs/Energy/E05-14_NukePwrEcon.pdf.
[62] A.B. Lovins, "Mighty Mice," pp. 44–48, Dec 2005, www.rmi.org/images/PDFs/Energy/E05-15_MightyMice.pdf.
[63] The WNA critique and my response are at www.neimagazine.com/comments.asp?sc=2033302.
[64] The methodology is described in www.rmi.org/images/PDFs/Energy/NukeCompMeth_2007.pdf. We updated RMI's 2005–06 analysis (ref. 61's Appendix A) by using the GDP Implicit Price Deflator (1.09) to convert all 2004 to 2007 $; retaining the 2003 MIT study's nuclear and combined-cycle gas plant costs; adding the range of 2007 Keystone study's nuclear costs (ref. 22), but not the even higher estimates quoted above and in ref. **Error! Bookmark not defined.**; applying 30% real escalation to the 2003 MIT study's coal-plant capex based on the 25–30% estimate in Table 3.1n of the 2007 MIT *Future of Coal* study (http://web.mit.edu/coal/); raising the levelized natural-gas price to $6.84/GJ (*id*.) for central plants and 13% higher for cogenerators; using the empirical capacity-weighted median windpower prices for 2004–05 U.S. installations (equal to the 1991–2006 average) and their average O&M costs, plus the mean of nine recent studies of windpower firming and integration costs (ref. 90); showing for comparison the higher 2006 median windpower cost; adding nuclear reserve margin cost based on Koomey and Hultman's plant-specific U.S. analysis (ref. 15); and adding a nominal 0.1¢/kWh to all onsite generators as a proxy for any excess of backup costs over distributed benefits to the utility (the actual value may well be negative in most cases). The delivery costs (shown in red) assumed for central stations are deliberately low to favor central plants: they're from 1996 and for investor-owned utilities, which generally have denser loads than the one-fourth of U.S. demand served by public utilities.

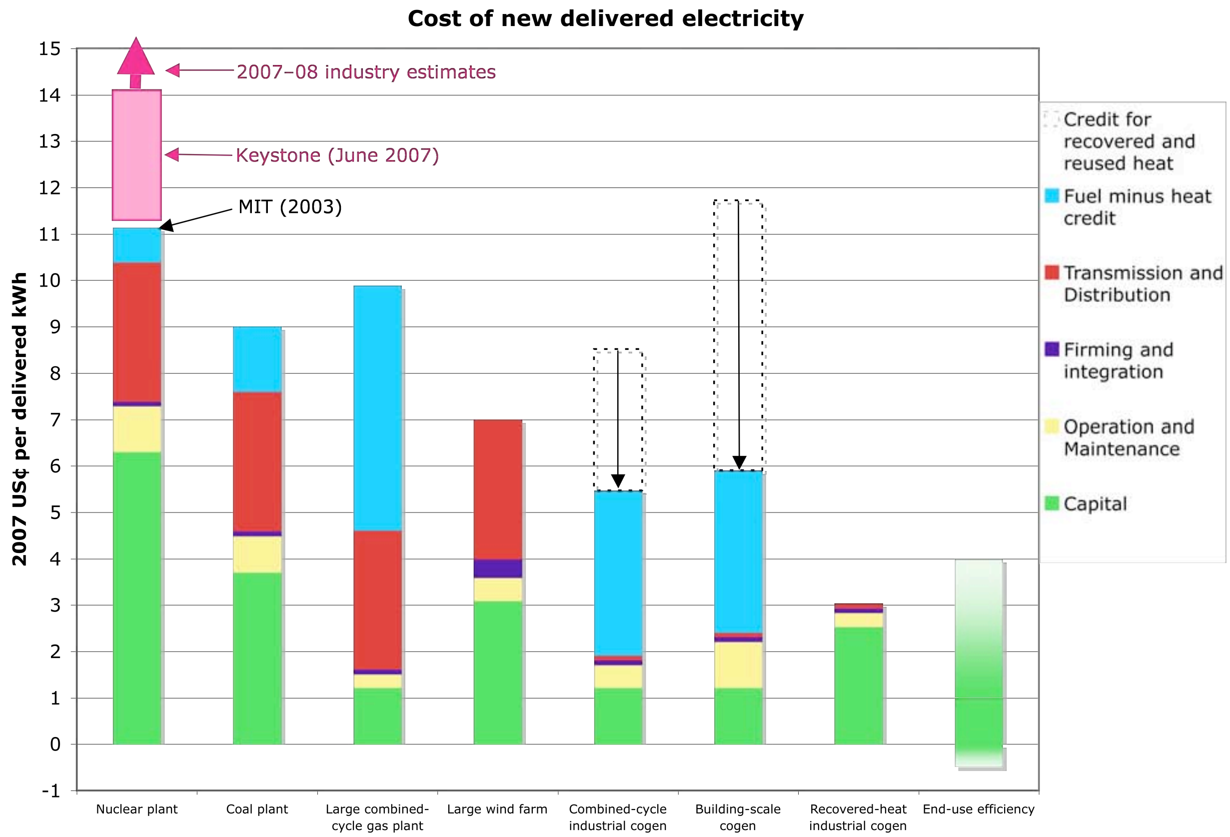

Fig. 1. The representative levelized U.S. cost of saving or delivering 1 kWh of new electricity at the retail meter with comparable reliability by choosing competing technologies. The displayed values have been chosen from larger empirical ranges in ways that favor nuclear power, but for reasons explained later, don't reflect potential future costs to capture and sequester carbon emissions. Cogeneration and efficiency are "distributed resources," located near where energy is used; hence they don't incur the capital costs and energy losses (red bars, deliberately understated) of the electric grid, which links large power plants and remote wind farms to customers.[65] *Wind farms, like solar cells, also require "firming" to steady their variable output, and all types of generators require some backup for when they inevitably break. The graph reflects these costs (purple bars). Making electricity from fuel creates large amounts of byproduct heat that is normally wasted. Combined-cycle industrial cogeneration and building-scale cogeneration recover most of that heat and use it to displace the need for separate boilers to heat the industrial process or the building, thus creating the economic "credit" shown (dotted black lines). Cogenerating electricity and some useful heat from currently discarded industrial heat is even cheaper because no additional fuel (aqua bars) is needed. Just the* operating *cost (aqua plus yellow bars) of an old nuclear or coal plant can undercut the* total *cost of most new generators—a misleading comparison often made by nuclear advocates. Efficiency, though, beats everything, often including just* running *an existing thermal power station even if building it were free. The three bars on the left represent relatively mature technologies with rising costs, while the rest generally have falling costs and much room for further improvement.*

[65] Distributed generators may rely on the power grid for emergency backup power, but such backup capacity, being rarely used, doesn't require a marginal expansion of grid capacity, as does the construction of new centralized power plants. Indeed, in ordinary operation, diversified distributed generators *free up* grid capacity for other users.

This update confirms, as Fig. 1 summarizes, that new delivered nuclear power costs from ~2×[66] to ~10× more than equivalent firm delivered power from micropower and negawatts—a gap far too big for any conceivable technical, institutional, or financial improvements to bridge. This gap is widening, for three reasons:

- nearly all[67] the distributed competitors are trending inexorably cheaper over the long run[68] through routine improvement and production volume (though in the short term, photovoltaic prices have temporarily stabilized for photovoltaics and turned up for wind power due to extraordinarily rapid growth in demand)—while central plants, for fundamental reasons,[69] have historically tended to become costlier as more are built, contrary to normal learning-curve assumptions;[70]
- markets are starting to recognize distributed benefits, chiefly in financial economics and electrical engineering, that will ultimately increase by another *tenfold* or so the economic value of distributed resources,[71] but, in a major conservatism, aren't shown here (except for recovery of waste heat); and
- negawatts and such potentially potent very-large-scale competitors as photovoltaics exhibit many paths for disruptive technological breakthroughs[72] that can drastically cut cost

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[66] For example, the average delivered busbar price of windpower sold in the United States since 1999, 3.7¢/kWh (2007 $, ref. 90), plus its levelized Protection Tax Credit, 0.94¢/kWh (2007 $) (manyfold smaller than nuclear subsidies—indeed, since 2005, the next 6 GWe of new nuclear plants have gained their *own* eight-year PTC to match wind's), plus firming and integration to make the output fully dispatchable, is ~5¢/kWh—one-half to one-third the delivered cost of new nuclear power. Not counted here is the ~1–2+ ¢/kWh extra value of windpower for avoiding gas-price volatility, updated from LBNL-50484's 2002 assessment at http://eetd.lbl.gov/EA/EMP/reports/50484.pdf.
[67] See refs. 90 and 64 for recent U.S. windpower capital-cost escalation. Neglecting short-term fluctuations in turbine supply/demand balance and commodity factor costs, windpower's cost/kWh falls ~9–17% per capacity doubling. The 1.3¢/kWh escalation observed during 2005–06 is caused mainly by a temporary shortage of turbine-making capacity and key parts that's expected to resolve during 2009, and much less by commodity cost escalation and the weakening U.S. dollar.
[68] For renewables, see the NREL forecasts in slides 9–10 of the .PPT at www.rmi.org/sitepages/pid171.php#E05-09. For examples of ever-cheaper negawatts, see Tom Eckman's data for the Pacific Northwest (www.state.mn.us/mn/externalDocs/Commerce/Regional_Technical_Forum_Tom_Eckman_051507012223_Tom_Eckman_ppt.pdf, slide 16) and A.B. Lovins, "Public Lectures in Advanced Energy Efficiency: 2. Industry," slide 15 and the content of all five lectures (MAP/Ming Professorship, School of Engineering, Stanford University, 27 Mar 2007, at www.rmi.org/stanford). This set of five detailed lectures condenses 30 years of cutting-edge efficiency practice into ~7 hours.
[69] Documented in ref. 18.
[70] The hypothesis of cost rising with volume was proposed by I.C. Bupp, J.-C. Derian, M.-P. Donsimoni, and 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 Lovins (ref. 18) and Krause (ref. 174), Vol. II, Part 3E, 1994. Koomey and Hultman (ref. 15, Fig. 8) found that U.S. nuclear busbar electricity costs, which exhibited a fivefold real-cost scatter, did indeed trend upwards for plants commissioned later.
[71] Documented in ref. 120.
[72] *E.g.*, cheap 65%-efficient quantum-dot photovoltaics (which NREL's Dr. Garry Rumbles expect will get to ≤5¢/kWh delivered within at most a few nuclear-plant lead times), cheap PV concentrators (*e.g.*, www.sunengy.com), or a recently developed retrofittable swing-circuit device that can roughly double PVs' average

and improve performance. Indeed, important new classes of technology are emerging.[73] After a half-century of refinement, nuclear fission offers no such leapfrog prospects.

Investors' appropriate concerns about the financial risks posed by its high cost, long lead time, and the uncertainty of both have already stifled nuclear investment. Yet the capital markets haven't yet understood an even greater risk: that nimbler competitors with lower and decreasing costs could grab nuclear projects' revenues, so even if construction went as planned, the costly nuclear electricity may not sell, let alone continue to sell for the decades required to repay and reward nuclear investors. Whether or not the utility is traditionally regulated, customers can at any time buy more efficient lights, motors, appliances, buildings, and industrial equipment if efficiency looks cheaper than the kilowatt-hours they're offered. Customers can even mostly or wholly abandon their costly suppliers and produce their own power, as many large users have done. The market, long focused on which kind of central power plant produces the cheapest kilowatt-hours, and content to assume ever-growing demand for electricity at any price, is only starting to appreciate the bigger risk that *no* central plant can compete with the smaller, faster, cheaper, more accessible options that customers increasingly prefer.

But regardless of market preferences, should governments encourage or require the revival of nuclear power to help combat the menace of climate change? Is nuclear, as claimed, the only big, fast, proven way to combat global warming? Or could it make climate change worse than if other options were bought instead? The comparative costs in Fig. 1 cast a surprising new light on this question.

How can power plants' carbon emissions be cost-effectively reduced?

Generating electricity causes two-fifths of U.S. and more than one-third of global fossil-fueled CO_2 emissions, which in turn are about three-fourths of total CO_2 emissions, excluding the additional effects of other greenhouse gases. Nuclear power addresses only part of the electrical fraction of fossil CO_2 emissions—the fraction of chiefly coal-fired power generation that runs fairly steadily, not at widely varying output, in grids large enough to accommodate nuclear units' size (far too big for many smaller countries or rural users).[74] Nuclear power's potential climate solution is further restricted by its inherent slowness of deployment (in capacity or annual output added per year), as confirmed by market data below. And its higher relative cost than nearly all 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*.

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daily output by accumulating low-light-level electrons into a low-impedance load, then storing them and delivering them at load voltage.

[73] For example, the National Renewable Energy Laboratory estimates that if half the 2050 U.S. car fleet were plug-in hybrids, their added market for night recharging power could add ~230 GW of windpower, whose operation whenever the wind blows could make more annual electricity than the United States now gets from coal. Advances in vehicle and battery technology and in innovative business models now make this a realistic prospect, and can also permit cost-effective fuel-cell vehicles that could sell electricity to the grid when parked (~96% of the time). A superefficient fuel-cell vehicle fleet would have ~6–12× as much generating capacity as is now on the U.S. grid, so adoption by even a small fraction of drivers—the first ~2 million of whom would earn back from power sales the whole cost of their car—would suffice to put the remaining central thermal plants out of business. See A.B. Lovins and D.R. Cramer, *Intl. J. Veh. Design* **35**(1/2):50–85 (2004), RMI Publ. #T04-01, www.rmi.org/images/other/Trans/T04-01_HypercarH2AutoTrans.pdf.

[74] The claim that 10–20-MWe mini-reactors like Toshiba's design can offer a realistic option for remote communities such as Galena, Alaska is rebutted in my reply to WNA at www.neimagazine.com/comments.asp?sc=2033302.

The reason is simple:[75] you can't spend the same dollar on two different things at the same time. (Economists call this "opportunity cost"—making any investment foregoes others.) New nuclear power *costs far more* than its distributed competitors, so it *buys far less coal displacement* per dollar than the competing investments it stymies. Let's take this argument in two graphical steps built on the cost comparison in Fig. 1 above. One can quibble about many details of the numbers, but their qualitative message is incontrovertible. As the Italian proverb says, *L'aritmetica non è un'opinione* (arithmetic is not an opinion).

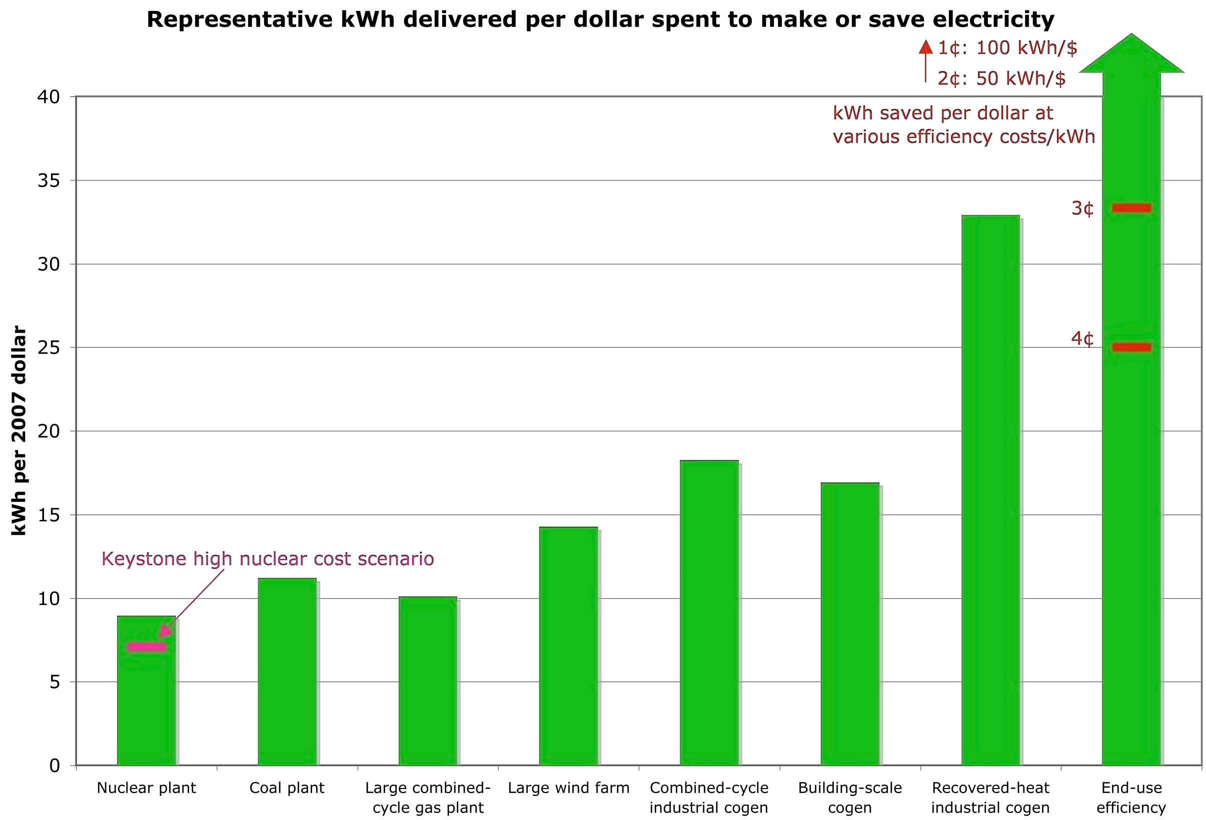

Fig. 2. How much coal-fired electricity can be displaced by investing one dollar to make or save delivered electricity by the means shown in Fig. 1. To interpret the bar on the far right, note that the historic-average cost of U.S. electricity-saving programs is ~2¢ per saved kWh, though many programs, especially for business customers, have cost less than 1¢/kWh, far off the chart.

Fig. 2 shows the reciprocal of—*i.e.*, 1.0 divided by—the costs of various options in Fig. 1 (converted from cents to dollars). It therefore shows how cheaper options displace more coal per dollar than costly options can. That's what "cheap" means. However, before comparing these different ways to displace coal-fired electricity, we must adjust for the carbon emitted by fossil-fueled cogeneration. Those emissions are lower than those of the power plants and boilers that cogeneration displaces, but they're not zero (like efficiency and renewables). Thus cogeneration's *net* carbon displacement is smaller than the gross carbon displacement shown in Fig. 2. However, as Fig. 3 shows, it's bigger (with good design) than the carbon displaced by combined-

[75] Refs. 62 and 61 explain this without the fuller graphics presented below for the first time.

cycle gas-fired plants, which don't capture and reuse waste heat for buildings or industrial processes as cogeneration does:

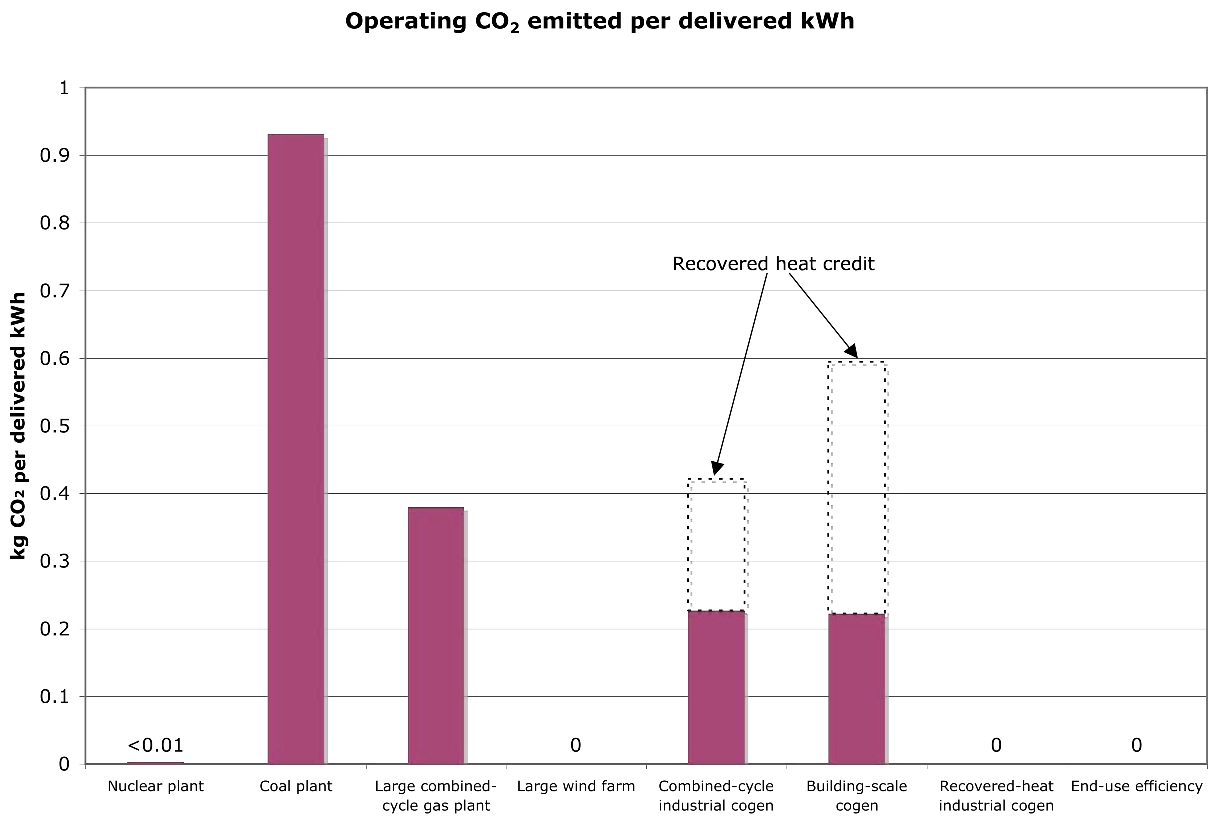

Fig. 3. Net carbon emitted per kWh of power delivered by operating typical electrical resources.

Coal is by far the most carbon-intensive source of electricity, so displacing it is the yardstick of carbon displacement's effectiveness. A kilowatt-hour of nuclear power does displace nearly all the 0.9-plus kilograms of CO_2 emitted by producing a kilowatt-hour from coal. But so does a kilowatt-hour from wind, a kilowatt-hour from recovered-heat industrial cogeneration (ascribing its carbon emissions to the process heat that was being produced anyway), or a kilowatt-hour saved by end-use efficiency. And all of these three carbon-free resources cost at least one-third less than nuclear power per kilowatt-hour, so they save more carbon per dollar.

Combined-cycle industrial cogeneration and building-scale cogeneration typically burn natural gas, which does emit carbon (though half as much as coal), so they displace somewhat less net carbon than nuclear power could: around 0.7 kilograms of CO_2 per kilowatt-hour.[76] Even though cogeneration displaces less carbon than nuclear does per kilowatt-hour, it displaces more carbon than nuclear does *per dollar spent on delivered electricity*, because it costs far less. With a net delivered cost per kilowatt-hour approximately half of nuclear's, cogeneration delivers twice as many kilowatt-hours per dollar, and therefore displaces around 1.4 kilograms of CO_2 for the same cost as displacing 0.9 kilograms of CO_2 with nuclear power.

[76] Since its recovered heat displaces boiler fuel, cogeneration displaces more carbon emissions per kilowatt-hour than a large gas-fired power plant does.

Fig. 4 compares different electricity options' cost-effectiveness in reducing CO_2 emissions, counting both their cost-effectiveness in delivering kilowatt-hours per dollar and their carbon emissions if any:

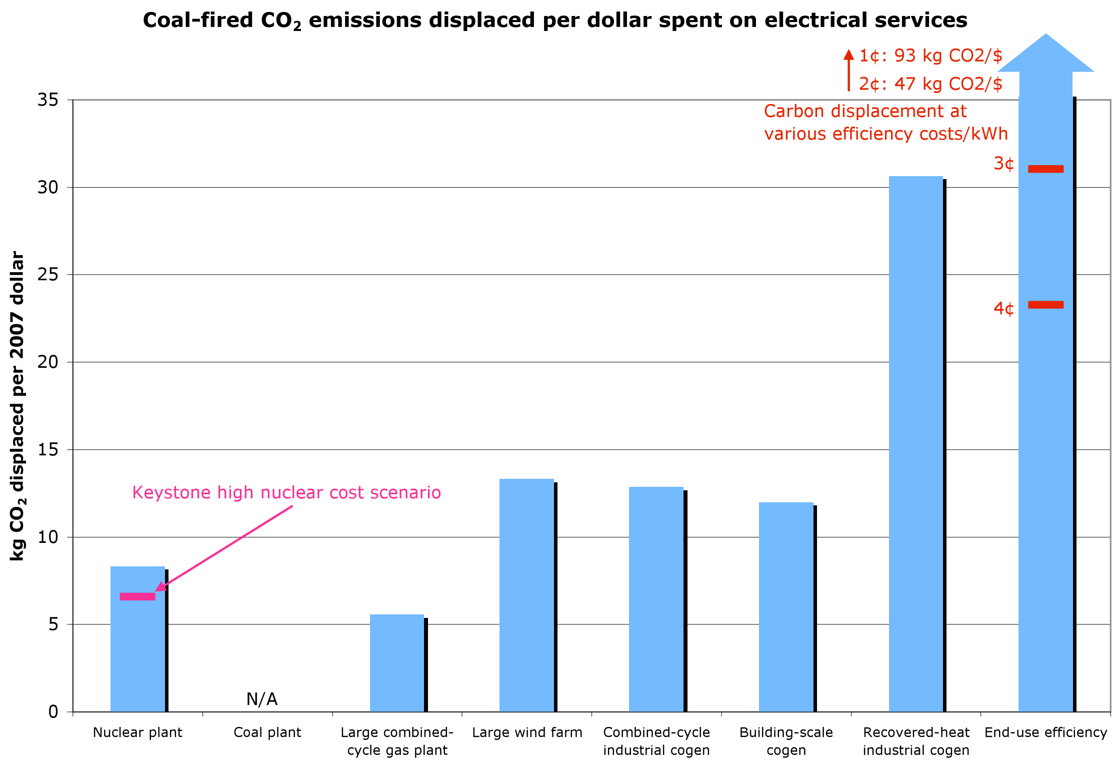

Fig. 4. Relative cost-effectiveness of different ways to save carbon emitted by coal-fired power plants. Since the "currency" here is kilowatt-hours, the cost of generating a coal-fired kilowatt-hour is irrelevant to this calculation. Nuclear's apparent superiority over combined-cycle gas-fired power in carbon reduction per dollar is valid only for one plant in isolation (and only if the nuclear plant is relatively cheap and the gas relatively costly): in an actual power system, gas's greater load-following ability enables it to displace more coal and to support more variable renewables (faster and at lower cost) than equivalent nuclear capacity could do.

Nuclear power, being the costliest option, delivers less electrical service per dollar than its rivals, so, not surprisingly, it's also a climate-protection loser, surpassing in carbon emissions displaced per dollar only centralized, non-cogenerating combined-cycle power plants burning natural gas at the relative prices assumed. Firmed windpower and cogeneration are 1.5 times more cost-effective than nuclear at displacing carbon. So is efficiency at even an almost unheard-of 7¢/kWh. Efficiency at normally observed costs beats nuclear by a wide margin—for example, by about ten-fold for efficiency costing one cent per kWh.

New nuclear power is thus so costly that shifting a dollar of spending from nuclear to efficiency protects the climate severalfold more than shifting a dollar of spending from coal to nuclear. Indeed, under plausible assumptions, spending a dollar on new nuclear power *instead of* on efficient use of electricity has a worse climate effect than spending that dollar on new coal power!

Fig. 4 shows that making and delivering new nuclear power displaces 1.4 to ≥11 times less carbon per dollar than doing the same tasks by using electricity more efficiently or by providing electricity in other, cheaper ways that produce little or no carbon (windpower, cogeneration, or end-use efficiency, but not including combined-cycle gas-fired power plants). That is, *every dollar spent on new nuclear power will produce 1.4–11+ times less climate solution than spending the same dollar on its cheaper competitors*. For a power source merely to emit no carbon isn't good enough; it must also produce the *least carbon per dollar,* and must do so *sooner* than its competitors. That's because, if climate is a problem, then we must invest judiciously, not indiscriminately, to buy the most solution per dollar and the most solution per year—best buys first, not the more the merrier. Buying a costlier and slower solution, like new nuclear power, will make the climate problem worse than it would have been if we'd bought cheaper, faster options instead.

Whether *existing* nuclear plants have displaced and are displacing any carbon emissions, as is often claimed,[77] depends on what assets would have been bought instead to generate the same electricity. Buying coal-fired plants instead would have released more carbon. But buying low- or no-carbon micropower or negawatts instead would have released *less* carbon, because more of those cheaper coal-displacing resources could have been bought with the same money.[78]

Summarizing this analysis, the best investments for both the environment and the economy are those toward the upper-right corner of Fig. 5:

[77] *E.g.*, by the Nuclear Energy Industry's Senior VP Alex Flint, in testimony to USHR Select Committee on Energy Independence and Global Warming, 12 Mar 2008, at p. 13: "At a global level, 439 nuclear plants produce 16% of the world's electricity while avoiding the emissions of 2.6 billion metric tons of CO_2 each year…."

[78] This comparison, and this paper, neglect the fossil fuels needed to build and fuel nuclear plants or their low- or no-carbon competitors. My 1977 analysis of nuclear net energy with Dr. John Price (*Non-Nuclear Futures*, Ballinger [Cambridge MA], Part Two) found that a typical pressurized-water reactor over its lifetime would produce ~16× more electricity than was used to build and fuel it with the technologies of that time using 0.3% uranium ore, or ~8× with Chattanooga Shale. Today, uranium enrichment is more efficient, high-grade ores are scarcer, nuclear plants may have become more materials-intensive, and materials production has become more efficient. The net change is unknown but probably not great. Most comparisons show that embodied construction and fuel-cycle energy is broadly comparable for nuclear *vs*. renewable alternatives (nuclear is often a bit higher), but this indirect energy usage is not important unless the nuclear fleet is growing so quickly that at any given time its energy inputs rival or exceed its outputs (*Non-Nuclear Futures* provides a closed-form analytic solution for this dynamic analysis), as was the case with the high-growth nuclear forecasts of the 1970s. Such analysts as van Leeuwen and Smith (2004, www.stormsmith.nl) have published a different argument: they find a net energy loss for nuclear power in the static case too by assuming very-low-grade uranium resources and/or significant long-term energy inputs to manage nuclear wastes and decommissioning (http://nuclearinfo.net/Nuclearpower/WebHomeEnergyLifecycleOfNuclear_Power). Others have extended this theme by including their estimates of the amount of fossil fuel needed to win and use fossil fuel itself (*e.g*., http://blog.greenparty.ca/files/Nuclear_In_Out_3.pdf). These analyses are very complex and often inconclusive. Having helped create the generally accepted accounting principles for net energy analysis in the 1970s, I believe it's simpler and clearer nowadays just to use normal economic analysis. However, global uranium resources and their net energy yield and economic cost would become a significant concern with a large and expanding nuclear program: Peter Bunyard's brief tutorial is at www.i-sis.org.uk/DTNPM.php; *cf*., for contrasting views, *cf*. E. Schneider and W. Sailor, "Long-Term Uranium Supply Estimates," *Nucl. Technol.* **162**(3):379–387 (June 2008), and Mudd, G M and Diesendorf, M, 2008, "Sustainability of Uranium Mining: Towards Quantifying Resources and Eco-Efficiency, *Envtl. Sci. & Technol.* **42**(7):2624–2630, 10.1021/es702249v, http://pubs.acs.org/cgi-bin/sample.cgi/esthag/2008/42/i07/pdf/es702249v.pdf?isMac=793670.

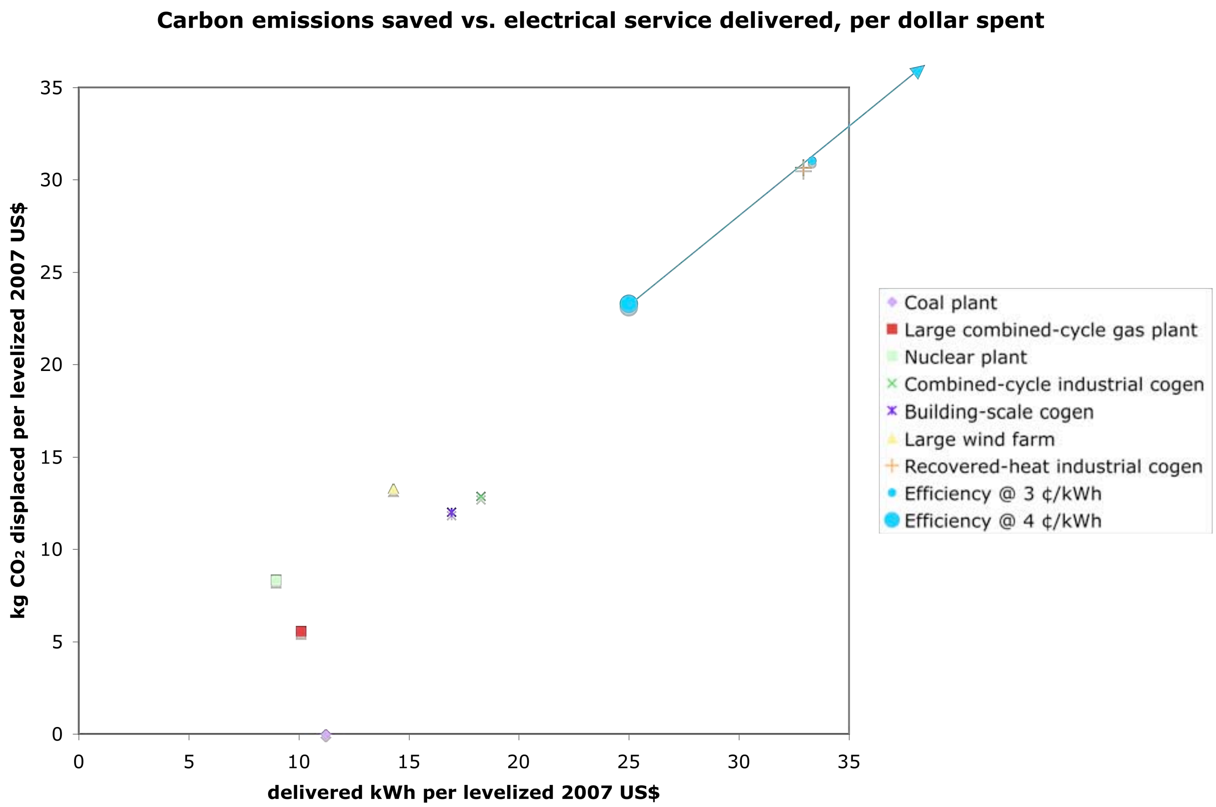

Fig. 5. The relative cost-effectiveness of different ways to spend a dollar to displace carbon emissions from coal-fired power plants (vertical axis) and to deliver new electrical services (horizontal axis). Options toward the lower left are worst for both priorities.

Some say we need to buy everything, so we needn't actually make choices. But if you order that way from a Chinese restaurant menu, one item from each section, you can spend most of your money on the shark's-fin soup, run out of money to buy rice, and go away hungry. We have only so much money and appetite, so we must choose wisely. The more urgent it is to protect the climate, the more vital it is to spend each dollar in ways that will displace the most carbon soonest. This means focusing on big wins. To gain big climate benefits, deploying the efficiency and micropower resources that now provide upwards of half the world's new electrical services is vital—but deploying the nuclear resource that provides ~1% of that service growth and yields ~1.4–11+ times less carbon saving per dollar is irrelevant or worse. Ignoring the former and fixating on the latter only reduces and retards climate protection.

The nuclear industry is eager that the public does not understand this argument, which to my knowledge has not previously been explained in major public or business media in the U.S., and rarely elsewhere. Rather, the industry emphasizes its belief that properly pricing carbon (figures like €20 or $30 per tonne of carbon are often cited) will make nuclear power cost-competitive. That marginal price would be nearly three times McKinsey and Company's 2007 estimate[79] of the €2/tonne-CO_2 average cost of abating 45% of the world's 2030 business-as-

[79] The results are summarized for the world at www.vattenfall.com/www/ccc/ccc/577730downl/index.jsp and for the United States at www.mckinsey.com/clientservice/ccsi/pdf/Greenhouse_Gas_Emissions_Executive_Summary.pdf.

usual greenhouse-gas emissions. This whole comparison, however, wrongly assumes that the competitor is a coal- or gas-fired central power plant. Those are the costliest but *not the only* competitors. *Properly pricing carbon will advantage all other zero-carbon resources—renewables and efficiency—as much as it advantages nuclear* (and will also advantage low-carbon cogeneration to a lesser degree). Thus taxing or trading carbon will not help nuclear power beat its most formidable and successful competitors.

Some advocates claim that a hydrogen economy will rescue nuclear power by harnessing its electricity or heat to make hydrogen. But these processes are prohibitively costly. Hydrogen fuel cells in buildings, industry, or vehicles, far from giving nuclear power a vital new market, would instead add yet another fatal competitor to its electricity production.[80]

In the end, the nuclear industry's increasingly explicit assumption (as in current French and UK policy) that governments must guarantee an above-market-clearing carbon price sufficient to ensure nuclear power's competitiveness not only jettisons market logic and EU rules; it also reveals how thoroughly both the industry and those governments misperceive the competitive landscape. Failure to recognize micropower and negawatts as authentic, successful, and major alternatives to nuclear power has not stopped those sources from already outgenerating, outcompeting, and far outpacing it, as we'll see below.

How do the competitors' reliability compare with nuclear power's?

The nuclear industry's central stated reason for omitting renewables, such as windpower (which accounts for nearly half the recent growth in decentralized renewables' global capacity), from its list of admissible competitors with nuclear power is that windpower isn't "24/7" or "reliable." Unlike some important sources of distributed renewable power—such as small hydro, geothermal, biofueled, and even much solar-thermal-electric[81] generation—that can be dispatched whenever desired, windpower (and smaller but even faster-growing photovoltaics) do produce varying output depending on the weather. Yet this variability, often assumed to pose a fatal obstacle,[82] becomes far less important in a renewable energy supply system using diverse

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[80] 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.

[81] Modern solar-thermal-electric systems typically have 8+ hours of heat storage (typically in hot heat-transfer oil or molten salt) so they can keep generating all night or through storms. Older versions, usually with onsite gas-firing for backup, operate commercially in three U.S. states, with ten modern plants in advanced planning stages in the U.S. Southwest and nine more in such countries as Mexico, China, and Israel (where the technology originated). Lead times are a few years, and annual installation could readily ramp up to 50–100+ GW/y. Sandia National Laboratory in 2008 projected the busbar cost of firm power to drop to 8–10¢/kWh when capacity passes 3 GW. Yet with 4 GW of new projects already under contract, world capacity will probably reach 6 GW by 2013—before a nuclear plant ordered now could deliver power at about twice the cost. A good overview by J. Romm is at www.salon.com/news/feature/2008/04/14/solar_electric_thermal/ and further background at www.nrel.gov/csp/troughnet/publications.html and http://en.wikipedia.org/wiki/Solar_thermal_energy. Whether onsite or grid-integration storage or backup will cost less depends on site-specific conditions.

[82] One of the milder statements of this view is in the World Nuclear Association's white paper "Renewable energy and electricity," July 2007, www.world-nuclear.org/info/inf10.html: "[T]here must be reliable duplicate sources of electricity beyond the normal system reserve, or some means of electricity storage….In practical terms non-hydro renewables are…able to supply up to some 15–20% of the capacity of an electricity grid, though they cannot directly be applied as economic substitutes for most coal or nuclear power, however significant they become in particular areas with favourable conditions. Nevertheless, they will make an important contribution to the world's energy future, even if they cannot carry the main burden of supply." This is slight progress from the Feb. 2005 edition, which added: "[A]ny substantial use of solar or wind for electricity in a grid means that there must be allowance for almost

technologies, because weather that's bad for one source is good for another: stormy weather is generally good for windpower and hydro but bad for solar, while fine weather does the opposite. Diversifying locations helps too, because weather varies over areas that are often smaller than power grids. Technical reliability of single generating units is not the issue: modern wind turbines are ~98–99% available, far better than any thermal plant. The issue is rather the *aggregate* effect of some renewables' variability. As we'll now see, that effect is small.

The United Kingdom has 2.6% the land area, 7.7% the 2005 grid capacity, and 9.9% the 2005 electricity usage of the United States. A 34-year, >15-million-site-hour analysis of UK wind data found excellent properties for reliable windpower[83] and even better ones for its contributions to diversified renewable power supply.[84] A review of more than 180 European analyses through 2005 confirmed[85] that windpower's variability even at penetrations of at least 20% for Europe, ~14% for Germany,[86] or 30% for West Denmark[87] are manageable at modest cost if renewables are properly dispersed, diversified, forecasted, and integrated with the existing grid and with demand response.[88] Not one of more than 200 international studies has found significant

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100% back-up with hydro or fossil fuel capacity…."

[83] For example, the annual variation in capacity factor has a standard deviation of only 7.4%; output correlates well with loads both seasonally and daily; windpower is nearly three times more productive during the highest- than the lowest-demand hours; in the highest-10%-demand hours, ~82% of the wind sites work; windpower output is less correlated between sites farther apart; and not for a single hour was the whole country becalmed or too windy. Of the ~20% of a given site's zero-output hours, ~99% were due to underspeed, ~1% to overspeed. But extreme conditions are not problematic: Underspeed affects over half the UK for <10% of all hours, ≥75% for 0.8% (0.2% in winter), >90% for only 1 h/y, and <20% for >60% of hours. The most extreme overspeed affects 43% of the UK for ~1 hour in 30 years. Overspeed for >30% of the UK at once is always during periods of very low load. And strong winds affect <0.1% of the UK at any one time. G. Sinden (www.eci.ox.ac.uk), "Characteristics of the UK wind resource: Long-term patterns and relationship to electricity demand," *En. Pol.*, in press, www.eci.ox.ac.uk/publications/downloads/sinden06-windresource.pdf.

[84] Supplying 20% of UK electricity with windpower, wavepower (42% correlated with wind), and tidal-current power (only 1% correlated with either), can serve the same load with the same reliability using 76 instead of 84 GW of conventional capacity. Combining three distributed sources—offshore wind, photovoltaics, and household cogeneration—to meet 10% of English and Welsh loads in a 65/10/25% ratio would cut backup requirements to one-sixth those needed with offshore wind alone. Meeting the most extreme conditions of low variable-source output plus high demand needs additional backup capacity of only 0.78% of peak load, while supply by big thermal stations normally needs at least 15% "reserve margin." A 20% variable UK power supply would need ~2 GW of backup for one hour a year—less than a third of the backup capacity ("reserve margin") already installed on the grid. G. Sinden, basic and supplemental submissions to House of Lords Select Committee on Science & Technology, 2004, www.eci.ox.ac.uk/research/energy/renewable.php; A.B. Lovins, address to Royal Academy of Engineering (London), 13 May 2006, www.rmi.org/images/PDFs/Energy/E06-04_NucPwrEconomics.pdf.

[85] *Large Scale Integration of Wind in the European Power Supply*, European Wind Energy Association, Dec 2005, www.ewea.org/fileadmin/ewea_documents/documents/publications/grid/051215_Grid_report.pdf.

[86] 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.

[87] European Wind Energy Association, "Wind Power Technology: Operation, Commercial Developments, Wind Projects, and Distribution," ~2004, www.ewea.org/documents/factsheet_technology2.pdf.

[88] Windpower in 2004 generated the normal-wind-year equivalent of 21% of Denmark's electricity use and 25–30% of that of three German *Länder*. On windy days with light loads, wind provided over 100% of the load in certain regions, particularly in West Denmark, North Germany, and northern Spain. By 2007, those three north German states were >30% wind-powered on an annual basis; all Germany, 7.2%. For more detailed treatments of integrating intermittent resources into the grid, see *Small Is Profitable* (ref. 120), pp. 193–200, and J. C. Smith, E.A. DeMeo, B. Parsons, and 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.

costs or technical barriers to reliably integrating large variable renewable supplies into the grid.[89] U.S. utilities increasingly agree: Lawrence Berkeley National Laboratory (LBL-58450) notes that 2014 resource plans include 20% wind for SDG&E and 15% for Nevada Power—neither near a limiting value. Nine recent U.S. studies found that integrating windpower providing up to 31% of regional peak demand on Western utilities' grids would incur firming and integration costs of 0.04–0.5¢/kWh,[90] or ~1–15% of U.S. windpower's 3.7¢/kWh 1999–2006 average price[91]—far too little to disturb windpower's two- to threefold cost advantage over new nuclear.[92]

Some renewables' variability does require attention and proper engineering, but it's neither a serious issue nor unique to renewables: the grid is already designed for the sudden and unexpected loss of big blocks of capacity from transmission or central-plant outages. Whenever renewable penetration levels of supposed concern have been approached in practice, they've faded over the hazy theoretical horizon. For example, as the West Danish system operator gained experience with windpower, he became confidently able to manage nearly five times more windpower than he had thought possible 7–8 years earlier.[93] This horizon also continues to recede as distributed intelligence gradually permeates the grid and as more diversified combinations of resources are simulated. Recent University of Kassel field experiments have confirmed that just integrated wind, photovoltaics, and biogas generation could reliably provide *all* German electricity.[94] The north German state of Schleswig-Holstein, which got 39% of its 2007 electricity from windpower, now aims for 100% by 2020,[95] as it already achieves in windy months.

Power grids inherently cope with highly variable supply and demand. *Demand* varies from moment to moment as customers turn loads on and off; sudden variations, *e.g.* during the ads in popular televised UK sporting events, can ramp demand so rapidly (due largely to large water pumps when millions of toilets flush simultaneously, but euphemistically blamed on electric kettles) that utilities are hard-pressed to maintain stable supplies. Demand often varies widely from day to night and from summer to winter. Utility planners understand all this and design for it. Yet there is no technical difference between variations in demand and in supply; they are entirely fungible, and indeed onsite generation can be usefully considered a negative load. Calm winds or cloudy skies last up to a few days in decent sites, but can be offset by complementary renewables at the same sites or by any renewables at more distant sites. (The distance needed for very uncorrelated output depends on regional geography and weather patterns, but is typically many hundreds of km.) Yet whether a given solar roof, wind turbine, or wind farm is working at a given moment is about as irrelevant to the system operator as whether a particular big office building's chillers are on or off.

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[89] R. Gross *et al.*, *The Costs and Impacts of Intermittency*, UK Energy Research Centre (Imperial College, London), 2006, www.ukerc.ac.uk. Further findings are reviewed in *Small Is Profitable*, ref. 120, pp. 172–200.

[90] In mixed dollars of roughly 2002–06. R. Wiser and M. Bolinger, "Annual Report on U.S. Wind Power Installation, Cost, and Performance Trends: 2006," DOE/EERE, LBL-41435, May 2007, www1.eere.energy.gov/windandhydro/pdfs/41435.pdf, summarized at www1.eere.energy.gov/windandhydro/pdfs/wiser_data_report_summary_2006.pdf. Midwestern and Eastern firming could cost more if done with gas, or about the same as in the West using load-management virtual peakers. The majority of lower-49 U.S. windpower resources are in the Western Interconnect plus Texas; this region can lose windpower during sustained summer heat waves, but then virtual peakers also gain importance and value.

[91] Ref. 90.

[92] Ref. 66.

[93] Quoted in EWEA (ref. 87), p. 10.

[94] A nontechnical video is at www.triplepundit.com/pages/renewables-may-power-100-of-ge-002863.php; details are available from Prof Jürgen Schmid at ired.iset.uni-kassel.de/ and www.iset.uni-kassel.de.

[95] J. Sawin, "Wind Power Continues Rapid Rise," 2008, www.worldwatch.org/node/5448.

Moreover, *all* sources of electricity are unreliable—to differing degrees, for differing reasons, with differing frequencies, durations, failure sizes, and predictabilities. Major grid failures occur during regional blackouts, ice storms, and other disruptions. Individual power plants also break down: the average U.S. fossil-fuel-fired plant is unexpectedly out of service ~8% of the time. Power systems are designed to cope with all this too. Yet size does matter. Even if all sizes of generators were equally reliable, a single one-million-kilowatt unit would *not* be as reliable as the sum of a thousand 1-MW units or a million 1-kW units. Rather, a portfolio of many smaller units is inherently *more* reliable than one large unit—both because it's unlikely that many units will fail simultaneously,[96] and because 98–99% of U.S. power failures originate *in the grid*, which distributed generation largely or wholly bypasses.

Research is increasingly showing that if we properly diversify renewable energy supplies in type and location, forecast the weather (as hydropower and windpower operators now do), and integrate renewables with existing demand- and supply-side resources on the grid, then renewables' electrical supplies will be *more* reliable than current arrangements. That is, such a renewable-based power system, even if solar and wind form a large fraction of supply, will generally need *less* storage and backup capacity than we've *already* installed and paid for to cope with the intermittency of large thermal stations—which fail unpredictably, for long periods, in billion-watt chunks.[97]

Though micropower's unreliability is an unfounded myth, nuclear power's unreliability is all too real. Nuclear plants are capital-intensive and run best at constant power levels, so operators go to great pains to avoid technical failures. These nonetheless occur occasionally, due to physical causes that tend to increase with age due to corrosion, fatigue, and other wear and tear. Some nuclear power failures are major and persistent: of the 132 U.S. nuclear units that were built and licensed to operate (52% of the original 253 orders), 21% were permanently shut down because of intractable reliability or cost issues (or in one case a meltdown), while a further 27% have suffered one or more forced outages of at least a year.[98] When the remaining 68 units work well, their output is indeed commendably steady and dependable, lately averaging ~90% capacity factor in the United States. However, even these relatively successful nuclear plants also present four unique reliability issues:

- Routine refueling, usually coordinated with scheduled major maintenance, shuts down the typical U.S. nuclear plant for 37 days every 17 months.[99]
- In both Europe and the United States, prolonged heat waves have shut down or derated multiple nuclear plants when their sources of cooling water got too hot.[100]

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[96] Only a modest number of units, like the canonical six-company stock portfolio, is needed for effective diversification: see *Small Is Profitable*, ref. 120, pp. 183–184.
[97] See *e.g.* the UK analyses summarized by A.B. Lovins, 13 May 2006 lecture to Royal Academy of Engineering (London), RMI Publn. #E06-04, www.rmi.org/images/PDFs/Energy/E06-04_NucPwrEconomics.pdf. The late Astronomer Royal, Sir Martin Ryle, showed the same thing more simply in *Nature* **267**:111–117 (1977).
[98] D. Lochbaum (a nuclear engineer at Union of Concerned Scientists), testimony to USHR Select Committee on Energy Independence and Global Warming, 12 Mar 2008.
[99] 15 Nov 2005 data from www.nei.org/documents/NuclearPerformanceMonthly.pdf.
[100] In the ten-day heat wave of 2003, which killed an estimated 34,000 Europeans and cost over €13 billion (www.grid.unep.ch/product/publication/download/ew_heat_wave.en.pdf)—the hottest summer since 1500 (M. Poumadère *et al.*, *Risk Analysis* **25**(6):1483–1494 (2005))—France lost 4 GW of nuclear output due to warm rivers with low flows, and Germany lost some too; both governments exempted operators from legal temperature limits (*Nucleonics Week*, 14 and 21 Aug and 4 Sept 2003; www.world-nuclear.org/news/nl_nov-dec2003.htm). France, Germany, and Spain had to shut down or derate some nuclear plants for up to a week in the summer 2006 heat wave

- A major accident or terrorist attack at any nuclear plant could cause most or all others in the same country or even in the world to be shut down, much as all 17 of Tokyo Electric Company's nuclear units were shut down for checks in 2002–04 for many months, and some units for several years after falsified safety data came to light. Natural disaster can also intervene: a 7-unit Tokyo Electric Power Company (TEPCO) nuclear complex, the largest in the world—outproduced only by the Itaipu and Three Gorges Dams, and supplying 6–7% of Japan's power—was indefinitely shut down by 2006 damage from an earthquake stronger than its supposedly impossible design basis, and remains down in spring 2008. Its output is being replaced by recommissioned and hastily finished oil-, gas-, and coal-fired plants; the operator's extra cost in FY2007 alone was ~$5.6 billion.[101]
- Unlike scheduled outages, many nuclear units can also fail simultaneously and without warning in regional blackouts, which necessarily and instantly shut down nuclear plants for safety. But nuclear physics then makes restart slow and delicate: certain neutron-absorbing fission products must decay before there are enough surplus neutrons for stable operation. Thus at the start of the 14 August 2003 northeast North American blackout, nine U.S. nuclear units totaling 7,851 MW were running perfectly at 100% output, but after emergency shutdown, they took two weeks to restart fully. They achieved 0% output on the first day after the midafternoon blackout, 0.3% the second day, 5.7% the third, 38.4% the fourth, 55.2% the fifth, and 66.8% the sixth. The average capacity loss was 97.5% for three days, 62.5% for five days, 59.4% for 7 days, and 53.2% for 12 days[102]—hardly a reliable resource no matter how exemplary its normal operation. Canada's restart was even rougher, with Toronto teetering for days on the brink of complete grid failure despite desperate appeals to turn everything off. This nuclear-physics characteristic of nuclear plants makes them "anti-peakers"—guaranteed unavailable when they're most needed.

The grid is designed to cope, and does cope, with such massive and prolonged central-station outages, albeit with difficulty and at considerable cost for reserve margin, spinning reserve (spare capacity—generally coal-fired—kept running and synchronized for instant use), and replacement energy. The investments needed to manage central-thermal-plant intermittence (nuclear or fossil-fueled) have already been made and paid for. It is therefore hard to understand why the occasional and predictable becalming of wind farms or clouding of solar cells over a much smaller time and space, offset by higher output from statistically complementary renewable resources of other kinds or in other locations, is a problem. *All* generators—not just variable

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due to low water levels. A 23 Jan 2008 Associated Press analysis found 24 U.S. reactors currently in severely water-short areas. If the year-long drought persists until summer peak loads arrive, curtailed nuclear output could force utilities to buy spot replacement power at an order-of-magnitude higher cost (www.cnn.com/2008/TECH/01/23/drought.nuclear.ap/index.html).

[101] "TEPCO counts earth quake costs," 30 Jan 2008, www.world-nuclear-news.org/C/Tepco_counts_earthquake_costs310108.htm. Continuing analysis of the event suggests disquieting flaws in operations, design, siting, and regulation: *e.g.*, A. Kumar and M. Ramana, "Nuclear safety lessons from Japan's summer earthquake," *Bull. atom. Scient.*, www.thebulletin.org/web-edition/features/nuclear-safety-lessons-japans-summer-earthquake; M. Yamanaka, "Japan Nuclear Plant, World's Biggest, May Be on Fault", 7 Dec 2007, www.bloomberg.com/apps/news?pid=20601101&sid=aATSWPrhDSB8&refer=japan; J.-H. Chrisstoffels, "Earthquake Alarm: The Kashiwazaki nuclear incident and the consequences for Japan's nuclear policy," Clingendael Briefing Paper, Aug 2007, www.clingendael.nl/publications/2007/20070807_ciep_briefingpaper_chrisstoffels.pdf.

[102] RMI analysis from data at www.nrc.gov/reading-rm/doc-collections/event-status/reactor-status/2003/index.html and www.nrc.gov/info-finder/reactor/, graphed at http://old.rmi.org/sitepages/pid1200.php.

renewables—need reserves, backups, or storage to achieve a given level of reliability. It's wrong to count these as a cost for variable renewables but not for intermittent thermal plants. Every source's economics should duly reflect the amount of support they require for the desired reliability of retail service.

The economic comparisons offered above for windpower (Fig. 1) make generous provision for these storage and backup costs (Fig. 1). In contrast, some other comparisons (even, astonishingly, one by the UK's Royal Academy of Engineering)[103] assume that any variable renewable resource needs 100% backup. That's clearly wrong. Reliability is a statistical attribute of a power system, not an absolute attribute of a single unit, so on a statistical basis, wind and solar power do merit substantial "capacity credits" whose size depends on regional conditions. Grid operators care about the overall delivered-service reliability of a portfolio of technologically and geographically diversified units, integrated into a grid with diverse power resources and demand-response options, all appropriately forecasted (and optionally with storage, like the pumped-hydro-storage units sometimes associated with nuclear units but seldom attributed to them as a cost, or the overnight heat storage built into some modern solar-thermal-electric plants). Thus a forecasted temporary shortage of, say, windpower is of concern to the grid operator only if it occurs at a time of maximum load *and* if no other resource is available.

Already today, in wind-rich regions of North Germany, Spain, and Denmark, variable renewable power production exceeds regional demand, and annually provides 20–39% of all electricity, with no integration problems nor significant integration costs. As the European Wind Energy Association's integration report stated in 2005, "[L]arger-scale integration of wind [power] does face barriers; not because of its variability but because of a series of market barriers in electricity markets that are neither free [n]or fair, coupled with a classic case of new technologies threatening old paradigm thinking and practice."[104]

Can nuclear power enhance energy security?

Energy security has more dimensions than simply keeping the lights on. High on most governments' list is reducing dependence on other countries, especially those considered unfriendly or unstable. But only a few of the world's 31 nuclear countries (six of which produce nearly 75% of the nuclear electricity) have their own uranium resources, only a few enrich nuclear fuel, and just two—Japan and France—have the unique factories needed to make major light-water reactor parts. These three groups of countries don't overlap, so *any* country wishing to use nuclear power must depend on one or more other countries for vital supplies.

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[103] Royal Academy of Engineering (London) / PB Power, "The Costs of Generating Electricity" (Mar 2004, www.raeng.org.uk/news/publications/list/reports/Cost_of_Generating_Electricity.pdf) provided "simple," poorly specified, and systematically distorted comparisons of some generating options, nearly all centralized. It used a uniform (not risk-adjusted) discount rate, unstated financial assumptions and metrics, scarcely documented assumptions, unstated nuclear decommissioning costs, and zero nuclear waste management cost. Although it agreed that "All generation technologies exhibit some degree of 'intermittency' or 'unpredictability' to a greater or lesser extent," it overstated wind's backup-capacity needs by severalfold (65%, *vs. e.g.* Dale *et al.* (2004) 17%, House of Lords 2004 (15%), ILEX 2003 (12% at slightly lower share), even claiming that the backup requirement exceeded the conventional capacity that windpower displaces; yet it found zero backup costs for thermal plants, whose reserve margin was deemed a "system cost." Without saying so, it assumed extremely rapid wind penetration (to ~30% in 15 y, far beyond anyone's projection), yet assumed only a 15% price drop in 15 y from a high base: actually windpower's real capital cost/kW has historically fallen 12–18% per doubling of capacity, which worldwide in 1999–2004 occurred every 2.5 years.

[104] Ref. 85.

In this time of oil jitters, some political leaders conflate electricity with all forms of energy and suggest that nuclear power can help relieve oil dependence.[105] This is fallacious. Nuclear power makes electricity,[106] whose link to oil is extremely tenuous. Only 1.6% of U.S. electricity in 2007 was made from oil[107] and 1.6% of U.S. oil made electricity; in the UK in 2006, 1.3% and 0.8%; globally in 2006, ~7% and ~7%; and falling virtually everywhere. Nine-tenths of that oil, too, is gooey "residual" oil from the bottom of the barrel, not distillate usable for mobility. To the still-unclear extent that grid electricity's lower energy cost per mile could ultimately justify costly batteries to replace oil via battery-electric or hybrid-electric cars, renewable electricity could do the same thing, so the cost comparisons above would apply.[108]

France has striven with unique fervor since 1974 to substitute nuclear power for oil, but when this shift began, less than an eighth of French electricity was made from oil. France today, making 78% of its electricity or 18% of its total delivered energy from nuclear power, consumes only one-tenth less fossil fuel than in 1973; transport has increased oil use far more than nuclear power has reduced it. Oil still provides nearly half, and fossil fuels more than 70%, of France's final energy needs, while all uranium is imported. Carbon emissions are higher than in the mid-1980s. Nuclear overcapacity has become a serious problem, requiring "dumping" a dozen reactors' surpluses on neighboring countries and even weekend shutdowns of reactors that can't sell their output. Moreover, France heavily promoted electric space-heating to create a market for the excess nuclear power, so the winter peak load is 55 GW higher than the summer one—three-fourths of the 71-GW nuclear capacity, but very uneconomic to meet with baseload plants—forcing France to reactivate 2.6 GW of very old oil-fired plants and to import very costly fossil-fueled winter peak power (whose carbon emissions are ascribed to the exporting nations).[109] And electric heat is so costly that about three-fourths of French households still heat with fossil fuels; heavy financial losses throughout the nuclear value chain have required massive taxpayer bailouts and still-opaque subsidies. To be sure, the French nuclear program is an impressive technical and logistical achievement; yet the world is expected to add its capacity equivalent in windpower in just the next two years.

Nuclear's potential to displace natural gas is more complex, and of much interest in Europe after recent signs that Russia can be an unreliable supplier using gas exports for political leverage. Nuclear power is a slow and very costly way to displace gas-fired electricity, and has less domestic content and lower reliability than a diversified and integrated portfolio of renewable and efficiency resources. For the main uses of gas—heating buildings, water, and industrial processes, and as a petrochemical feedstock—nuclear electricity is unsuitable technically or economically or both.

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[105] President Bush regularly does this, *e.g.*, in the Fact Sheet accompanying his 5 May 2008 speech (www.whitehouse.gov/infocus/energy/).
[106] In some special cases, chiefly in Russia, it also produces district heating.
[107] The only state with very oil-dependent electricity is Hawai'i, which has just launched a major shift to renewables.
[108] In addition, outside such rare condensing-plant situations as Hawai'i's, 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.
[109] Most data in this paragraph are drawn from ref. 4 and from M. Schneider, www.world-nuclear-news.org/C/Tepco_counts_earthquake_costs310108.htm (*National Post*, 22 May 2008).

A common concern is that sustaining or increasing reliance on gas for generating electricity risks making gas scarce and costly. This could occur if gas, and gas-fired electricity, continued to be used very wastefully. However, half of U.S. natural gas can be saved at an average cost of ~$0.94/GJ—one-seventh the price assumed here for utility purchases of natural gas.[110] Two-thirds of the potential savings come from saving electricity, especially at times of peak load, met by gas-fired "peaker" combustion turbines so inefficient that saving 1% of U.S. electricity (including peak hours) would save ~2% of the total national use of natural gas, and cuts its price by ~3–4-fold—huge leverage for saving gas and money. Moreover, such savings typically have a *negative* cost because the efficiency investment costs less than its value in saved generating capacity. Thus a least-cost energy strategy, in the United States or elsewhere, would profitably free up a great deal of natural gas in buildings and industry. For example, "passive houses" in five EU nations (including more than 10,000 in Germany) provide superior comfort with *no* space heating,[111] at no extra construction cost for new houses and with attractive paybacks for retrofits. The saved gas can then be devoted to cogeneration that often about redoubles the gas savings by displacing gas in both power plants and boilers or furnaces.

One more dimension of energy and national security requires mention: proliferation. As President George W. Bush has rightly stated, the spread of nuclear weapons is the gravest threat to national security for the United States (and everyone else). Yet commercial nuclear power is the biggest driving force behind that proliferation, providing do-it-yourself bomb kits—nearly all the needed materials, skills, knowledge, and equipment—in innocent-looking civilian disguise, all concealed within a vast flow of civilian nuclear commerce. Acknowledging nuclear power's market failure would unmask and hence penalize proliferators by making the needed ingredients harder to get, more conspicuous to try to get, and politically costlier to be caught trying to get, thus revealing the motive for wanting them as unambiguously military. This would make proliferation far more difficult, and easier to detect sooner by focusing scarce intelligence resources on needles, not haystacks.[112]

Nuclear power, then, cannot in principle deliver the climate and security benefits claimed for it. But can its carbon-free competitors rival or exceed its potential scale and speed? Indeed, are they *already* surpassing it in these critical respects?

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[110] A.B. Lovins *et al.*, *Winning the Oil Endgame*, 2004, pp. 111–122, www.oilendgame.com. These natural-gas findings were confirmed by more detailed in-house RMI research in 2006–07.

[111] Even without using state-of-the-art U.S. glazings whose center-of-glass heat-loss coefficient *k* is now as low as 0.29 W/m^{2}K, yet whose extra cost is often repaid up front by eliminating heating equipment: see the publications of the Passivhaus Institut (Darmstadt, www.passiv.de) and its U.S. counterpart, the Affordable Comfort Institute (www.affordablecomfort.org), or for a general summary, http://en.wikipedia.org/wiki/Passive_house.

[112] A.B. and L.H. Lovins and L. Ross, "Nuclear power and nuclear bombs," *Foreign Affairs* **58**(5):1137–1177 (Summer 1980), www.foreignaffairs.org/19800601faessay8147/amory-b-lovins-l-hunter-lovins-leonard-ross/nuclear-power-and-nuclear-bombs.html or www.rmi.org/images/other/Energy/E05-08_NukePwrEcon.pdf, and *Foreign Affairs* **59**:172 (1980). Had that paper's market-driven strategy been adopted 28 years ago, the world would not today be worrying about Iran and North Korea. See also 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, and V. Gilinsky, H.W. Hubbard, and M. Miller, "A Fresh Examination of the Proliferation Dangers of Light Water Reactors," 2004, www.npec-web.org/projects/NPECLWRREPORTFINALII10-22-2004.pdf. This thesis strengthens when proposed new reactor types are considered. 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.

Are nuclear power's new competitors already significant?

Nuclear power is promoted[113] as "the only energy option available today that can provide large-scale electricity 24/7 at a competitive cost without emitting greenhouse gases." Each part of this case, as we'll see, is false, but two important parts—the implication that electricity supply must be "large-scale" and must come from constantly operating ("24/7") generators—require deeper discussion, starting with unit size. As with the climate-protection claim, the truth is just the opposite.

Global industry and government data compiled annually by Rocky Mountain Institute[114] show that micropower surpassed nuclear power in 2006 in total electricity production (each provides one-sixth of the world's power), surpassed nuclear generating capacity in 2002, and is growing enormously faster. In 2005, global micropower provided one-fourth of the world's new electricity: it added 10–14× (without or with peaking and standby units) as much capacity and 3× as much output as global nuclear added in the same year. In 2006, nuclear lost 0.2% or 0.75 GW of net capacity as retirements exceeded new units, offset this loss by 2.2 GW of upratings for a 1.44-GW net gain, and raised its output 1.3% through the upratings plus higher capacity factors.[115] Yet in 2006, micropower added 43.4 GW, or 57.7 GW including peaking and standby units that can generally be made dispatchable (able to send out power reliably whenever desired). During 2007, for which cogeneration data are not yet available, we estimate that distributed renewables added another ~30 GW to achieve ~222 GW of total capacity[116] (60% as much as nuclear), and they are expanding by ~15% a year[117] while nuclear power struggles to expand at all.

Figs. 6 and 7 compare the historic and industry-forecast global evolution of nuclear power (heavy black line) and of micropower (colored areas) so far in the 21st Century, when nuclear power has remained stagnant while micropower has burgeoned:

[113] *E.g.*, by the Nuclear Energy Industry's Senior VP Alex Flint, ref. 77.

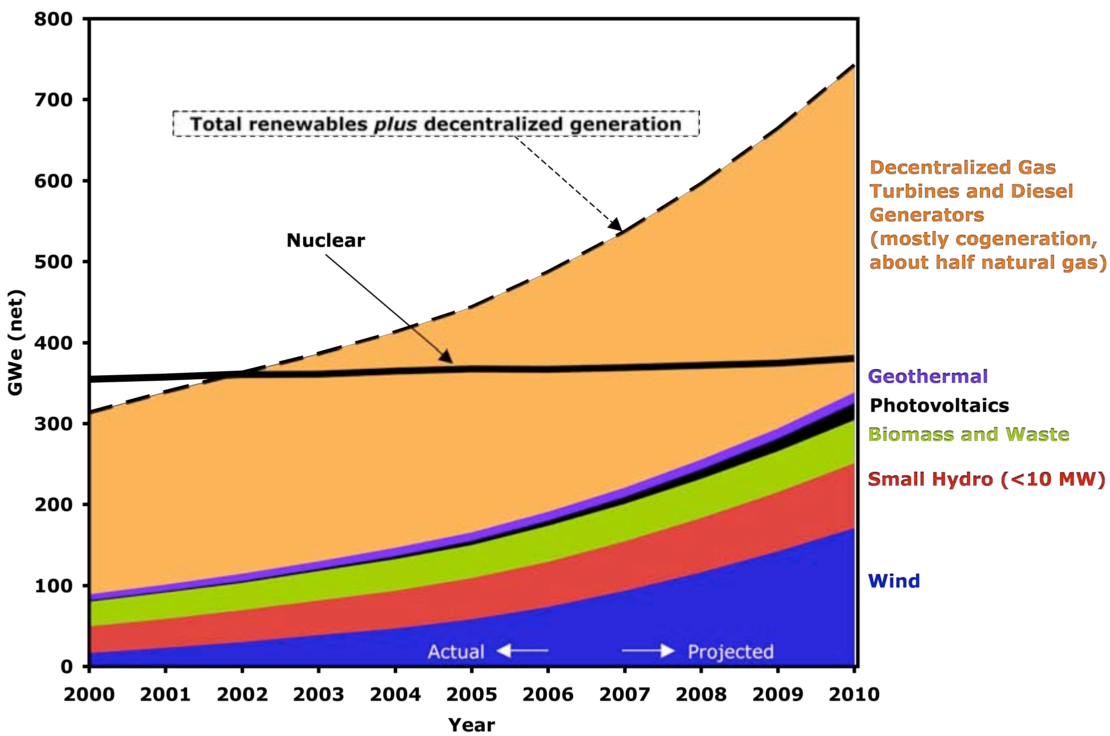
[114] This documented database, now including 2006 updates, is at www.rmi.org/sitepages/pid256.php#E05-04. It is consistent with the authoritative *Renewables Global Status Report: 2006 Update* and its www.ren21.net database, independently derived by a global expert network; that database shows slightly larger totals because it counts small hydro units up to 50 MW in China and 30 in India, *vs*. our 10-MW limit worldwide.

[115] According to the International Atomic Energy Agency's PRIS database and data kindly provided by IAEA, excluding two units that are in long-term shutdown.

[116] Using our more restrictive 10-MW small-hydro limit; REN21 estimates ~240 GW using its broader limits (50 MW in China, 30 MW in Brazil).

[117] Excluding ~780 GW of big hydropower: *Renewables 2007 Global Status Report*, www.ren21.net/pdf/RE2007_Global_Status_Report.pdf, 2008.

Low- or no-carbon worldwide installed electrical generating capacity (except large hydro)



Low- or no-carbon worldwide electrical output (except large hydro)

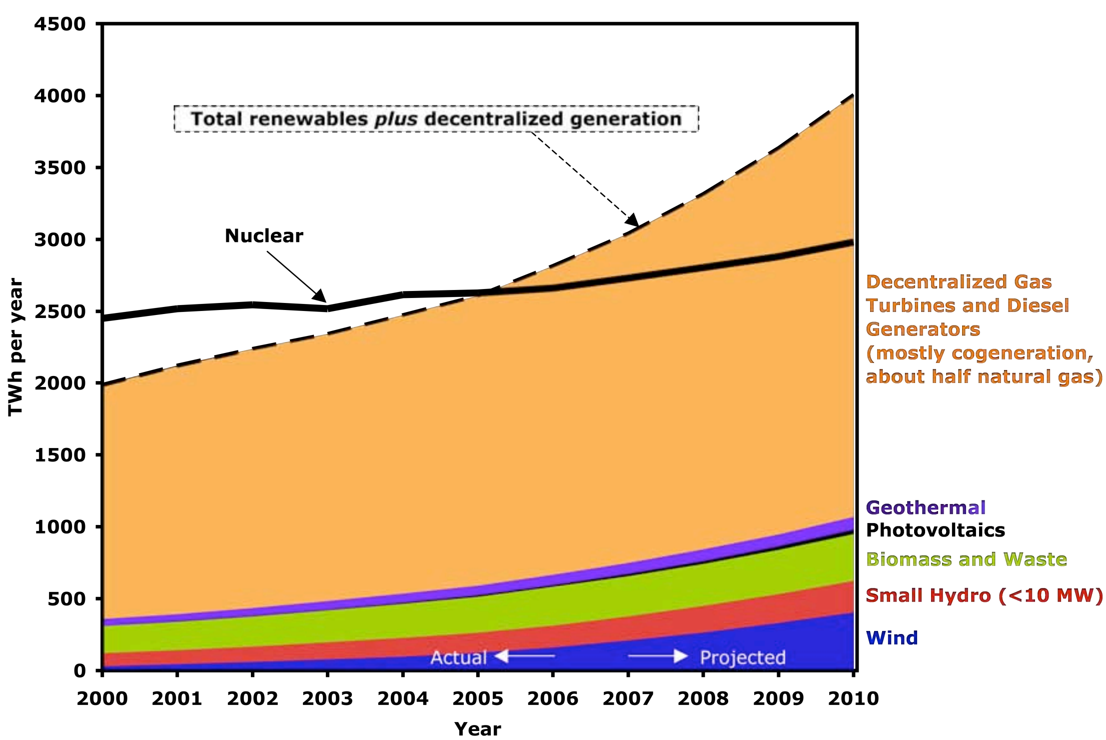


Fig. 6 (top): generating capacity of distributed electric generation worldwide and Fig. 7 (bottom): its electrical output; data are actual through 2006 or 2007 depending on data set, then industry-projected. Neither graph shows decentralized peaking nor standby generators, which have added large amounts of capacity since data collection began in 2000 (Fig. 8 below); also, some kinds of cogenerators in some countries are not yet included. By the end of 2006, micropower had 32% more capacity, and distributed renewables had more than half as much capacity, as nuclear power did, and together, both kinds of micropower generated 5.8% more electricity than nuclear power did.

Dismissed as unimportant, uneconomic, unreliable, and futuristic, micropower in 2005 provided from one-sixth to more than half of all electricity in a dozen industrial countries,[118] including 53% in Denmark, 38% in Finland and Holland, ~31% in Russia, 20% in Germany, 17% in Japan and Poland, *vs.* ~6%[119] in the United States, which still has many barriers to fair competition.[120]

Meeting the large total needs of a modern society for electrical services requires a lot of electricity, or less electricity used more productively, or some combination. But the total scale of the electricity enterprise has been widely confused with the size of its parts. The first objection commonly raised to micropower and negawatts is that their small *individual* scale somehow makes them insufficient *collectively*. Yet like total electricity demand that is the sum of many mainly small loads, the sum of many small generators' output can be enormous. The same revolution that has often replaced computer centers with networked PCs and central telephone exchanges with distributed packet-switching is already starting to transform the electricity industry.

The word "baseload" is often misused to describe the power plants that big economies supposedly need. But in utility load-dispatch parlance, "baseload" doesn't mean big, steadily operating, or dispatchable; it means plants that generate electricity at the lowest *operating* cost, so they're dispatched whenever available, supplemented as needed by costlier-to-run plants. (Thus any renewable generator is run as a baseload resource because it has almost no operating cost. Its capital cost, which must be paid whether it runs or not, is irrelevant to this calculus.) As explained below, no sensible criterion requires a given power plant to be big nor to run steadily, since many small plants, even variable ones, can add up to big and reliable supply—as they increasingly do in competitive power systems that allow them.

For their first century of the electricity industry, power plants were costlier and less reliable than the grid, so it made sense to build bigger plants that backed each other up via the grid. But in the latest quarter-century, power plants have become cheaper and more reliable than the

[118] World Alliance for Decentralized Energy (WADE), *World Survey of Decentralized Energy 2006*, May 2006, p. 31, www.localpower.org. WADE uses a narrower definition of distributed resources than this paper does. At least two more countries appear to qualify based on distributed resources that WADE's survey omits—wind farms, central PV, small hydro, geothermal, solar-thermal-electric, and biomass/waste-fueled generation. However, even as defined, WADE's figures are conservative because they omit <0.5-MWe thermal systems and all steam-turbine cogeneration outside India and China—a significant omission because backpressure turbines are popular in Europe. Steam turbines were not included in the analysis for this paper.

[119] Possibly more if, as claimed at http://uschpa.org/images/RoadmapSep03_77GW.jpg, installed U.S. cogeneration capacity is about twice what USEIA reports.

[120] A.B. Lovins *et al.*, *Small Is Profitable*, RMI (2002, an *Economist* book of the year), www.smallisprofitable.org, documents 207 such "distributed benefits." Despite these barriers, a recent Sierra Energy Group survey found that of 150 U.S. utilities surveyed, 80% of investor-owned, 70% of municipal, and ~50% of cooperatives already used one or more forms of distributed generation.

grid, so cheap and reliable power must now be made at or near customers. This can create many hidden economic benefits—not counted in the comparisons in this paper—that typically raise distributed resources' economic value by roughly a game-changing *tenfold*.[121] Markets are starting to recognize and capture these "distributed benefits," such as reduced financial risk from small and fast rather than big and slow increments of capacity, fuel-price hedging by renewables (which have no fuel and hence no fuel-price volatility), avoided grid costs and losses, and better avoidance and handling of faults on the grid. Utility planners are also starting to realize that, as the late Dr. Shimon Awerbuch showed at the International Energy Agency, a balanced portfolio of electrical sources should include a substantial fraction—typically tens of percent—of renewables, even if they cost more, for the same reason and with the same mathematics that a financial portfolio should include riskless Treasuries even of they cost less: renewables' constant price improves the price/risk profile of the entire portfolio.

Moreover, negawatts, though less carefully measured, seem to add each year about as much effective new "capacity" as micropower does worldwide.[122] Thus probably more than half of the world's new electrical services now come from negawatts and micropower, while *all* central plants—big thermal stations plus big hydro—provide probably less than half.[123] The electricity revolution is already well underway and is rapidly accelerating.

Which power sources are fastest to deploy?

Nuclear power is often claimed to be the only power source that can be deployed quickly enough to deal with urgent issues like climate change. For it to displace much coal-fired power would require an immensely larger nuclear industry:[124] in perhaps the most ambitious vision, John Ritch, director-general of the World Nuclear Association, envisages[125] a 20× nuclear expansion by 2100, starting with more than 1,000 reactors in the next 25 years and 2,000 to 3,000 by 2050 (*vs*. ~440 today, most or all of which will have retired by about 2050). Yet during 2004–07, global nuclear installations averaged just 1.5 GW/y, or about one big plant's worth per year, including upratings of older plants, while the world added ~135 GW/y of total generating capacity. Nuclear power had only a ~2% share of global growth in electric generating capacity, while

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[121] *Id*. Note that this comparison refers to value, not cost or price.
[122] As a rough indication, the 6.7% (1.73%/y compounded) drop in U.S. electrical intensity (total electricity end-use consumption per real dollar of GDP, per USEIA, *Monthly Energy Review*, Mar 2008, without weather adjustment) during the four years 2002–06, whatever its causes, would correspond at constant load factor to saving 49 GW_p in 2006 or ~12 GW_p/y. The United States uses only one-fourth of the world's electricity, and much of the world has comparably or more vigorous intensity-reducing efforts, so it's hard to imagine that global savings, perhaps on the order of four times U.S. savings or ~50 GW/y, don't rival or exceed global additions of distributed generating capacity, which, excluding/including peaking and standby units, totaled ~124/168 GW during the four years 2002–06 (comparing year-end figures), or an average of ~31/42 GW/y. Thus the total effect of negawatts *plus* micropower may average on the order of 100 GW/y as of a few years ago, or substantially more today.
[123] The latest (7 Sept 2007) USEIA data (www.eia.doe.gov/pub/international/iealf/table64.xls) show that 2002–05 world physical additions of generating capacity averaged 120 GW/y. Adding the negawatt effects in the previous note would imply annual electrical-service-capacity additions averaging ~214 GW/y, of which ~94 GW/y would come from micropower and negawatts—nearly half on 2002–06 average, half or more nowadays (annual micropower additions nearly doubled during 2002–06). It's unclear how much micropower EIA's totals include.
[124] Analyzed by S. Squassoni (Carnegie Endowment for International Peace), "The realities of nuclear expansion," USHR Select Committee on Energy Independence and Global Warming, 12 Mar 2008.
[125] R. Black, "Nuclear needs 'huge expansion,'" 16 Oct 2006, reporting Mr. Ritch's remarks in Sydney, http://news.bbc.co.uk/2/hi/science/nature/6054986.stm.

windpower (13.7 GW/y) had 10%, all distributed renewables 17%, and all micropower 28% (probably rising to around one-third in 2007–08). These empirical data contradict the claim that nuclear is fast and big while its non-central-thermal-plant alternatives are small and slow. On the contrary, during 2004–07, micropower added ~14× more capacity (~20× in actual installations without upratings of old nuclear plants) and ~3× more electrical output than nuclear, and is pulling away. The nuclear industry projects that its gross additions (excluding retirements and upratings) will total 17 GW during the five years 2006–2010, but micropower is now adding 17 GW about every 15 weeks—17× faster.[126]

Of course, the nuclear industry hopes for a giant turnaround. But this supposedly irresistible force is colliding with a nearly immoveable object: the existing nuclear fleet was mostly built in the 1970s and 1980s, so its demographics entail retirements at an increasing pace. If operating lives remain the normal 40 years (32 by law in Germany), the industry must exceed any plausible global construction rate just to replace retiring plants, which would otherwise be all gone by 2050.[127] Further life extensions, which the United States and some other authorities are routinely allowing (though increasing doubts are being raised about their soundness),[128] could postpone but not eliminate this problem. It also remains to be seen whether plants older than their operators have high enough uptime and low enough repair costs to justify their continued long-term operation against ever-stiffer competition from rapidly evolving rivals.

Even neglecting retirements, it's hard to imagine how even the most vigorous nuclear revival could catch up with competitors' momentum shown in Figs. 6–7 (plus a roughly comparable if not larger contribution by negawatts not shown in those graphs). This is not just because the competitors are winning so decisively; it's also because of fundamental market dynamics: many small, short-lead-time units accessible to numerous market actors, and selling like PCs or cellphones, can empirically add capacity faster than a few big, long-lead-time units that need specialized institutions and are built more like cathedrals.

Nuclear growth has indeed been overtaken by some of the technologies claimed to be least able to do so—even, ignominiously, by the costliest one, photovoltaics (solar cells). In 2006 worldwide, nuclear power added less net capacity (1.44 GW) than photovoltaics added (1.74 GW), or one-tenth as much as windpower added (15.1 GW). In 2007, nuclear capacity added or uprated by 2.5 GW of net capacity according to the IAEA or 3.2 GW according to the World Nuclear Association,[129] while windpower alone added ~20.6 GW, including 5.2 GW in the United States,[130] 3.5 GW in Spain (now one-tenth wind-powered), and 3.2 GW in China.[131] Thus each of those three countries in 2007, and Spain alone in the past few years, added more wind-

[126] Plant-by-plant nuclear data from IAEA and WNA; all data are at www.rmi.org/sitepages/pid256.php#E05-04. In 2010, the projected global net capacity increases are 79 GW for micropower (excluding standby and peaking cogeneration units), *vs*. 6 GW for nuclear.
[127] See ref. 4, graphs 2, 3, and 5. An earlier version is M. Schneider and A. Froggatt, "On the Way Out," *Nucl. Eng. Intl.*, June 2005, pp. 36–38, www.neimagazine.com/story.asp?storyCode=2030047.
[128] R. Smith, "Nuclear-Plant Analyses Ordered," *Wall St. J.*, p. A4, 18 Apr 2008.
[129] Ref. 126. The World Nuclear Association data are from www.world-nuclear.org/info/reactors.html (Jan. 2008, date unspecified) *vs*. www.world-nuclear.org/info/reactors-jan07.html (Jan. 2007, date unspecified).
[130] Windpower provided 12% of new U.S. capacity in 2005, 19% in 2006, and 30% in 2007.
[131] Global Wind Energy Council, "Continuing boom in wind energy—20 GW of new capacity in 2007," www.gwec.net/index.php?id=30&no_cache=1&tx_ttnews%5Btt_news%5D=121&tx_ttnews%5BbackPid%5D=4&cHash=f9b4af1cd0, 18 Jan 2008.

power capacity than the world added net nuclear capacity. By spring 2008, global installed windpower capacity had exceeded the United States' 100 GW of installed nuclear capacity.[132]

To be sure, per kW of capacity, a typical well-performing nuclear plant[133] produces ~2× the electric output of excellent or ~3× that of typical windpower, or ~4× that of typical solar photovoltaics, so windpower is adding electrical output only about 2–3 times faster than nuclear power. But because cogeneration and many renewables (such as geothermal, small hydro, biomass/waste-fueled generation, and solar-thermal-electric with thermal storage) produce power quite steadily, micropower as a whole has about a capacity factor of about 0.65, three-fourths of nuclear's in the United States (or a higher fraction worldwide, since most countries' nuclear plants have lower capacities than U.S. ones now do).

Moreover, micropower's output is soaring while nuclear's lesser output has nearly flatlined (Fig. 7) as its capacity stalls out. For example, the European Union during 2000–07 installed 158 GW of generating capacity (excluding some distributed resources): 88 GW gas, 47 GW wind, 9.6 GW coal, 4.2 GW oil, 3.1 GW hydro, 1.7 GW biomass, and 1.2 GW nuclear. In 2007 alone, wind added 8.5 GW to Europe's net capacity (40% of the total, exceeding gas's 8.2 GW); coal lost 0.8 GW and nuclear lost 1.2 GW.[134] In 2007, the United States added more wind capacity than it had added coal capacity in the past five years combined.

Such market success is sometimes dismissed as an artifact of subsidy. That may be partly true in Germany, which pays high "feed-in" prices for renewables that sell power to the grid—probably above any historic German nuclear subsidies but below Germany's big coal subsidies.[135] But the broad claim doesn't stand up to scrutiny. Such support is generally being phased down in Germany and in a few other countries that have used limited pump-priming variants of this system. In Spain, and in Japan (which generously subsidized early photovoltaic installations to build the #1 world PV industry), the decline is generally even faster. The United States sporadically gives windpower an inflation-adjusted Production Tax Credit with a levelized value of 0.94¢/kWh in 2007 $, but has interrupted it several times, each time crashing the nascent domestic windpower industry,[136] which therefore provides only about half of U.S.-installed turbines. Similarly misguided policies have cut U.S. photovoltaic makers' share of their domestic market

[132] J. Dorn, "Global Wind Power Capacity Reaches 100,000 Megawatts," 4 Mar 2008, www.earthpolicy.org/Indicators/Wind/2008.htm.

[133] U.S. plants have lately averaged ~90% capacity factor (E. Blake, "U.S. capacity factors: A small gain to an already large number," *Nucl. News*, pp. 27–32, May 2007, www.ans.org/pubs/magazines/nn/docs/2007-5-3.pdf), and the Nuclear Energy Institute's preliminary Apr 2008 data suggest a record 91.8% in 2007 (www.redorbit.com/news/business/1339027/record_performance_by_us_nuclear_power_industry/).

[134] European Wind Energy Association, "Wind energy leads EU power installations in 2007, but national growth is inconsistent," www.ewea.org, 4 Feb 2008.

[135] Last assessed by the European Environment Agency in 2004, when fossil fuels and nuclear power got three-fourths of all EU energy subsidies: http://reports.eea.europa.eu/technical_report_2004_1.

[136] Lapse of the credit, which Congress typically holds hostage to subsidies for nuclear and fossil-fuel-burning facilities, reduced U.S. windpower installations by 93% in 2000, 73% in 2002, and 77% in 2004—an immense disruption to orderly industrial development (www.awea.org/newsroom/releases/AWEA_Market_Release_Q4_011708.html). These dramatic drops in orders, however, do not mean windpower is uneconomic without the credit—only that investors rationally preferred projects with the credit to projects without it, given a realistic process that lapsed credits would be reinstated. That is, uncertainties about future availability of the PTC undercut planning, investment, and hence development, not just of windpower but also of its manufacturing capacity and of transmission projects vital to exploiting the biggest wind resources. The PTC is well summarized by R. Wiser, "Wind Power and the Production Tax Credit: An Overview of Research Results," LBNL/PUB-971, Lawrence Berkeley National Laboratory, 2007, http://eetd.lbl.gov/ea/ems/re-pubs.html. LBNL research suggests that longer-term renewal of the PTC may cut U.S. windpower costs by 5–15+%, whereas current short-term renewals add a capital risk premium of up to 12%.

from over half to ~8%. But robust growth in renewables continues to accelerate after, and in many countries without, significant subsidies. Nearly all subsidies to renewables, where present, are far smaller than historic or current nuclear subsidies. And neither cogeneration nor efficient end-use receives or has received subsidies of any consequence almost anywhere. A simpler and more plausible explanation for distributed resources' competitive success against nuclear power, and other central stations, is thus that they have lower costs and financial risks, as discussed above.

To illustrate how David is beating Goliath, Fig. 8, which underlies Figs. 6 and 7, compares the actual and industry-projected profiles of capacity additions by each distributed generation technology with that of nuclear power (including a thin orange dotted line for its construction starts, a leading indicator). The heavy "total" lines show that micropower's net capacity additions have lately been an order of magnitude bigger than nuclear's, and that this gap is widening. Indeed, U.S. Energy Information Administration data, which have a four-year reporting lag, show that during 2001–04, the global rate of ordering fossil-fueled power plants declined by approximately 20 GW, presumably displaced by micropower and negawatts.

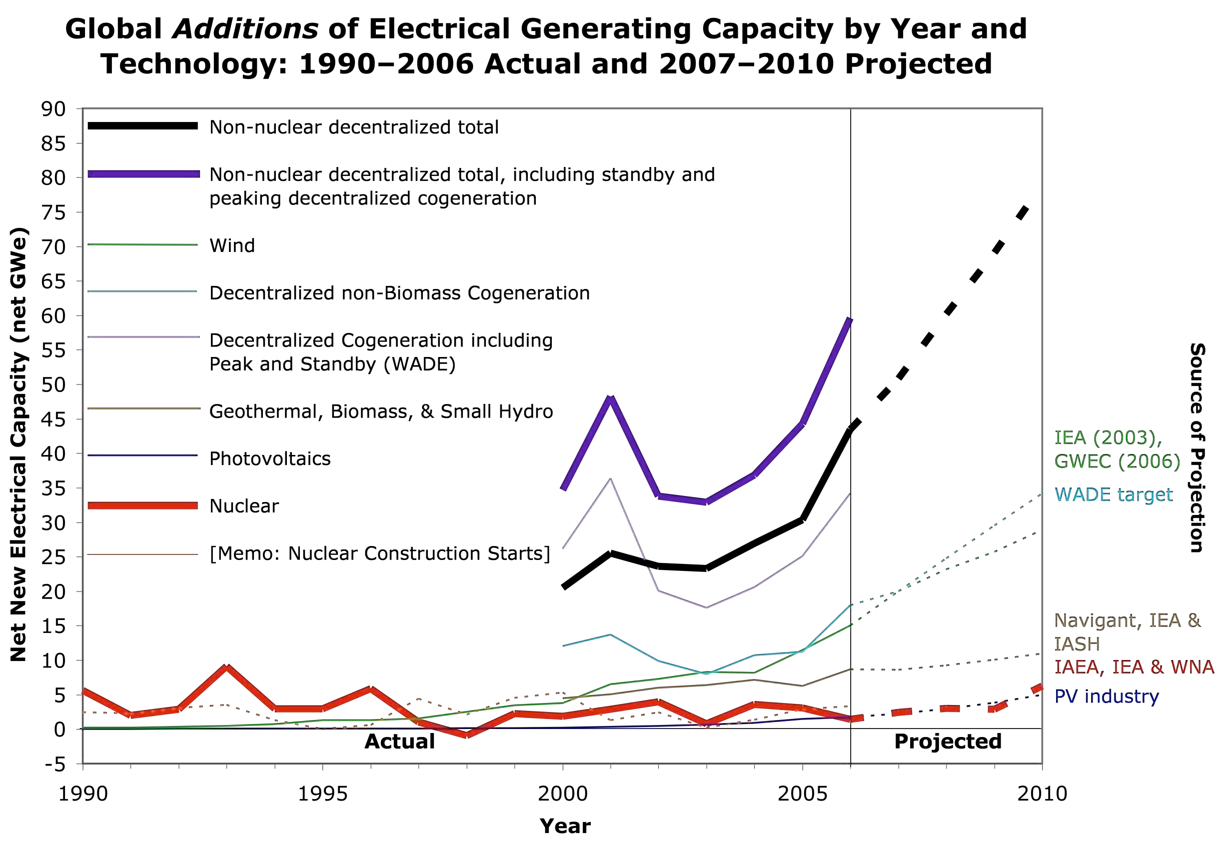

Fig. 8: Relative annual global capacity additions by nuclear power (red) vs. *its main distributed generation competitors, whose 44–58-GW combined effect in 2006 (depending on whether standby and peaking fossil-fueled units are included) is the* sum *of their individual curves. The orange dotted line is nuclear construction starts—a leading indicator—whose history suggests that the 2010 jump in nuclear completions is probably optimistic. The thin aqua cogeneration line excludes, and the thin purple line above it includes, an additional 14 GW of peaking and standby units, most of which could be made dispatchable if desired; those units weren't reported*

before 2000. All capacity changes shown are net of reported additions, retirements, and up- and downratings, though nuclear upratings are not clearly reported. Electrical savings *(negawatts) aren't shown in this graph, but their capacity effect probably rivals and may exceed that of distributed-resource additions.*

The collective power of many small, quick-to-build investments has already been amply demonstrated. For example, in 1982–85, California allowed all ways to save or produce electricity to compete on a relatively level playing field, and ran an auction for distributed supplies on terms more favorable than some thought it merited but far less favorable than terms offered to central stations by national policy. During those three years, California's utilities contracted to buy 23 GW of electric savings and 13 GW of decentralized (mainly renewable) supply and had firm offers for a further 8 GW of such generation, rising by 9 GW *per year*. These resources added up to 143% of the state's 37-GW peak load in 1984. The state's Public Utilities Commission, spooked by success, shut down the bidding in April 1985; otherwise one more year of this gold rush would have forced the shutdown of the state's entire fossil-fueled and nuclear capacity (which in hindsight might not have been such a bad idea).[137] This performance by quarter-century-old technologies (much inferior to today's) confirms the lesson, now widespread in modern energy markets, that letting everything compete fairly is likelier to yield too many attractive options than too few.

Energy efficiency offers many similar examples. In 1983–85, ten million people served by Southern California Edison Company were cutting its decade-ahead forecast of peak load by $8^1/_2$% each year, at a tiny fraction of the long-run marginal cost of supply. In 1990, New England Electric System signed up 90% of a pilot market for small-business retrofits in two months. In the same year, Pacific Gas and Electric Company (PG&E) marketers captured one-fourth of the new commercial construction market for design improvements in three months, so in 1991, PG&E raised the target—and got it all in the first nine days of January. Since these early examples, marketing improvements, delivery methods, technologies, and integrative designs that combine technologies for bigger savings at lower costs have all advanced markedly—faster than the efficiency opportunities have been used up. In 2005–06, the United States cut its electric intensity 2.6%[138] and primary energy intensity 3.4%;[139] few noticed or were really trying to save energy, and the great majority of the potential remains uncaptured and almost unknown.[140] Just in the two years ended April 2008, California utilities have saved more than 6 TWh, or nearly the annual output of a large nuclear unit.

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 rules in his California community let a neighbor's objections block his installing photovoltaics on his roof. Some powerful politicians are blocking a wind farm offshore Cape Cod. Efficiency has numerous obstacles—~60–80 market failures, each convertible to a business opportunity[141]—that leave most of it as yet unbought. But efficiency's obstacles are being overcome sufficiently to have sus-

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[137] A surprising summary of the causes of the 2000–01 California electricity crisis, even before evidence of malfeasance came to light, is at www.rmi.org/images/PDFs/Energy/E01-20_CwealthClub.pdf.
[138] This is twice the average for the past 12 years, and is not weather-adjusted.
[139] Intensity fell faster than GDP grew, so in 2006, U.S. use of total energy, oil, gas, and coal all went *down*.
[140] Lovins (2005), ref. 60.
[141] This taxonomy is at pp. 11–20 of A.B. and L.H. Lovins, *Climate: Making Sense* and *Making Money*, RMI, 1997, www.rmi.org/images/other/Climate/C97-13_ClimateMSMM.pdf.

tained an unprecedented 1.6%/y average decline in U.S. electric intensity since 1996. That was achieved despite four countervailing factors: electricity is the form of energy most heavily subsidized and most prone to split incentives, electricity is seldom priced on the margin, and electricity is sold by distributors which nearly all states reward for selling more kWh and penalize for selling fewer kWh. Customers with knowledge and capital can save much faster: *e.g.*, such firms as DuPont, IBM, and STMicroelectronics routinely cut their energy intensity by 6–8%/y.[142] 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 one-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.

What is the ultimate potential of nuclear power's new competitors?

The need for new nuclear build as part of a least-cost portfolio to meet the energy service needs of a dynamic national or global economy is often alleged, but has no analytic foundation. (Extrapolative projections that don't assess competition between modern options are sleepwalking, not analysis.) Many careful analyses published over the past few decades show the opposite;[143] one of the best was published in 1989, though not implemented, by Sweden's Vattenfall.[144] What careful analysis does consistently show is that new nuclear is so costly and slow relative to its winning competitors that it will *retard* the provision of energy services.

142 Other such examples are at www.pewclimate.org/companies_leading_the_way_belc/company_profiles/index.cfm and at www.cool-companies.org/homepage.cfm.

143 See *e.g.* references in A.B. and L.H. Lovins, "Least-Cost Climatic Stabilization," *Ann. Rev. En. Envt.* **16**:433–531 (1991), www.rmi.org/sitepages/pid171.php#E91-33.

144 In this cold, cloudy, northerly, heavily industrialized, and relatively efficient country, Vattenfall found that half of electricity could be saved at 78% lower cost than making more. Combining that doubled end-use efficiency with some fuel-switching and environmental dispatch (operating most the plants that emit the least carbon) could achieve the forecast 1987–2010 GDP growth of 54%, complete the 100% nuclear shutdown earlier demanded by voters, reduce the heat-and-power sector's CO_2 emissions by one-third, and cut the cost of electrical services by $1 billion per year (B. Bodlund *et al.*, "The Challenge of Choices," in T.B. Johansson *et al.*, *Electricity*, Lund University Press, 1989). Vattenfall's then CEO ordered removed from the report the usual disclaimer that the findings didn't represent official Vattenfall policy. Yet this sound and lucid analysis, published mainly in English, remained so little-known that the Parliamentary energy committee I briefed several years later had never heard of it. Nuclear interests successfully suppressed the report and its implementation; yet its analysis remains valid, especially in light of the current practice of cost-effectively superinsulating both new and retrofit homes in Sweden so they no longer require heat (ref. 111). Sweden, like France, promoted electric heat in order to soak up its excess nuclear capacity, leading to unimpressive overall thermal efficiency in a country that had once led the world (with Denmark) in building thermal efficiencies. But building efficiencies generally stagnated in the 1990s (J. Nässén and J. Holmberg, *En. Pol.* **33**(8):1037–1051 [May 2005]). Of course, if the 1989 Vattenfall report were updated in the same spirit, rather than to echo current pronuclear policy, it would find even more and cheaper efficiency and renewables potential, due to major technical advances meanwhile. Unfortunately, Sweden's new government, in Jan 2008, lowered its renewable electricity target for 2020 from 55% (*vs.* today's 40%) to 49%, allegedly to encourage other EU countries to do more. Leadership has shifted to Germany, which has 12% (with a quarter-million jobs) and targets 40% by 2020, along with dramatic efficiency gains. Windpower alone in 2007 was a $36b global industry employing ~200,000 people (ref. 95).

Consider China, which at the end of 2007 got 2% of its electricity from 11 nuclear plants (8.6 GW) and had by far the world's most ambitious nuclear target—40 GW by 2020, exceeding China's 2020 windpower goal of 30 GW.[145] Nuclear construction, currently five units totaling 3.3 GW, seems threefold slower than this schedule would require, but if successful, the 40 GW could offset one-tenth of the world's plausible retirements of reactors meanwhile passing age 40.[146]

Yet China's impressive and widely heralded nuclear ambitions have been far eclipsed by its little-noticed world leadership in distributed renewables. By the end of 2006, *China had already installed 49 GW of distributed renewables* (excluding an additional 37 GW of big hydro).[147] *That's 7× its nuclear capacity, growing 7× faster*. While China's nuclear expansion falters, partly due to escalating construction costs,[148] its renewable expansion is rapidly accelerating. In 2007, windpower alone grew 3.4 GW (156% more than in 2006) to 6 GW, exceeding the 5-GW target for 2010. China's renewable industries stated in November 2007 that by 2020, 50 GW of windpower is likely under current policies, and with a supportive policy environment, 122 GW would be feasible—5× the Three Gorges Dam's capacity, 4× the 2020 windpower target, or 3× the 2020 nuclear target.[149] China's vibrant windpower sector now includes more than 50 firms, 56% of its 2007 installations were domestically produced, and it's starting to exploit world-class wind resources.[150] China's installed wind capacity doubled in 2006 alone, and in that year, China was the world's second biggest investor in renewable power investor, the world's third biggest photovoltaic producer, and the world's fifth largest windpower installer, rising quickly in all categories. In 2007, China's wind capacity grew another 156%; it has more than doubled in each year since 2004, surpassing even the most optimistic projections.

In September 2007, the chair of China's National Development and Reform Commission announced an increase of planned renewable energy investments to RMB 2 trillion ($265 billion). China also plans 200 GW of cogeneration and 328 GW of total hydropower by 2020,[151] plus rapid energy efficiency gains sufficient to cap energy use at twice the 2000 level while GDP quadruples to 2020. Meanwhile, China's power market is becoming more competitive and its polity more transparent; both trends bode ill for the Treasury-financed state nuclear monopoly.

There's another competitor too: reduced energy intensity. For a quarter-century, China saved energy faster than any other country, lowering its slope of energy growth by 70% during 1980–2001. That progress was checked and slightly reversed by a 2002–06 surge in energy-

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[145] E. Martinot and Li Junfeng, "Powering China's Development," Worldwatch Special Report, Nov 2007, www.worldwatch.org/node/5491. The World Nuclear Association reports a further 2030 nuclear target of 160 GW.
[146] *World Nuclear Industry Status Report 2007*, *op. cit. supra*, reports the International Energy Agency's skepticism of China's 40-GW-by-2020 nuclear target. India, with 3.8 GW (2.6% of electrical supply, less than half of installed windpower capacity of >8 GW by the end of 2007), has a similarly implausible 2025 nuclear target of 40 GW and a similarly fast-growing windpower and other renewables sector, plus fractious politics and nonproliferation issues.
[147] E. Martinot *et al.*, www.ren21.net, ref. 114.
[148] Reported for nuclear but not for coal plants in Guangdong: see ref. 198.
[149] Chinese Renewable Energy Industries Association, *China Wind Power Report 2007*, 1 Nov 2007, www.gwec.net/uploads/media/wind-power-report.pdf. CREIA also estimates 500–600 GW of Chinese wind (equivalent to 300 GW of coal power) as feasible by 2040–2050.
[150] China's official estimate of windpower potential at 250 GW onshore plus 750 GW offshore is at only 10-m hub height. Windspeed increases with height, and extractable power rises as the cube of windspeed. UNEP estimates a 3× higher (3-TW) total potential at the newer but still suboptimal 50-m hub height (Martinot and Li, ref. 145).
[151] M. Mei, J. Zhu, and S. Du, CS China, "Clean and Renewable Energy in China," www.export.gov/china/trade_events/EE_Presentation1_CSBeijing.ppt; "Chinese Clean Energy Development to Beat Targets," New Energy Finance (London), 18 Sept 2006, www.gwec.net/uploads/media/wind-power-report.pdf.

intensive materials production,[152] now being reversed. But in 2005, reducing energy intensity, especially for electricity, became China's top strategic priority in the Eleventh Five-Year Plan. In 2007, a new Energy Conservation Law and a flurry of enforcing regulations supported this goal. A January 2008 decree specifies rewards for top provincial officials who meet, and punishments for those who miss, their targets to cut energy intensity; failure brings not only personal perdition but also prohibitions on new energy-intensive facilities in the offending jurisdiction.[153]

All China's new nuclear plants are commanded and funded by Beijing, while two-thirds of the new coal plants are "bootleg" units not authorized by Beijing. All are meant to meet burgeoning electricity demand that negawatts will increasingly soften and distributed sources will meet. That demand growth is driven largely by construction of inefficient buildings and factories made from inefficiently produced materials; half the demand growth is due to largely wasted air conditioning and refrigeration. And since Beijing still holds many economic levers, it's easier to take a big bite out of demand than in the even more unruly U.S. economy, where most infrastructure is already built. In principle, a fast-growing economy can reduce its intensity even faster than its service demands rise: even the severalfold-more-efficient United States did so in 2005–2006, *reducing* its absolute use of coal, oil, gas, and total energy. China's top priority on energy efficiency reflects its leaders' understanding that unless efficiency is the foundation of growth, supply-side investments will eat the capital budget and starve end-use investments.

On 24 January 2008, the European Union announced a climate strategy aiming by 2020 to slash CO_2 emissions to 20% below the 1990 level, raise energy efficiency 20%, and get 20% of its primary energy from renewables (now 8.5%), displacing ~€50 billion of annual oil and gas costs.[154] The United States has less coherent policies but comparable or greater energy efficiency opportunities and huge micropower potential:

- Rocky Mountain Institute has calculated the U.S. technical potential to save electricity at ~75%—4× the 19% nuclear share of power generation—at an average cost ~1¢/kWh, less than nuclear *operating* cost. The utility industry's think tank, the Electric Power Research Institute, estimated negawatts' potential at only 2–3× nuclear's market share, at an average cost ~3¢/kWh (even less today)[155]—less than one-fourth of new nuclear's delivered cost (Fig. 1).

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[152] D.H. Rosen and T. Houser, "China Energy: A Guide for the Perplexed," May 2007, China Balance Sheet (Center for Strategic and International Studies/Peterson Institute for International Economics). See also A.B. Lovins's preface to the forthcoming (~Nov 2008) Tsinghua University Press edition of *Winning the Oil Endgame*, preposted in English at www.rmi.org/images/PDFs/Energy/ChiEdnPrefaceDr4final.doc.

[153] National Development and Reform Commission (Beijing), "Energy Consumption per Unit of GDP Performance Evaluating System," www.gov.cn/gongbao/content/2008/content_848836.htm.

[154] L. Centrowicz, "EU Aims to Choke Carbon Emissions, *Time*, 24 Jan 2008, www.time.com/time/world/article/0,8599,1706123,00.html?xid=feed-cnn-topics; the EC's press release is at http://europa.eu/rapid/pressReleasesAction.do?reference=IP/08/80&format=HTML&aged=0&language=EN&guiLanguage=fr. Some biofuels provisions are controversial.

[155] RMI's estimate is based on a detailed supply curve reflecting measured cost and performance data for ~1,000 technologies, documented in 1986–92 in the first-edition RMI/COMPETITEK *State of the Art* series (6 vols., 2,509 pp., 5,135 notes) later summarized in E SOURCE's *Technology Atlas* series in the *Electronic Encyclopedia* (www.esource.com). EPRI's estimate is in *Efficient Electricity Use: Estimates of Maximum Energy Savings*, CU-6746, 1990, summarized in A.P. Fickett, C.W. Gellings, and 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, nor a further 6.5% likely to be saved by utilities' planned efficiency programs. The

- The U.S. industrial cogeneration potential is at least comparable to current U.S. nuclear capacity, excluding cogeneration potential in buildings, which use two-thirds of electricity.[156]
- The U.S. windpower potential on available land is more than twice the entire U.S. annual use of electricity[157] (and likewise in China—the British figure is ~6×): worldwide, the global windpower potential onshore and nearshore, without land-use exclusions, is ~35× global electricity demand.[158]

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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, ref. 143, 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 (see also A.B. Lovins, "Apples, Oranges, and Horned Toads," *El. J.* **7**(4):29–49 (1994), available through www.sciencedirect/com or as RMI Publ. #U94-16). Normalizing for these non-substantive differences makes the RMI and EPRI supply 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, and that negawatts are getting bigger and cheaper.

[156] O. Bailey and E. Worrell, "Clean Energy Technologies: A Preliminary Inventory of the Potential for Electricity Generation," LBNL-57451, Apr 2005, http://repositories.cdlib.org/lbnl/LBNL-57451/.

[157] D.L. Elliott, L.L. Wendell, and 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 55% of total U.S. 2006 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 and 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. How important, then, are land-use exclusions? 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; the main obstacle is limited access to transmission lines, which incumbent utilities sit on to protect themselves from competition. 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). It also appears that siting options are far more constrained for new nuclear plants (by cooling water, seismicity, population, security, etc.) than for new windpower in high-wind zones.

[158] C.L. Archer and M.Z. Jacobson, "Evaluation of global windpower," calculated at 80 m hub height, www.stanford.edu/group/efmh/winds/global_winds.html. Class ≥3 sites, normally economic, could yield ~72 TWe. Contrary to the widespread impression that the best lower-49-states wind areas are only in the Great Plains, offshore East Coast, and certain West Coast sites, the Great Lakes wind resource, conveniently near upper Midwest load centers, is also Class 6±1. The underlying data are in *J. Geophys. Res.* **110** (2005), D12110, doi:10.1029/2004JD005462, www.stanford.edu/group/efmh/winds/2004jd005462.pdf. The global windpower potential will become far larger even just on land if tethered high-altitude wind-turbine R&D projects succeed.

Empirical results carefully evaluated for hundreds of utility and business programs validate the practical potential for saving electricity:

- 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;[159] the U.S. historic average is ~2¢/kWh. In striking contrast, many programs targeting commercial and industrial savings cost much less, and the best ones cost far less than 1¢/kWh.[160]
- Negawatt program costs tend to decline with experience, as shown by evaluations for the three California investor-owned utilities[161] and the aggregate of the 79 Pacific Northwest utilities evaluated by the Northwest Power Planning Council.[162] California has generally mild climates, high building and appliance efficiency standards, and a long history of world-class demand-side management efforts, so other places lacking those attributes should tend to have bigger potential at lower costs.

Very detailed bottom-up analyses for Danish buildings[163] and for all electricity uses in Sweden[164] and the United States,[165] and EPRI's moderately detailed estimate of U.S. potential sav-

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[159] For example, the Western Governors' Association found in 2005 that typical total costs ~2–3¢/kWh, and that leading programs were achieving savings ~0.8–1%/y (~2%/y in California): Energy Efficiency Task Force, www.westgov.org/wga/initiatives/cdeac/Energy%20Efficiency-full.pdf.

[160] *E.g.*, S. Nadel, *Lessons Learned: A Review of Utility Experience with Conservation and Load Management Programs for Commercial and Industrial Customers*, NYSERDA 90-8, NYSERDA (Albany), 1990. Consistent with this, the 1–2-y average paybacks commonly observed from retrofits in U.S. heavy industry correspond to a levelized cost of 0.4–0.8¢/kWh at a typical 5¢/kWh tariff and a 5%/y real discount rate.

[161] C. Rogers, M. Messenger, and 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 and 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.

[162] 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. A graphical time-series summary of these and other empirical and analytic findings on the cost of negawatts is in Lovins, ref. 61.

[163] 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, and R.H. Williams, eds., *Electricity: Efficient End Use and New Generation Technologies and Their Planning Implications* (Lund U. Press, 1989).

[164] 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.

[165] 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 source notes, 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 Lovins (ref. 143), referencing similar sectoral findings by other analysts. The RMI analyses excluded fuel-switching lifestyle changes, load management, technologi-

ings,[166] show very large technical-potential savings (~40–75+%) at total societal costs similar to or below today's broad-based utility program costs. But these studies used 1980s technologies that generally cost more and saved less than today's. Moreover, 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[167] and some retrofits.[168]

Thus full U.S. deployment of just three winning competitors—recovered-waste-heat cogeneration (conservatively excluding all cogeneration that uses fresh fuel), windpower, and end-use efficiency—could provide ~13–15× nuclear power's current 19% share of U.S. electric generation, all without significant land-use, reliability, or other constraints, and with considerable gains in employment.[169]

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cal 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.

[166] EPRI, *Efficient Electricity Use: Estimates of Maximum Energy Savings*, CU-6746, 1990, summarized in A.P. Fickett, C.W. Gellings, and 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 an additional 8.6% expected to occur spontaneously by then, 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 ref. 143, 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.

[167] See *e.g.* P.G. Hawken, A.B. Lovins, and 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 Lovins (2005), ref. 60. 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.* **7**(4):29–49 1995).

[168] 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.

[169] Observed employment intensity in the United States and Europe, per unit of electricity produced, is typically much larger for renewables than for coal- or gas-fired plants, including all construction and fuel cycles: D. Kammen, "Green Jobs Created by Global Warming Initiatives," testimony to U.S. Senate Committee on Environment and Public Works, 25 Sept 2007, http://rael.berkeley.edu/files/2007/kammen_senate_epw-9-26.pdf.

Renewables other than windpower, not yet counted, also have immense potential.[170] Solar technologies aren't resource-limited nor even, in practice, area-limited. For example, on conservative assumptions, just a 100×100-mile area of Nevada—less than one-fourth the nation's paved road and street area—containing 10%-efficient photovoltaics in half its area could annually produce as much electricity as the United States uses.[171] In practice, of course, PVs would be building-integrated, rooftop-mounted, and built into parking-lot shades, alongside highways, etc. to avoid marginal land-use and to produce the power near the load,[172] and PVs would be complemented by other renewable sources (wind, geothermal, small hydro, etc.).[173]

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. And 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.[174]

All these options avoid paying a premium for nuclear power's siting, fuel, and manufacturing constraints; its proliferation, accident, terrorism,[175] waste, and political risks; and its inherent unsuitability for the distributed service needs of billions of people in developing countries, few of which even have an electric grid large enough to accommodate a modern nuclear plant. For the two billion people with no electricity, and generally with no wires and no money, waiting

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[170] Including resources often overlooked: for example, Federal assessments indicate ocean-energy potential of 560 TWh/y offshore the lower 48 states plus 1,250 offshore Alaska and 300 offshore northern Hawai'i. This total of 2,060 TWh/y is 74% of 2006 global and 2.6× 2006 U.S. nuclear electricity output.

[171] J.A. Turner (NREL), "A realizable renewable energy future," *Science* **285**:687-689 (1999). The most efficient solar cells in the laboratory now exceed 37%, with major further improvements underway.

[172] 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.

[173] 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. Interestingly, R.H. Williams (Princeton U.) and the author have separately calculated that a gram of silicon produces more lifetime electricity in amorphous solar cells than a gram of uranium in a light-water reactor. For the energy consumption to produce photovoltaics (another area rife with old fallacies), see V.M. Fthenakis, H.C. Kim, and E. Alsema, "Emissions from Photovoltaic Life Cycles," *Envir. Sci. & Technol.* **42**(6):2168–2174 (1998), http://pubs.acs.org/cgi-bin/abstract.cgi/esthag/2008/42/i06/abs/es071763q.html.

[174] A.B. and L.H. Lovins, F. Krause, and 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 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.

[175] *E.g.*, F.N. von Hippel, "Revisiting Nuclear Power Plant Safety," *Science* **291**:201 (2003); A.B. and 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. However, forced-entry attacks are also of concern: in nearly half of U.S. 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), so the NRC has shut off discussion of this problem.

for the grid is too costly and too slow; efficient use and distributed renewables such as solar cells are the only practical, affordable, and prompt solutions. These are highly successful where deployed, *e.g.* in Kenya, the world leader in installations per capita: nearly twice as many Kenyans "adopt solar power each year [as] make connections to the country's electric grid."[176]

Negawatts are an extraordinarily potent macroeconomic lever for global development, too, because saving electricity requires far less capital than expanding its conventional supply,[177] and the power sector is the world's most capital-intensive, gobbling about one-fourth of global development capital. Even the wealthy United States can't afford to squander such capital—China and India, far less.

In short, a world that is carbon-constrained but needs more electrical services has a large, diverse, and expanding menu of options. Choosing among them requires a balanced portfolio fitting appetite and wallet. The successful alternatives to nuclear are cheaper, bigger, and faster, so rational market choices of what to buy next won't favor a nuclear plant over a competitor with similar or better climate impacts, no matter if or how carbon is priced or what politicians prefer.

Historically, featuring and favoring nuclear power in national energy policy has ultimately harmed its progress by weakening market discipline and suppressing legitimate regulatory concerns, leading to failed projects and unpleasant accidents. But such policies' greatest damage is typically to competing technologies. "Pursuing all plausible paths," says one of the most seasoned observers, "costs too much, and some activities are inconsistent with others. *The builder of a 1500-MW nuclear plant must oppose efficiency investments sufficient to reduce the price for the plant's output*."[178] This point pithily encapsulates the futility of trying to do everything at once regardless of relative costs. Any firm that has just built a nuclear plant will do its utmost to sell every kWh it can, not only suppressing efficiency efforts but also promoting wasteful end-uses like electric-resistance space heating (which uses, for example, about half the nuclear output of otherwise-efficient Sweden).[179]

Advocates often plead for "retaining the nuclear option" rather than "abandoning" or "closing off" new nuclear build. But "keeping the nuclear option open" doesn't mean benign neglect or mere tolerance of free-market investments. Rather, it means, and has always meant, massive government intervention—ever-larger subsidies and other advantages to try to sustain or revive an industry dying of an incurable attack of market forces. Inevitably, such largesse comes at competitors' expense in funds, attention, markets, and—most precious—time. In the United States, that opportunity cost is now reaching a critical stage as the industry, still unable to attract private investors, desperately seeks ever-greater public funding.

Increasing market distortions

The simplest scorecard for a nuclear revival is how private investors vote with their dollars. Just distributed renewables (with no cogeneration or negawatts) attracted $56 billion of pri-

[176] D. Kammen, "The Rise of Renewable Energy," *Sci. Amer.*, pp. 84–93, Sept 2006, http://rael.berkeley.edu/files/2006/Kammen-SciAm-Renewables-9-06.pdf; see also http://lightingbop.blogspot.com/2007/02/photovoltaic-systems-in-kenya.html.

[177] By about 10,000×—intensity times velocity—if efficiency means a compact-fluorescent-lamp factory and a low-emissivity window-coating factory: A.B. Lovins and A. Gadgil, "The Negawatt Revolution: Electric Efficiency and Asian Development, RMI Publ. #E91-23, www.rmi.org/images/PDFs/Energy/E91-23_NegawattRevolution.pdf.

[178] Bradford, refs. 9 and 194, emphasis added.

[179] Nässén and Holmberg, ref. 144).

vate risk capital in 2006 and $71 billion in 2007,[180] growing by tens of percent per year even in a soft economy. New nuclear power, as usual, got zero private risk capital from the market: it's bought only by central planners[181] drawing ever more heavily on the public purse. Focusing its immense political power—most major countries' electricity policy has for decades been dominated by nuclear interests—the nuclear industry is trying to stem its reverses and turn its fictitious revival into reality by shifting ever more of its costs from reluctant investors and customers to unwitting, inattentive, or powerless taxpayers, as recent U.S. history illustrates.[182]

Longstanding pre-2005 U.S. Federal nuclear subsidies totaling ~0.9–4.6¢/kWh[183] have elicited no nuclear orders since 1973. In 2005, the Chairman of Dominion, an applicant for early nuclear site approval, told *The New York Times*, "We aren't going to build a nuclear plant anytime soon. Stanford & Poor's and Moody's would have a heart attack. And my chief financial officer would, too."[184] Chairman John Rowe at Exelon, the nation's largest nuclear operator, ex-

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[180] Bottom-up, transaction-by-transaction data compiled by Michael Liebreich, New Energy Finance, London (www.newenergyfinance.com), found 2006 new investments totaling $31 billion in windpower, $12 billion in solar power, $8 billion in biomass- and waste-fueled electricity, and $3 billion in other distributed renewable electricity, for a total of $56 billion (*vs*. ~$38b in 2005). In 2007, despite the global credit crunch, new investment in clean energy worldwide soared to $148 billion (19% of global energy infrastructure investment), of which $**TK**b, including $50b in windpower and $29b in solar power, for was non-fossil-fuel, non-nuclear electric generating projects and R&D.

[181] Of a national economy or, as in France, Japan, and South Korea, of the electricity system.

[182] Some other countries have taken a different approach. Électricité de France, for example, asserts that new nuclear plants are competitive without subsidy, though the only recent order (Flamanville-3) for its already over-nuclearized system—an effort to keep the industry alive and offset lost reprocessing revenues to the same locality (ref. 4)—was proposed to cost €3.3 billion (2005 €) for 1.6 GWe per ÉdF's 4 May 2006 press release. At the Jan 2008 exchange rate but without escalation nor, apparently, ~20% owner's costs (per Keystone's n. 29), that's ~$2,700/kW ("EDF orders Flamanville-3 EPR NSSS, with startup targeted in 2012," *Nucleonics Week*, 26 Jan 2008). This identical plant to the underbid Finnish project is thus projected to cost 25% more, with no fixed-price contract, and to take a half-year longer to build. France's longstanding approach instead is to hide nuclear subsidies—for plants, their fuel cycle, and electricity transactions—inside opaque accounting that flouts EU transparency requirements. Britain, like France, has repeatedly bailed out its nuclear industry, and puts formidable policy obstacles in the path of competitive alternatives, notably windpower. (For example, UK nuclear plants enjoy old socialized transmission lines, but wind developers needing new lines must build their own, and multiple developers sharing lines are made jointly and severally liable for their cost—an odd policy that has made financing nearly impossible.) UK land-use procedures are also fertile ground for local windpower siting objections, two-thirds of which the top UK nuclear advocate, Sir Bernard Ingham (former Press Secretary to Prime Minster Thatcher, then Vice President of the anti-windpower lobby Country Guardian), has claimed to have personally fomented (P. Toynbee, *Guardian*, 23 Aug 2003; see also G. Lean, "Wind power flop blamed on Sir Bernard Ingham," *Independent* (London), 6 Dec 1998, http://findarticles.com/p/articles/mi_qn4158/is_19981206/ai_n14203681). And nearly all EU countries flout the "polluter pays" principle in collecting and managing funds for nuclear decommissioning, with the UK reportedly having made provision for only ~1% of its ~€100 billion liability ("EC's decommissioning principles broadly flouted, report finds," *Nucleonics Week*, 3 Jan 2008).

[183] 2003 estimate by D. Koplow (the most careful independent student of this complex subject), "Reforming Subsidies in the U.S. Energy Sector," OECD Workshop on Subsidy Reform and Sustainable Development: Political Economy Aspects" (Helsinki, 21–21 June 2006), www.oecd.org/dataoecd/45/33/36943302.pdf. That summary estimates total 2003 U.S. energy subsidies at $37–64 billion per year, increased by $90–120 billion over ten years by the Energy Policy Act (EPACT) of 2005. (Koplow's www.earthtrack.net is the authoritative energy-subsidy clearinghouse for both the United States and other countries.) Oxford's Dr. Norman Myers estimates global perverse subsidies at >$1T/y.

[184] M. Wald, "Interest in Building Reactors, but Industry Is Still Cautious," 2 May 2005, www.nytimes.com/2005/05/02/politics/02nuke.html.

pressed similar skepticism.[185] Desperate for orders, in 2005 the moribund U.S. nuclear industry sought additional federal subsidies, allegedly for just a few "first mover" plants to restart itself. It got its subsidies raised to ~4.6–8.9¢/kWh—*i.e.*, ~60–90% of the projected levelized total cost of new nuclear electricity.[186] These new 2005 subsidies included up to $4 billion in 100% loan guarantees for up to 80% of project cost for 30 years,[187] and offered the first 6 GWe of new nuclear units an eight-year 1.8¢/kWh tax credit plus limited insurance against legal or regulatory delays.

The U.S. Department of Energy's strict draft rules weren't to the industry's liking,[188] though, and the market wasn't thrilled either. Standard & Poor's predicted that these new subsidies wouldn't materially raise builders' credit ratings, because most of the risks that concerned the capital markets remained.[189] On 9 January 2006, S&P reiterated that resurgent interest and government encouragement "may not be enough to mitigate the risks associated with operating issues and high capital costs that could hinder credit quality….[The new 2005 subsidies] may not be substantial enough to sustain credit quality and make [new construction] a practical strategy."[190] A year later, S&P repeated its concerns about new nuclear plants' high construction and operational financial risks, concluding: "Standard & Poor's does not anticipate construction of new [U.S.] plants to start in the next few years….[T]he challenges…will be significant." New nuclear construction, S&P concluded, "can be extremely risky," a "daunting proposition," and with operating risk "inherently" higher than average.[191]

In April 2007, the industry asked that Federal coverage of nuclear loan guarantees be raised from 80% to 100% to stimulate orders, and said even the 90% guarantee requested by the Department of Energy "will probably not be workable."[192] A month later, DOE obligingly raised its guarantee to 90% of proposed 80%-debt financings (several times the leverage of merchant projects), *i.e.*, to ~72% of total investment; but Wall Street was still unwilling to put its money where the industry's mouth is.

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[185] Exelon is still often claimed to be about to order a new nuclear plant, and has also sought an advance site license (a relatively cheap way of keeping options open), but in a panel at the ACEE Energy Efficiency Finance Forum, 12 Apr 2007, Chairman Rowe confirmed that within his firm, "nobody I would trust with a capital budget" could give him a plausible case that a new nuclear plant would be economically competitive.

[186] D. Koplow, "Nuclear Power in the U.S.: Still Not Viable Without Subsidy," NPRI Symposium, Nov 2005, www.earthtrack.net/earthtrack/library/NuclearSubsidies2005_NPRI.ppt.

[187] *Id*.

[188] Under DOE's Aug 2006 guidelines, the $4-billion loan guarantees subordinated private to Federal debt and couldn't be stripped out and resold—reducing the debt rating, one banker reckoned, from potentially AAA to "single B or double D" ("DOE's Loan Guarantee Proposal Raises Questions About Viability," *Nucleonics Week*, 17 May 2007, http://construction.ecnext.com/coms2/summary_0249-243519_ITM_platts). DOE later abandoned this position (*infra*) under intense lobbying pressure. Some points still remain unclear, such as whether an expiring eight-year Production Tax Credit could be reassigned to a new nuclear plant and continued (ref. 186).

[189] *Nucl. Eng. Intl.* News, "Energy Policy Act 2005 has limited credit implications: S&P," 18 Aug 2005, www.neimagazine.com/story.asp?sc=2030540&ac=7969460. Among these risks is the one former USNRC member and NARUC President Peter Bradford noted: "The abiding lesson that Three Mile Island taught Wall Street was that a group of NRC-licensed reactor operators, as good as any others, could turn a $2-billion asset into a $1-billion cleanup job in about 90 minutes." Quoted by Wald, ref. 184; see also ref. 191 *infra*.

[190] J. Kennedy and A. Zsiga, "Credit Aspects of North American and European Nuclear Power," S&P Research.

[191] D. Nikas, "Why U.S. Utilities Are Seeing Nuclear Power In A New Light," S&P Corporates, 9 Jan 2007, summarized in *Nucleonics Week*, 11 Jan 2007, "S&P continues to see construction of new nuclear as being risky."

[192] K. Bogardus, "Nuclear power, banks link up in bed to get better financing," *The Executive*, 24 May 2007, http://thehill.com/the-executive/nuclear-power-banks-link-up-in-bid-to-get-better-financing-2007-05-24.html.

On 2 July 2007, six top investment firms standing to profit from nuclear financings wrote to DOE:[193]

> We believe many new nuclear construction projects will have difficulty accessing the capital markets during construction and initial operation without the support of a federal government loan guarantee. Lenders and investors in the fixed income markets will be acutely concerned about a number of regulatory and litigation-related risks that are unique to nuclear power, including the possibility of delays in commercial operations of a completed plant or "another Shoreham."[194] We believe these risks, combined with the higher capital costs and longer construction schedules of nuclear plants as compared to other generation facilities, will make lenders unwilling at present to extend long-term credit to such projects in a form that would be commercially viable.

They concluded that 100%-guaranteed debt was one of the "minimum conditions necessary to secure project financing from lenders and from investors in the fixed income markets"—*i.e.*, those investors were unwilling to assume any of the risk. Responding to this pressure, DOE's final rule in October abandoned all previous restrictions. It raised the loan guarantee ceiling to 100% of 80%-debt financings, made the guarantee strippable and resalable if it didn't exceed 90% of the loan, and even suggested that DOE might volunteer to give up defaulted Federal debt's priority over commercial debt.[195] But by then, rapid escalation of nuclear costs made the 2005 law's $4-billion loan-guarantee total, to be shared with other carbon-free energy projects, insufficient for even a single nuclear plant.[196] DOE also still required borrowers have a "significant equity stake" in the project (whatever that might mean). Wall Street remained unimpressed even with the 100%-guaranteed debt prospect, let alone the equity.

Meanwhile, in July 2007, Senator Domenici (R-NM) had buried in the Senate Energy Bill an undebated sentence, opposed by the Administration's Office of Management and Budget, that would let the Secretary of Energy issue *unlimited* loan guarantees for "clean" power generation, which under 1995 legislation would include nuclear power. A *New York Times* page-one story drew attention to this little-noticed provision.[197] Ultimately the bill failed to gain House concurrence. But strong industry pressure continued because, as Constellation's CEO told the *Times*, "Without [bigger] loan guarantees, we will not build nuclear power plants….[C]ost overruns are highly probable." In May 2007, the President of UniStar Nuclear (a Constellation Energy/Areva/Bechtel venture) is reported by *Nucleonics Week* to have said that "a nuclear plant can be financed in the United States only if the government provides a sufficient level of loan guarantees to allow utilities to 'shed the risk' of the first few units."[198]

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193 Citigroup, Credit Suisse, Goldman Sachs, Lehman Brothers, Merrill Lynch, and Morgan Stanley, "Loan Guarantees for Advanced Nuclear Energy Facilities," 2 July 2007, www.lgprogram.energy.gov/nopr-comments/comment29.pdf. This group, perhaps with an eye to upcoming elections, also expressed concern that loan guarantees be irrevocable and unconditional, lest a future administration not pay up (see *Nucleonics Week*, ref. 199).

194 Peter Bradford (www.thebulletin.org/roundtable/nuclear-power-climate-change/), former Chairman of the NY Public Service Commission, calls this "a praiseworthy sentiment of mystifying relevance, since bondholders didn't lose a penny over Shoreham, and loan guarantees wouldn't have made a difference to any aspect of that project."

195 See www.lgprogram.energy.gov/ for details, stakeholder comments, and DOE responses, and www.eesi.org/briefings/2007/Energy%20&%20Climate/10-30-07_loan_guarantees/Nuclear_LGP_Issue_Brief_2007.pdf for a cogent brief on the loan-guarantee history and issues.

196 S. Winn (Exec. VP, NRG), testimony to LPG public meeting, DOE, 15 June 2007, www.lgprogram.energy.gov/061507-TPH.pdf, at pp. 19–20.

197 E.L. Andrews and M.L. Wald, "Energy Bill Aids Expansion of Atomic Power," 31 July 2007.

198 "Nuclear 'renaissance' could falter if costs rise, Icapp meeting told," *Nucleonics Week*, 24 May 2007.

Private investors concurred, so in December 2007, Congress tucked into a ~3,500-page omnibus spending bill[199] an additional $18.5 billion of loan guarantees,[200] plus $2 billion for a uranium enrichment venture that the private sector had refused to finance. Abandoning its initial pretext of pump-priming for just a handful of early plants, the industry continues today to push for this $18.5 billion to be raised to at least $50 billion before President Bush's term ends. Taxpayers would thus bear nearly all of the risks that the private capital market rejects.[201]

Just the 2007 *increases* in U.S. nuclear subsidies are comparable to new plants' *total capital costs*: the new 2007 loan guarantees alone are worth *$13 billion for a single plant*, or an additional 4.3¢/kWh, bringing the total Federal subsidy to 1.6–2.3× private investment.[202] Indeed, under some scenarios, public subsidies on offer to a new U.S. nuclear plant could now exceed its entire levelized electricity cost.[203] Yet the ante keeps rising, and the quest for market credibility is evidently growing more difficult, not less: Constellation said in June 2007 that the loan guarantees should be "temporary," meaning that "by the time the 5th nuclear plant (of each technology) has operated for five years, the market will have achieved the necessary level of comfort for the program to terminate."[204] That would be well into the 2020s at best, implying loan guarantees well north of $100 billion.

One would expect the promoters of an allegedly robust and mature technology to risk more of their own assets on the veracity of their claims. These enterprises are certainly big

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[199] This now-common substitute for more normal and transparent legislative processes emerges from a conference committee that tends to add new language, not reconcile disparate versions. Of course legislators have no time to read such a gigantic bill before voting, so mischievous language is often slipped in by unknown authors, then discovered, after approval, only when lobbyists brag about their achievements. In this instance, the loan guarantees were moved from the actual legislation into an accompanying report, which lacks the force of law; the effects of this odd procedure are unclear ("DOE gets congressional approval for nuclear energy loan guarantees," *Nucleonics Week*, 20 Dec 2007).

[200] See pp. 121–122 at www.rules.house.gov/110/rept/110_omnirpt.pdf: funds can be disbursed by the Secretary of Energy 45 days after submission of an implementation plan to the Committees on Appropriations, but apparently without obtaining their further approval.

[201] Benefiting project developers would pay a fee to "insure" against the risk that the loan guarantee would be called, but the nuclear-friendly Department of Energy, not private insurance firms, would set the premia and can be expected to undercollect, sticking future taxpayers with the deficit. If history is any guide, these loan guarantees will go sour, just as about three-fourths of earlier ones reportedly did ("Loan guarantee costs still unclear, former DOE general counsel says," *Nucleonics Week*, 22 Nov 2007). Ten of 14 similar guarantees were called in the Carter years, including one synfuel plant that cost taxpayers $13 billion. DOE's Inspector-General found "significant risk" in the new loan guarantees, and the Congressional Budget Office estimated the default risk at 30–50%. (in 2003, CBO had estimated a "very high—well above 50 percent" risk of default: http://energy.senate.gov/legislation/energybill2003/s14.pdf, p. 11.) CBO, OMB, and GAO all fear the government will be underpaid: http://article.nationalreview.com/?q=YWM5ZWQxYjdiZDQ2YjE4OTEwYmVkM2Q4MTJkZDc5NjU=. DOE's former General Counsel (*supra*) says a fee based on a predicted 50% default rate would be "unmanageable" for the industry, which apparently expects a much lower value. Perhaps it's expecting its friends to offer Federal funds to pay their Credit Subsidy Costs, as Title XVII expressly authorizes (*Fed. Reg.* **72**(204):60129, 23 Oct 2007). Oddly, the loan-guarantee language is not in statue but in a Committee report, apparently so to evade budget-scoring rules. This conceals the cost of the subsidy in a way disturbing like recent concealment of subprime mortgage risks.

[202] According to Koplow's "Government Subsidies to Nuclear Power: A Case Study of UniStar's Calvert Cliffs III Reactor," 5 Nov 2007 draft, www.npec-web.org/carbon/DRAFT-20071105-Koplow-NuclearSubsidiesCaseStudy.pdf. His $13-billion estimate is based on data for Calvert Cliffs III from its proposed builder UniStar.

[203] Koplow, ref. 186.

[204] Dr. J. Turnage (Senior VP, Constellation), testimony to DOE, 12 June 2007, www.lgprogram.energy.gov/061507-TPH.pdf, at p. 129.

enough: the combined ~2004 revenues of the subsidized U.S. firms exceed the GDP of the world's 112 poorest nations, so if those firms were a country, they'd have the world's 13th-biggest economy.[205] Yet without government handouts even bigger than the current astronomical levels, the U.S. nuclear revival continues to lack a key element: buyers. And of course such crony-capitalism interventions that shift risk and its cost from investors to taxpayers (or customers) do not make those costs go away, but merely hide, delay, and reallocate them.[206]

It remains to be seen whether even these extraordinary market distortions will elicit any "orders." NRG, proposing speculative merchant development of two Texas nuclear units, admitted that it's seeking additional subsidies from the Japanese government to supplement the still-inadequate U.S. ones.[207] In early 2008, advocates' expectations of rapid nuclear orders began to crumble. The capacity-short City of Austin dropped out of the NRG project,[208] a South Carolina project was suspended, and legendary investor Warren Buffet's Mid-America Nuclear Energy abandoned its Idaho project because "it does not make economic sense."[209] Bearish market sentiment, too, is intensifying as the credit crisis unfolds, so more cancellations can be expected.

On 29 January 2008, a discreet blog interview by the Nuclear Energy Institute's Vice President, Richard J. Myers, sought to start damping down the unrealistic expectations that the industry had created. He explained[210] that the U.S. nuclear revival, rather than coming in one great escalating surge as previously envisaged, will instead come in two wavelets: a mere 5–8 initial plants online in 2015–16,[211] plus more ordered as those units approach completion—*if* they're on time and within budget. He added the sobering observation that in 2006–07, 28.5 GW of new coal plants had been announced and 22.3 GW cancelled,[212] but he didn't comment on whether the U.S. nuclear "revival" might follow a similar course. The market's jaundiced reaction suggests that it may:[213] that broadly speaking, governments can have at most as much new nuclear capacity as they're willing to pay for, either directly or, in some countries, via parastatal utilities or other indirect means. Market behavior increasingly suggests that ever more heroic nuclear subsidies will elicit the same response as defibrillating a corpse: it will jump, but it won't revive.

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[205] Koplow, "NuSubsidies Nuclear Consortium," 2005, www.earthtrack.net/earthtrack/library/NNC_Overview.ppt.
[206] At www.thebulletin.org/roundtable/nuclear-power-climate-change/.
[207] Ref. 52, n. 53, citing Reuters, 26 Sept 2007.
[208] K. Alexander, "Investment in second reactor at South Texas Project carries too much risk, officials say," *American-Statesman* (Austin TX), 9 Feb 2008.
[209] http://midamericannuclear.com/html/overview.asp, downloaded 14 Feb 2008.
[210] "The Nuclear Resurgence and Reasonable Expectations," http://neinuclearnotes.blogspot.com/2008/01/nuclear-resurgence-and-reasonable.html.
[211] Six weeks later, his colleague Alex Flint (ref. 77) trimmed this to "four to eight…in operation by 2016 or so."
[212] According to another industry source, the *cumulative* fraction of announced U.S. coal plants cancelled was 1% in 2001, 6% in 2002, 22% in 2003, 26% in 2004, 36% in 2005, 36% in 2006, and 54% in 2007.
[213] The International Energy Agency's 2006 *World Energy Outlook* correctly noted that "nuclear power will only become more important if the governments of countries where nuclear power is acceptable play a stronger role in facilitating private investment." *Lighting the Way*, a major 2007 energy study by the InterAcademy Council, a consortium of 90 national academies of science, concluded that "a global renaissance of commercial nuclear power is unlikely to materialize over the next few decades without substantial support from governments" (www.interacademycouncil.net/?id=12161). And in the United States, widely touted as the core of that renaissance, Moody's Investors Services "does not believe the sector will bring more than one or two new nuclear plants on line by 2015…[M]any of the current expectations regarding new nuclear generation are overly ambitious. In fact, [the next unit] could be well beyond 2015 and [its project costs] could be significantly higher than the approximately \$3,500/ kW estimates cited by many industry participants"—in fact, could be \$5,000 to \$6,000/kW or more, as noted above.

After a half-century of intense effort to make nuclear power competitive, the market's verdict is unforgiving. Nuclear salespeople scour the world for single orders despite lavish and rising subsidies, while negawatts and micropower struggle to meet exploding and order-of-magnitude-larger market demand despite meager R&D funding[214] and generally smaller and decreasing subsidies.[215] This disparity can be expected to widen as more investors learn about negawatts and micropower—both still absent from many official energy statistics, hence scarcely visible to less sophisticated investors—and as the market better recognizes their distributed benefits. And the worse the 2008 credit crunch and economic downturn, the more investors will turn from slow, big, costly units to fast, small, cheaper ones. Even a multi-megawatt wind turbine can be built so quickly that the United States will probably have a hundred billion watts of them installed before it gets its first one billion watts of new nuclear capacity, if any—and the world will probably have more wind than nuclear capacity before a nuclear plant ordered today could be built.[216]

Yet we all seem to live not in this fact-based world but in an Alice-in-Wonderland parallel universe in which an uncompetitive technology that has dwindled to a 2% share of the global market for new generating capacity (or on the order of 1% of the market for new electrical services) gets ever-increasing subsidies because it's indispensable, while the privately financed technologies that have soared to upwards of 50% market share[217] with far less help[218] are dismissed as too small, slow, and costly to be taken seriously.

Conclusions

What, then, should a rational climate-protection policy do to abate emissions of fossil-fuel-caused CO_2? The foregoing logic suggests that:

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[214] G.F. Nemet and D. Kammen note that total U.S. energy R&D has declined from 10% to 2% of total U.S. R&D spending and is now below pre-OPEC levels: annual public funding for energy R&D fell by more than half, private R&D by three-fourths. Thus "total private R&D funding for the entire energy sector is less than that of a single large biotech company." *En. Pol.* **35**(1):746–755 (2007), http://rael.berkeley.edu/files/2007/NemeKamm_EP07.pdf. Their data (Fig. 7) show that the lion's share of all public energy R&D funding for the past half-century (*e.g.*, 49% in the U.S. 1950–93, ref. 186) went to nuclear technologies.

[215] For example, Japan has nearly phased out the initial subsidies that gave it the world's biggest photovoltaic market, yet sales continue robust, partly because a $0.8-billion investment has cut PV costs by >8%/y for a decade. The last detailed technology-by-technology comparison of Federal subsidies, for FY1984 (RMI Publs. #CS85-7 and –22), sound that decentralized competitors were subsidized 24× less per kWh than was nuclear power in the same year; since then, this ratio has almost certainly risen. Since President Bush took office in 2001, U.S. federal funding for nuclear energy has risen 330%: Squassoni, ref. 124.

[216] The Global Wind Energy Council expects the world will have installed 240 GW of windpower by 2012 ("Global Wind Energy Report," 1 Apr 2008, www.gwec.net/uploads/media/Global_Wind_2007_Report_final.pdf), growing by 36 GW/y in 2011–12. By 2015, such ~18%/y compound growth would surpass the world's 2007 379-GW nuclear capacity, which is expected to stay about flat net of decelerating upratings and accelerating retirements.

[217] Or about a third of the physical generating-capacity market, not counting negawatts.

[218] U.S. Federal subsidies during 1950–2000 were (in 1999 $) $145.4b to nuclear energy, $4.4b to solar power, and $1.3b to windpower, so nuclear got ~96% of this total; in their first 15 years of commercialization, wind produced 73% as much electricity as nuclear, but got <1/40th as much subsidy: Staff memorandum for hearing "Nuclear Power in a Warming World: Solution or Illusion?" 12 Mar 2008, U.S. House of Representatives, Select Committee on Energy Independence and Global Warming, p. 2, citing M. Goldberg, "Federal Energy Subsidies: Not All Technologies Are Created Equal," Renewable Energy Policy Project, July 2000, www.crest.org/repp_pubs/pdf/subsidies.pdf.

- 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 quick to deploy;
- end-use efficiency should save not just coal but also oil—especially in transportation,[219] which in the United States in 2003 emitted 82% as much CO_2 as power generation: indeed, since power generation emits only two-fifths of U.S. and world CO_2,[220] 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[221] 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;
- 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);
- a diversified portfolio needn't and shouldn't contain every possible option, any more than a financial portfolio should include obvious losers just because they're on the market; and
- intelligent investment should follow the order of *economic* priority—which is also the order of *environmental* priority—because not choosing the best buys first releases more carbon than would otherwise occur.

This is not a new idea. As Keepin and Kats arrestingly put it in 1988,[222] based on their reasonable and now-conservative estimate that efficiency would save ~7× as much carbon per dollar as nuclear power, "*every $100 invested in nuclear power would effectively release an additional tonne of carbon into the atmosphere*." Thus, counting the opportunity cost of nuclear power *vs*. a reasonable modern efficiency cost of 1¢/kWh, "the effective carbon intensity of nuclear power is nearly eight times *greater* than the direct carbon intensity of coal-fired power." That is, buying nuclear instead of coal-fired electricity saves carbon *if those are the only two choices*, but they're not: efficiency is so much cheaper than either that buying 1¢/kWh efficiency instead of nuclear power saves about eight times more carbon than would have been released if the same money had bought new coal-fired electricity! Today, their 20-year-old estimate looks sounder than ever.

These facts and findings raise a disquieting issue. Clearly the nuclear industry's sales pitch is false. The case for nuclear power to protect the climate and enhance security is purely rhetorical and cannot withstand analytic scrutiny. The supposed nuclear revival is a carefully manufactured illusion that seeks to become a self-fulfilling prophecy, yet it cannot actually occur in a market economy, as many energy-industry leaders privately acknowledge. But then thought-

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[219] Oil-fired power stations have already been displaced and can't be displaced again. In the United States, <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.

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

[221] 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.

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

ful citizens must ask: how can a credulous press continue to accept, report as fact, and promulgate a vision so divergent from observed market realities?[223]

To be sure, some leading newspapers have described nuclear regulatory and construction complications, and a few have mentioned that financing may present challenges. Yet the broader story—an industry that is failing and unfinanceable despite wildly escalating subsidies, has been massively outpaced by competitors it doesn't even recognize, and is unable even in principle to deliver its claimed climate and security benefits—remains virtually untold.

Perhaps this article can stimulate journalists to sharpen their critical faculties, legislators to study evidence, and citizens to demand choices based on demonstrable facts. Sooner or later, truth will out. Sooner will do less harm to our climate, economy, and security.

Physicist Amory Lovins, a 45-year student of this subject, is Cofounder, Chairman, and Chief Scientist of Rocky Mountain Institute (www.rmi.org) and Cofounder and Chairman Emeritus of Fiberforge, Inc. (www.fiberforge.com). Published in 29 books and hundreds of papers, his work has been recognized by the Volvo, Right Livelihood, Blue Planet, Onassis, Nissan, Shingo, and Mitchell Prizes, a MacArthur Fellowship, the Benjamin Franklin and Happold Medals, ten honorary doctorates, Foreign Membership of the Royal Swedish Academy of Engineering Sciences, honorary membership of the American Institute of Architects, Life Fellowship of the Royal Society of Arts, and the Heinz, Lindbergh, Jean Meyer, World Technology, and Time *"Hero for the Planet" Awards. He has consulted for more than three decades for major firms and governments (including the U.S. Departments of Energy and Defense) on advanced energy and resource efficiency in ~50 countries, has advised scores of electric utilities (many of them nuclear operators), and has led the technical redesign of >$30 billion worth of facilities in ~29 sectors to achieve very large energy savings at typically lower capital costs (www.rmi.org/stanford, encapsulating his 2007 MAP/Ming Professorship in Stanford University's School of Engineering). Engineer Imran Sheikh, who provided extensive graphical and analytic support for this paper as an RMI Research Analyst, is now a graduate student at the Energy and Resources Group of the University of California at Berkeley.*

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[223] Sustaining actual and perceived media independence on this contentious issue requires special care where, as often occurs, media are: (1) state-controlled and reflect government policy, as in Russia and China; (2) private but controlled by a pro-nuclear political leader, as in Italy, where the new Berluscone government recently announced an intention of nuclear revival; and (3) private but controlled or owned by the nuclear industry, as in the United States, where of the two dominant nuclear vendors, one owns NBC, CNBC, MSNBC, and ~26 TV stations, while the other bought and morphed into CBS, which during 1997–99 was itself a major nuclear power vendor. For example, on 8 Apr 2007, CBS's *60 Minutes*, normally considered a pioneering and fiercely independent investigative program, ran an embarrassingly lopsided ode to the French nuclear power program (transcript at www.cbsnews.com/stories/2007/04/06/60minutes/main2655782.shtml). Avoiding unworthy suspicions of undue influence in such circumstances demands special sensitivity and journalistic excellence.