Nuclear Power: Climate Fix or Folly?

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Nuclear power, we're told, is a vibrant industry that's dramatically reviving because it's proven, necessary, competitive, reliable, safe, secure, widely used, increasingly popular, and carbon-free —a perfect replacement for carbon-spewing coal power. New nuclear plants thus sound vital for climate protection, energy security, and powering a vibrant global economy.

There's a catch, though: the private capital market isn't investing in new nuclear plants, and without financing, capitalist utilities aren't buying. The few purchases, nearly all in Asia, are all made by central planners with a draw on the public purse. In the United States, even new 2005 government subsidies approaching or exceeding new nuclear plants' total cost failed to entice Wall Street to put a penny of its own capital at risk during what were, until autumn 2008, the most buoyant markets and the most nuclear-favorable political and energy-price conditions in history—conditions that have largely reversed since then.

This semi-technical article, summarizing a detailed and documented technical paper[1], compares the cost, climate protection potential, reliability, financial risk, market success, deployment speed, and energy contribution of new nuclear power with those of its low- or no-carbon competitors. It explains why soaring taxpayer subsidies haven't attracted investors. Capitalists instead favor climate-protecting competitors with lower cost, construction time, and financial risk. The nuclear industry claims it has no serious rivals, let alone those competitors—which, however, already outproduce nuclear power worldwide and are growing enormously faster.

Most remarkably, comparing all options' ability to protect the earth's climate and enhance energy security reveals why nuclear power *could never deliver* these promised benefits even if it *could* find free-market buyers—while its carbon-free rivals, which won more than $90 billion of private investment in 2007 alone[2], do offer highly effective climate and security solutions, far sooner, with higher confidence.

Uncompetitive Costs

The Economist observed in 2001 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's become severalfold costlier to build, and in a few years, as old fuel contracts expire, it is expected to become severalfold costlier to run.[3] Its total cost now markedly exceeds that of coal- and gas-fired power plants, let alone the even cheaper decentralized competitors described below.

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[1] A.B. Lovins & I. Sheikh, "The Nuclear Illusion," *Ambio,* forthcoming, 2009, RMI Publ. #E08-01, preprinted at www.rmi.org/images/PDFs/Energy/E08-01_AmbioNuclIllusion.pdf, to be updated in early 2009 for publication.

[2] Justin Winter for Michael Liebreich (New Energy Capital, London), personal communication, 1 Dec 2008, updating that firm's earlier figure of $71b for distributed renewable sources of electricity. The $90b is bottom-up, transaction-by-transaction and excludes M&A activity and other double-counting. Reliable estimates of investment in no-carbon (recovered-waste-heat) or relatively low-carbon (fossil-fueled) cogeneration are not available, but total global cogeneration investment in 2007 was probably on the order of $20b or more.

[3] Due to prolonged mismanagement of the uranium and enrichment sectors: *Nuclear Power Joint Fact-Finding*

Construction costs worldwide have risen far faster for nuclear than for non-nuclear plants. This is not, as commonly supposed, due chiefly to higher metal and cement prices: repricing the main materials in a 1970s U.S. plant (an adequate approximation) to March 2008 commodity prices yields a *total* Bill of Materials cost only ~1% of today's overnight capital cost. Rather, the real capital-cost escalation is due largely to the severe atrophy of the global infrastructure for making, building, managing, and operating reactors. This makes U.S. buyers pay in weakened dollars, since most components must now be imported. It also makes buyers worldwide pay a stiff premium for serious shortages and bottlenecks in engineering, procurement, fabrication, and construction: some key components have only one source worldwide. The depth of the rot is revealed by the industry's flagship Finnish project, led by France's top builder: after three years' construction, it's at least three years behind schedule and 50% over budget. An identical second unit, gratuitously bought in 2008 by 85%-state-owned Électricité de France to support 91%-state-owned vendor Areva (orderless 1991–2005), was bid ~25% higher than the Finnish plant and without its fixed-price guarantee, and suffered prompt construction shutdowns for lax quality.

The exceptionally rapid escalation of U.S. nuclear capital costs can be seen by comparing the two evidence-based studies[3,4] with each other and with later industry data (all including financing costs, except for the two "overnight" costs, but with diverse financing models—*cf.* cols. 3 *vs.* 4):

Date	*Source*	*Capital cost (2007 $/net el. W)*	*Levelized busbar cost, 2007 $/MWh*
7/03	MIT[4]	2.3	77–91
6/07	Keystone[3]	3.6–4.0	83–111
5/07	S&P	~4	
8/07	AEP	~4	
10/07	Moody's	5–6	
11/07	Harding	4.3–4.6	~180
3/08	FPL filing	~4.2–6.1 [3.1–4.5 overnight]	
3/08	Constellation	[3.5–4.5 overnight]	
5/08	Moody's	~7.5	150
6/08	Lazard	5.6–7.4	96–123
11/08	Duke Power	[4.8 overnight]	

As the Director of Strategy and Research for the World Nuclear Association candidly put it, "[I]t is completely impossible to produce definitive estimates for new nuclear costs at this time…."[5]

By 2007, as Figure 1 shows below, nuclear was the costliest option among all main competitors, whether using MIT's authoritative but now low 2003 cost assessment, the Keystone Center's mid-2007 update (pink bar), or later and even higher industry estimates (pink arrow).[6] For plants

(June 2007, Keystone Center, www.keystone.org/spp/documents/FinalReport_NJFF6_12_2007(1).pdf) estimated new fuel contracts will rise from the canonical ~0.5¢/kWh to ~1.2–1.7¢ for open or ~2.1–3.5¢ for closed fuel cycles.

4 This is very conservatively used as the basis for all comparisons in this article, but we show some later variants.

5 S. Kidd, *Nucl. Eng. Intl.*, 22 Aug 2008, www.neimagazine.com/storyprint.asp?sc=2050690.

6 All monetary values in this article are in 2007 U.S. dollars. All values are approximate and representative of the respective U.S. technologies in 2007 except as noted. Capital and fuel costs are levelized over the lifespan of the capital investment. Analytic details are in ref. 1, and for the underlying 2005 analysis, in 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, summarized in A.B. Lovins, "Mighty Mice," *Nucl. Eng. Intl.*, pp. 44–48, Dec 2005, www.rmi.org/images/PDFs/Energy/E05-15_MightyMice.pdf.

ordered in 2009, formal studies haven't yet caught up with the latest data, but it appears that their new electricity would probably cost (at your meter, not at the power plant) around 10–13¢/kWh for coal rather than the 9¢ shown, about 9–13¢/kWh for combined-cycle gas rather than the nearly 10¢ shown, but around 15–21¢/kWh for new nuclear rather than the 11–15¢ shown.[7] However, nuclear's decentralized competitors have suffered far less, or even negative, cost escalation: for example, the average price of electricity sold by new U.S. windfarms *fell* slightly in 2007.[8] The 4.0¢/kWh average windpower price for projects installed in 1999–2007 seems more representative of a stable forward market, and corresponds to ~7.4¢/kWh delivered and firmed—just one-half to one-third of new nuclear power's cost on a fully comparable basis.

Non-central-station competitors

Cogeneration and efficiency are "distributed resources," located near where energy is used. Therefore, they don't incur the capital costs and energy losses of the electric grid, which links large power plants and remote wind farms to customers.[9] Wind farms, like solar cells[10], also require "firming" to steady their variable output, and all types of generators require some backup for when they inevitably break. Figure 1 reflects these costs.

Making electricity from fuel creates large amounts of byproduct heat that's 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 in Figure 1. Cogenerating electricity and some useful heat from currently discarded industrial heat is even cheaper because no additional fuel is needed, so no additional carbon is released—only what the factory was already emitting.[11]

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[7] Based, as in Figure 1, on the June 2007 Keystone findings adjusted to Moody's May 2008 capital cost, on the assumption that a somewhat stronger dollar might partly offset escalation. Anecdotal reports suggest that real capital cost escalation remains rapid in Europe and Asia, depending on exchange rates: for example, eight recent Asian plants look to end up costing ~$4/W, consistent with mid-2007 U.S. cost estimates.

[8] From 4.8 in 2006 to 4.5¢/kWh, 0.9¢ higher than shown in Figure 1. U.S. wind turbines became 9% costlier during 2006–07, and may rise another ~10% in 2008, largely because rapid growth bottlenecked some key component supplies, but capacity factors improved too: *e.g.*, the average kW of Heartland wind projects installed in 2006 produced 35% more electricity than one installed in 1998–99, due mainly to better-designed turbines, higher hub heights, and better siting. All windpower data in this paper are from R. Wiser & M. Bolinger, "Annual Report on U.S. Wind Power Installation, Cost, and Performance Trends: 2007," USDOE/EERE, LBL-43025, May 2008, www1.eere.energy.gov/windandhydro/pdfs/43025.pdf. All windpower prices are net of some minor Renewable Energy Credit trading and of the U.S. Production Tax Credit whose levelized value is 1.0¢/kWh, far smaller than subsidies to central thermal power plants: D. Koplow, "Energy Subsidy Links Pages," Earthtrack (Washington DC), 2005, http://earthtrack.net/earthtrack/index.asp?page_id=177&catid=66.

[9] 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.

[10] Or *any* other plant. Solar power isn't included in Figure 1 because its delivered cost varies greatly by installation type and financing method. As will be shown in Figure 5 below, photovoltaics (PVs) are currently one of the smaller sources of renewable electricity, and solar thermal power generation is even smaller. However, PVs have probably *already* passed cost crossover with new coal, gas, or nuclear plants, as summarized on p. 6 below.

[11] A similar credit for displaced boiler fuel can even enable this technology to produce electricity at negative net cost. The graph conservatively omits such credit (which is very site-specific) and shows a typical positive selling price. The cogeneration results shown are based on actual projects considered representative by a leading developer.

End-use efficiency, by far the cheapest option, wrings more (and often better) services from each kilowatt-hour by using smarter technologies—substituting brains for dollars and carbon. That's mainly how California has held per-capita electricity use flat for the past 30 years, saving ~$100

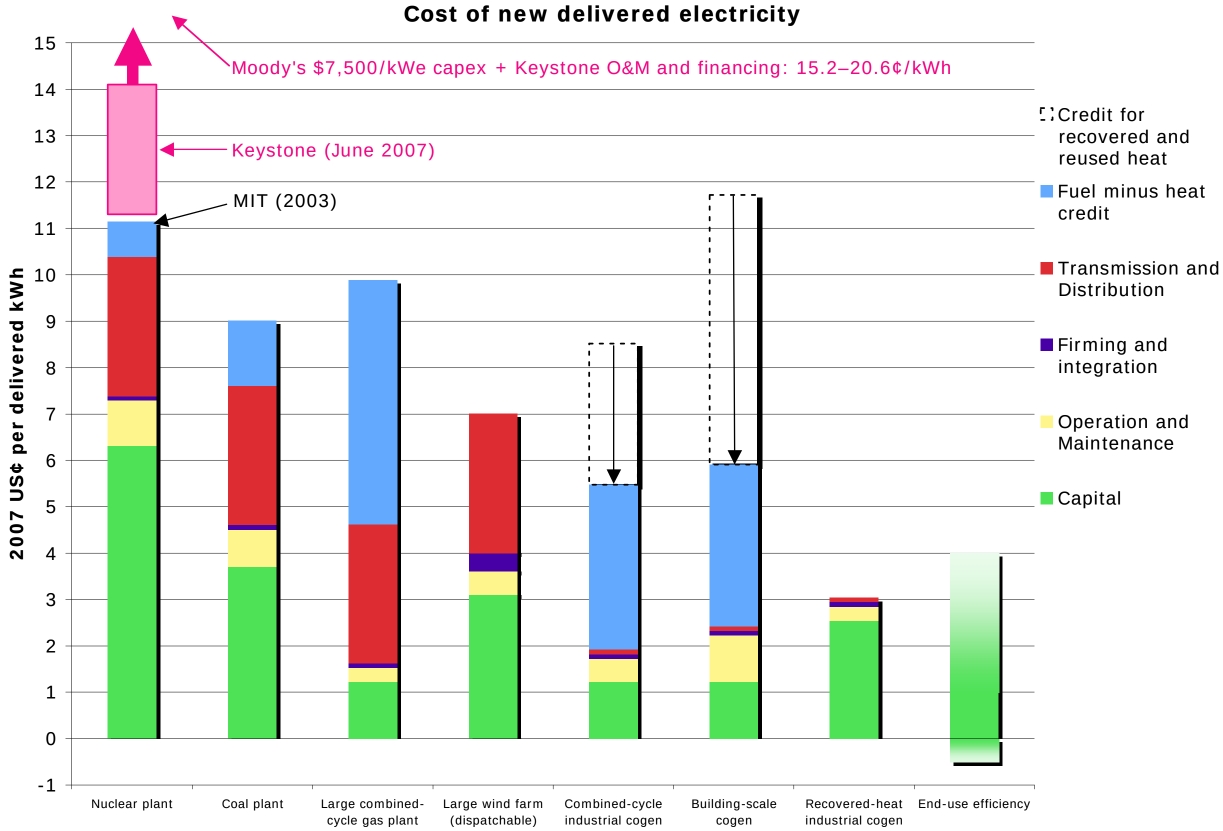

Figure 1: An apples-to-apples comparison of the cost of making and delivering *a new firm kWh of electrical services in the United States, based on empirical ~2007 market costs and prices.*

billion of investment to supply electricity, while per-capita real income rose 79% (1975–2005). Its new houses, for example, now use one-fourth the energy they used to. Yet California is further accelerating all its efficiency efforts, because there's so much still to save. McKinsey has found that efficiency can profitably offset 85% of the normally projected growth in U.S. electricity consumption to 2030.[12] Just using all U.S. electricity as productively as the top ten states now do (in terms of Gross State Product per kWh consumed, roughly adjusted for economic mix and climate) would save about 1,200 TWh/y—~62% of the output of U.S. coal-fired plants.[13]

Saving electricity costs far less than producing and delivering it, even from *existing* plants. California investor-owned utilities' efficiency programs cost an average of 1.2¢/kWh in 2004, and 83

[12] McKinsey&Company, "Reducing U.S. Greenhouse Gas Emissions: How Much at What Cost?," National Academies Summit on America's Energy Future, Washington DC, 14 Mar 2008, slide 7.
[13] Preliminary RMI analysis (K. Wang, kwang@rmi.org, personal communications, Dec 2008).

Pacific Northwest utilities' cost 1.3¢/kWh.[14] The national average is about 2¢, but hundreds of utility programs (mainly for businesses, where most of the cheap savings are) cost less than 1¢.[15] A major power engineering firm helped investment firm Lazard compare observed U.S. prices, finding that efficiency and many renewables cost less than a new central plants (Figure 2):[16]

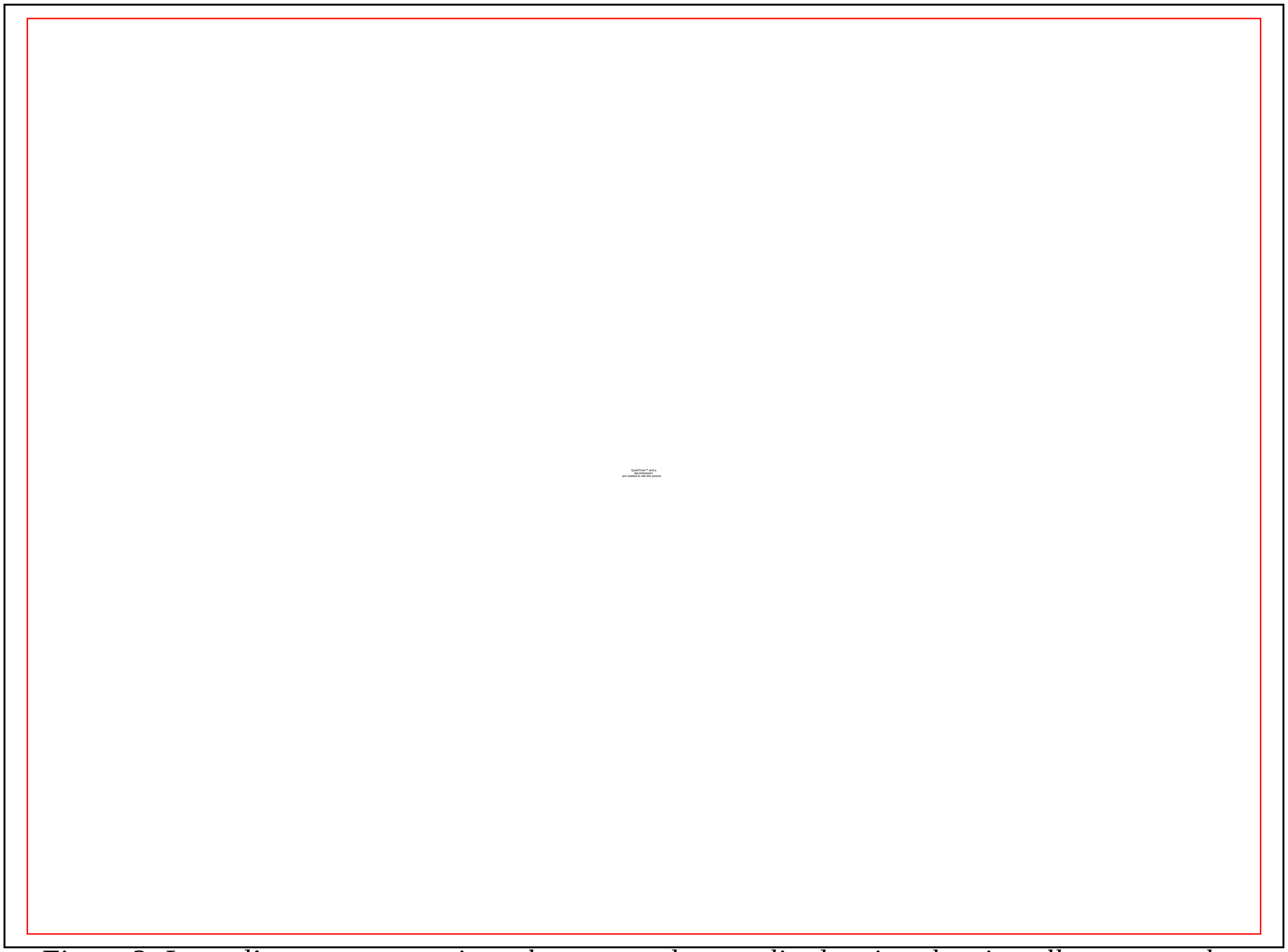

Figure 2: Lazard's recent comparison shows most decentralized options beating all new central stations; this chart omits cogeneration, overstates wind costs, and understates nuclear costs.

Why these comparisons understate nuclear power's uncompetitiveness

These conventional results and assessments greatly understate the size and profitability of today's electric-efficiency potential. In 1990, the utilities' think-tank EPRI and RMI, in a joint ar-

[14] C. Rogers, M. Messenger, & S. Bender, "Funding and Energy Savings from Investor-Owned Utility Energy Efficiency Programs in California for Program Years 2000 Through 2004," Aug 2005, www.energy.ca.gov/2005publications/CEC-400-2005-042/CEC-400-2005-042-REV.pdf; Tom Eckman, 1 May 2008 Northwest Power Planning Council memo "Conservation Savings—Status Report for 2005–07," www.nwcouncil.org/news/2008/05/3.pdf. For total societal cost, add ~30–80% depending on the sector.

[15] *E.g.*, S. Nadel, *Lessons Learned*, NYSERDA 90-8, ACEEE, 1990. These 1980s results remain valid today because most U.S. utilities have invested so little in efficiency that their opportunities are more like those of the 58 firms whose 237 programs through 1988 yielded median program costs of 0.3¢/kWh for industrial savings, 0.9¢ for motor rebates, 1.2¢ for loans, and 1.4¢ for new construction rebates.

[16] Lazard (New York), "Levelized Cost of Energy Analysis, v. 2.0," June 2008, www.narucmeetings.org/Presentations/2008%20EMP%20Levelized%20Cost%20of%20Energy%20-%20Master%20June%202008%20(2).pdf.

ticle, assessed that potential respectively as ~40–60% and ~75%, at respective average 2007-$ costs of about 3 and 1¢/kWh.[17] Now both those estimates look conservative, for two reasons:

- As EPRI agrees, efficiency technologies have improved faster than they've been applied, so the potential savings keep getting bigger and cheaper.[18]
- As RMI's work with many leading firms has demonstrated, integrative design can often achieve radical energy savings at *lower* cost than small or no savings.[19] That is, efficiency can often *reduce* total investment in new buildings and factories, and even in some retrofits that are coordinated with routine renovations.[20]

Wind, cogeneration, and end-use efficiency already provide electrical services more cheaply than central thermal power plants, whether nuclear or fossil-fuelled. *This cost gap will only widen*, since central thermal power plants are largely mature and getting costlier, while their competitors continue to improve rapidly. Indeed, a good case can be made that photovoltaics (PVs) can *already* beat new thermal power plants: if you start in 2010 to build a new 500-MW coal-fired power plant in New Jersey, plus an adjacent photovoltaic (PV) power plant, then before the coal plant comes online in 2018, the solar plant will produce a slightly larger amount of annual electricity at lower levelized cost, but with 1.5× more onpeak output, and the PV manufacturing capacity used to build your plant can then add 750 more MW *each year*.[21] Of course, the high costs

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[17] A. Fickett, C. Gellings, & A.B. Lovins, "Efficient Use of Electricity," *Sci. Amer.* **263**(3):64–74 (1990). The difference, analyzed by E. Hirst in ORNL/CON-312 (2001), was nearly all methodological, not substantive (A.B. & L.H. Lovins, "Least-Cost Climatic Stabilization," *Ann. Rev. En. Envt.* **16**:433–531 (1991), www.rmi.org/images/PDFs/Energy/E91-33_LstCostClimateStabli.pdf, at pp. 8–11): *e.g.*, EPRI excluded but RMI included saved maintenance cost as a credit against efficiency's capital cost, so their respective average costs of commercial lighting retrofits (~1986 $) were +1.2 and –1.4¢/kWh; EPRI examined potential savings only to 2000 (including 9–15% expected to occur spontaneously) while RMI counted the full long-term retrofit potential; and EPRI assumed drivepower savings 3× smaller and 5× costlier than EPRI adopted elsewhere in the same *Sci. Amer.* article. RMI's assessment summarized a 6-volume 1986–92 analysis of ~1,000 technologies' measured cost and performance (RMI/COMPETITEK, *The State of the Art* series, 2,509 pp., 5,135 sourcenotes, later summarized in the *Technology Atlas* series now maintained by spinoff firm E SOURCE, www.esource.com).

[18] RMI estimated that during 1984–89, U.S. efficiency potential roughly doubled while its real cost fell by threefold. Since 1990, mass production (often in Asia), cheaper electronics, competition, and better technology, according to James K. Rogers PE, cut the real cost of electronic T8 ballasts by >90% to 2003 (while lumens per watt rose 30%), turned direct/indirect luminaires from a premium to the cheapest option, and cut the real cost of industrial variable-speed drives by ~83–97% (some vendors of midsize motors now give them away). Compact fluorescent lamps became 85–94% cheaper during 1983–2003; window air-conditioners got 69% cheaper since 1993 while becoming 13% more efficient; and low-emissivity window coatings became ~84% cheaper in just five years.

[19] Integrative design produces these expanding (not diminishing) returns to efficiency investments: A.B. Lovins, "Energy End-Use Efficiency," 2005, www.rmi.org/images/PDFs/Energy/E95-28_SuperEffBldgFrontier.pdf, further elucidated in the senior author's five public lectures, "Advanced Energy Efficiency," delivered at Stanford's School of Engineering in March 2007 and posted at www.rmi.org/stanford. RMI's recent redesigns of over $30 billion worth of industrial projects consistently found ~30–60% energy savings on retrofit, typically paying back in 2–3 years, and ~40–90% savings in new projects, nearly always with *lower* capital cost.

[20] For example, an RMI design for retrofitting a 200,000-ft^2 curtainwall office building when it needed reglazing anyhow could save three-fourths of its energy at slightly *lower* cost than the normal 20-year renovation that saves nothing: A.B. Lovins, "The Super-Efficient Passive Building Frontier," *ASHRAE J.*, pp. 79–81, June 1995, www.rmi.org/images/PDFs/Energy/E95-28_SuperEffBldgFrontier.pdf.

[21] This is simply because PVs can ride down the cost curve (they'll clearly continue to get 18% cheaper for each doubling of cumulative global production volume, which is nearly doubling every year), they produce the most output on summer afternoons when most utilities' loads peak, and they can start producing energy and revenue in year one, reducing their financial risk. Many technological and institutional breakthroughs are in view that could well make PVs' costs drop even faster than their historic cost curve. Thomas Dinwoodie, SunPower Corporation, Systems (Founder and CTO), Richmond CA, "Price Cross-Over of Photovoltaics vs. Traditional Generation," 2008.

of conventional fossil-fuelled plants would go even higher if their large carbon emissions had to be captured—but this coal/solar comparison assumes a carbon price of *zero*.

The foregoing cost comparison is also conservative for four important *additional* reasons:

- End-use efficiency often has side-benefits worth 1– 2 orders of magnitude (factors of ten) more than the saved energy.[22]
- End-use efficiency and distributed generators have 207 "distributed benefits" that typically increase their economic value by an order of magnitude.[23] The *only* "distributed benefit" counted above is reusing waste heat in cogeneration.
- Integrating variable renewables with each other typically saves over half their capacity for a given reliability[24]; indeed, diversified variable renewables, forecasted and integrated, typically need *less* backup investment than big thermal plants for a given reliability.
- Integrating strong efficiency with renewables typically makes both of them cheaper and more effective.[25]

New nuclear power's uncompetitiveness is clear without these five conservatisms and overwhelming with them. As we'll see, the marketplace concurs—and that's good news for climate.

Uncompetitive CO_2 Displacement

Nuclear plant operations emit no carbon directly and rather little indirectly[26]. Nuclear power is therefore touted as the key replacement for coal-fired power plants. But this seemingly straight-

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[22] *E.g.*, ~6–16% higher labor productivity in efficient buildings, higher throughput and quality in efficient factories, better clinical outcomes in efficient hospitals, fresher food in efficient refrigerators, better visibility with efficient lighting, etc. Just counting such side-benefits can, for example, double the efficiency gains in a U.S. steel mill at the same cost.

[23] The biggest of these come from financial economics: *e.g.*, small fast modular projects have lower financial risk than big slow lumpy projects, and renewables hedge against fuel-price volatility risk. These 207 phenomena are explained and documented in an *Economist* book of the year: A.B. Lovins, E.K. Datta, T. Feiler, K.R. Rábago, J.N. Swisher, A. Lehmann, & K. Wicker, *Small Is Profitable: The Hidden Economic Benefits of Making Electrical Resources the Right Size*, 2002, Rocky Mountain Institute (Snowmass CO), www.smallisprofitable.org.

[24] For windpower in the three power pools that span the central U.S. from Canada to Texas: J. Traube, L. Hansen, B. Palmintier, & J. Levine, "Spatial Interactions of Wind and Solar in the Next Generation Utility," Windpower 2008, 3 Jun 2008 (to be posted shortly at ert.rmi.org).

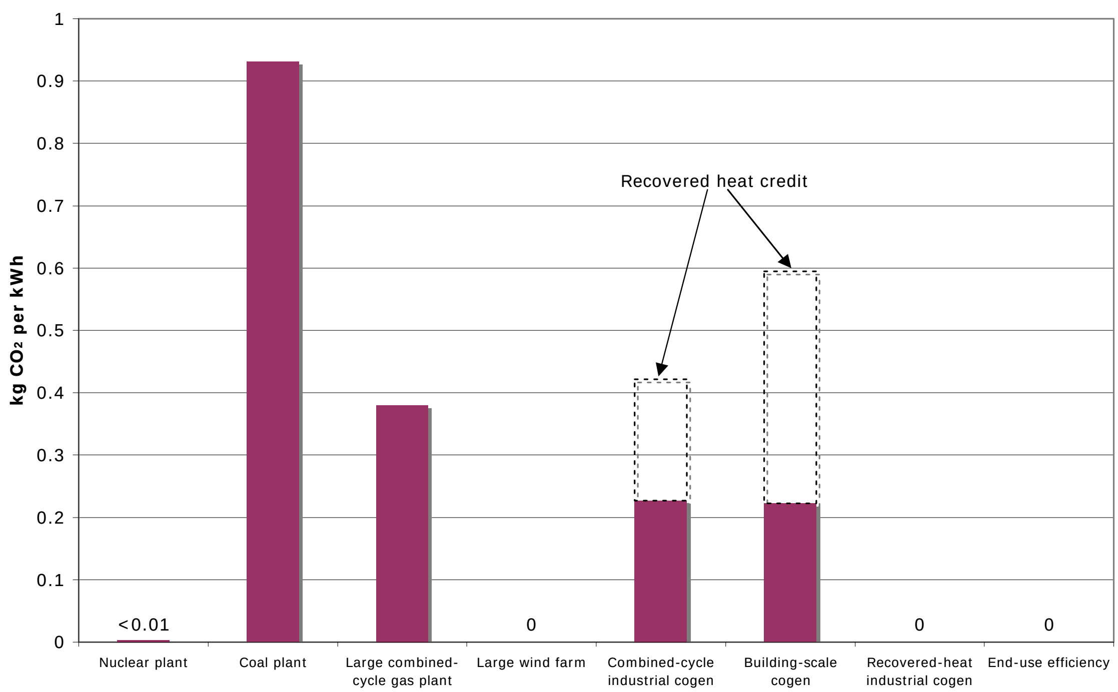
[25] *E.g.*, an integrated retrofit of efficiency, demand response, and 1.18 MW of PVs at the Santa Rita Jail in Alameda County CA easily met a 10%/y IRR hurdle rate—the $9-million project achieved a present-valued 25-year benefit of $15 million and hence would have made money even without its $4-million state subsidies—because on the hot afternoons when the PVs produced the most power, the efficient jail used little, leaving a bigger surplus to resell to the grid at the best price. Or my own household can run on ~120 average W (a tenth the U.S. norm), obtainable from 3 m^2 of PVs—a system cheaper than connecting to wires 30 m away. If built today, my household would need only ~40 average W, from 1 m^2 of PVs—a system cheaper than connecting to wires already on the side of the house. Both these comparisons assume free electricity; their point is that superefficient end-use can make the breakeven distance to the grid, beyond which it's cheaper to go solar than to connect, drop to about zero.

[26] We ignore here the modest and broadly comparable amounts of energy needed to build any kind of electric generator, as well as possible long-run energy use for nuclear decommissioning and waste management or for extracting uranium from low-grade sources and restoring mined land afterwards. B.K. Sovacool, *En. Pol.* **36**:2490–2953 (Aug 2008) surveyed these issues. He screened 103 published studies of nuclear power's energy inputs and indirect carbon emissions; excluded the 84 studies that were older than 10 years, not in English, or not transparent; and found that the other 19 derived gCO_2e/busbar kWh figures ranging from 1.4 to 288 with a mean of 66, which is roughly one-seventh the carbon intensity of combined-cycle gas but twice that of photovoltaics or seven times that of mod-

forward substitution could instead be done using *non*-nuclear technologies that are cheaper and faster, so they yield more climate solution per dollar and per year.

As Figure 2 shows, various options emit widely differing quantities of CO_2 per delivered kilo-watt-hour:[27]

Figure 2: Operating CO_2 emitted per delivered kWh



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, or a kilo-watt-hour saved by end-use efficiency. And all three of these carbon-free resources cost far less than nuclear power per kilowatt-hour, so they save far 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[28]. 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 (using the most conserva-

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ern onshore windpower. This comparison, or its less favorable dynamic equivalent described by A.B. Lovins and J. Price in 1977 (*Non-Nuclear Futures*, Ballinger, Cambridge MA, Part II), is however scarcely relevant, since the unarguable *economic opportunity cost* shown in this section is far more important and clear-cut.

[27] Conservatively assuming industry claims that nuclear power indirectly emits about one-seventh as much carbon as the mean of the 19 studies analyzed by Sovocool's literature review (ref. 26), and similarly omitting the probably even smaller carbon footprint of renewables, recovered-heat cogeneration, and efficiency.

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

tive comparison from Figure 1), 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.

Figure 3 compares different electricity options' cost-effectiveness in reducing CO_2 emissions, counting both their cost-effectiveness (kilowatt-hours per dollar), and any carbon emissions:

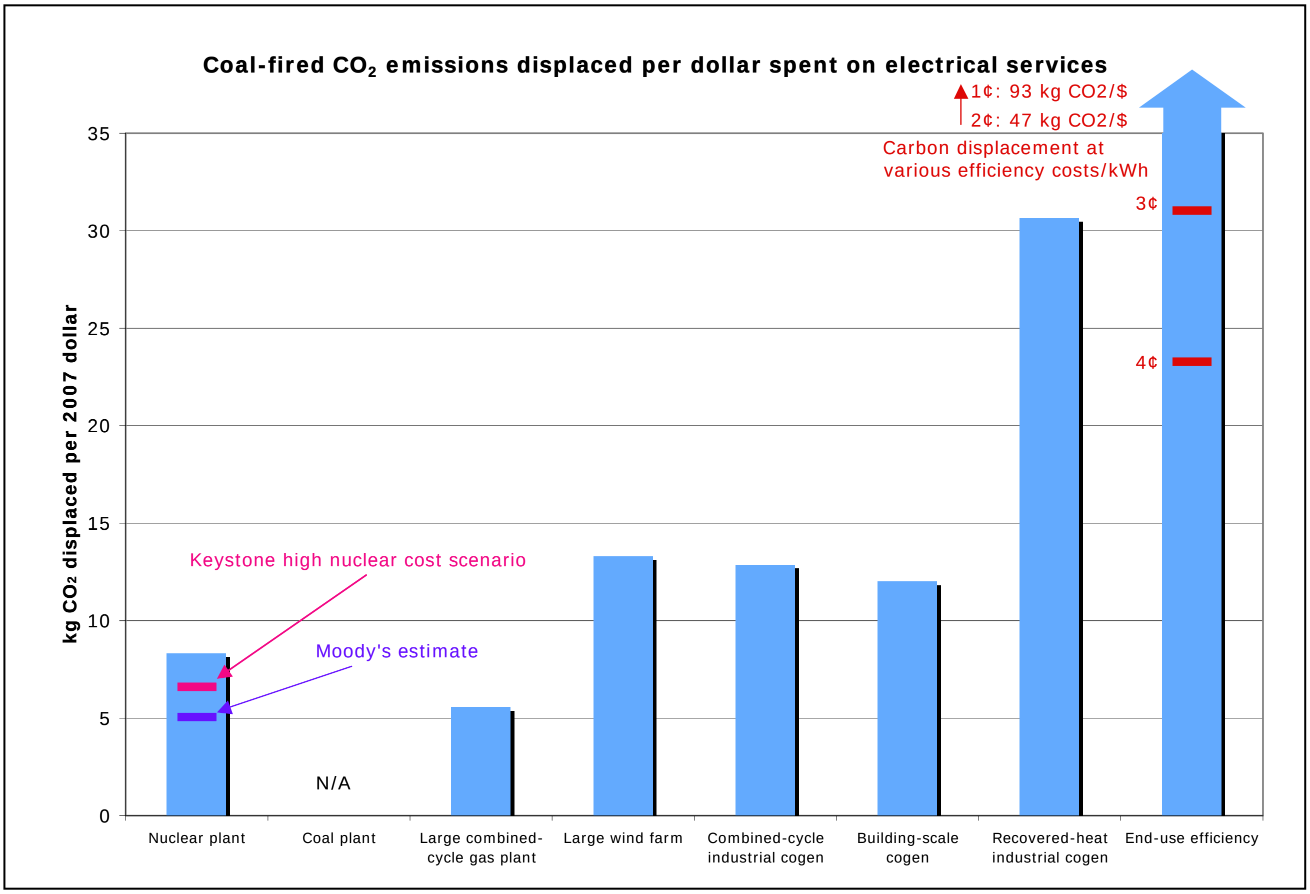

Figure 3: How much net carbon emissions from coal-fired power plants can be displaced by buying a dollar's worth of new electrical services using different technologies. Note that realistic efficiency investments' carbon savings are far above the upper-right corner of the chart.

Nuclear power, being the costliest option, thus 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[29]. Firmed windpower and cogeneration are at least 1.5 times more cost-effective than nuclear at displacing CO_2—or about 3 times using the latest nuclear cost estimates. So is efficiency at even an almost unheard-of seven cents per kWh. Efficiency at normally observed costs, say around one cent per kWh, beats nuclear by about 10–20-fold.

[29]However, at long-run natural-gas prices lower than assumed here (a levelized 2007-$ cost of $7.72 per million BTU) and at today's high nuclear costs, the combined-cycle plants may save more carbon per dollar than nuclear plants do. This may be true even at the prices assumed here, if one properly counts combined-cycle plants' ability to load-follow, thus complementing and enabling cleaner, cheaper variable renewable resources like windpower.

New nuclear power is 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!
If we're serious about addressing climate change, we must invest resources wisely to expand and accelerate climate protection. Because nuclear power is costly and slow to build, buying more of it rather than of its cheaper, swifter rivals will instead reduce and retard climate protection.

Questionable Reliability

All sources of electricity sometimes fail, differing only in how predictably, why, how often, how much, and for how long. Even the most reliable giant power plants are intermittent: they fail unexpectedly in billion-watt chunks, often for long periods. Of all 132 U.S. nuclear plants built (52% of the 253 originally ordered), 21% were permanently and prematurely closed due to reliability or cost problems, while another 27% have completely failed for a year or more at least once. The surviving U.S. nuclear plants produce ~90% of their full-time full-load potential, but even they are not fully dependable. Even reliably operating nuclear plants must shut down, on average, for 39 days every 17 months for refueling and maintenance, and unexpected failures do occur too. To cope with such intermittence by both nuclear and centralized fossil-fuelled power plants, which typically fail about 8% of the time, utilities must install a roughly 15% "reserve margin" of extra capacity, some of which must be continuously fuelled, spinning ready for instant use. Heavily nuclear-dependent regions are particularly at risk because drought, a serious safety problem, or a terrorist incident could close many plants simultaneously.

Nuclear plants have an additional disadvantage: for safety, they must instantly shut down in a power failure, but for nuclear-physics reasons, they can't then be quickly restarted. During the August 2003 Northeast blackout, nine perfectly operating U.S. nuclear units had to shut down. Twelve days of painfully slow restart later, their average capacity loss had exceeded 50 percent. For the first three days, just when they were most needed, their output was below 3% of normal.

The big transmission lines that highly concentrated nuclear plants require are also vulnerable to lightning, ice storms, rifle bullets, cyberattacks, and other interruptions.[30] The bigger our power plants and power lines get, the more frequent and widespread regional blackouts will become. Because 98–99 percent of power failures start in the grid, it's more reliable to bypass the grid by shifting to efficiently used, diverse, dispersed resources sited at or near the customer.

A portfolio of many smaller units, too, is unlikely to fail all at once: its diversity makes it more reliable even if its individual units are not.[31] The same logic applies to the two renewable electricity sources—windpower and photovoltaics—whose output varies with weather or daytime. Of course the sun doesn't always shine on a given solar panel, nor does the wind always spin a given turbine. Yet if properly firmed, both windpower, whose global potential is 35 times world electricity use[32], and solar energy, as much of which falls on the earth's surface every ~70 min-

[30] A.B. & L.H. Lovins, report to DoD republished as *Brittle Power: Energy Strategy for National Security*, Brick House (Andover MA), 1981, posted with summaries #S83-08 and #S84-23 at www.rmi.org/sitepages/pid114.php; Defense Science Board, *More Fight, Less Fuel*, 13 Feb 2008, www.acq.osd.mil/dsb/reports/2008-02-ESTF.pdf.
[31] These arguments are elaborated and documented in ref. 23.
[32] 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.

utes as humankind uses each year, can deliver reliable power without significant cost for backup or storage.[33] These variable renewable resources become *collectively* reliable when diversified in type and location and when integrated with three types of resources: steady renewables (geothermal, small hydro, biomass, etc.), existing fuelled plants, and customer demand response. Such integration uses weather forecasting to predict the output of variable renewable resources, just as utilities now forecast demand patterns and hydropower output. In general, keeping power supplies reliable despite large wind and solar fractions will require *less* backup or storage capacity than utilities *have already bought* to manage big thermal stations' intermittence. The myth of renewable energy's unreliability has been debunked both by theory and by practical experience.[34]

Large Subsidies to Offset High Financial Risk

The latest U.S. nuclear plant proposed is estimated to cost $12–24 billion (for 2.2–3.0 billion watts), many times industry's claims, and off the chart in Figure 1 above. The utility's owner, a large holding company active in 27 states, has annual revenues of only $15 billion. Even before the current financial crisis, such high, and highly uncertain, capital costs made financing prohibitively expensive for free-market nuclear plants in the half of the U.S. that has restructured its electricity system, and prone to politically challenging rate shock in the rest: a new nuclear kilowatt-hour costing, say, 18 cents "levelized" over decades implies that the utility must collect ~30 cents to fund its first year of operation.

Lacking investors, nuclear promoters have turned back to taxpayers, who already bear most nuclear accident risks, have no meaningful say in licensing, and for decades have subsidized existing nuclear plants by ~1–5¢/kWh. In 2005, desperate for orders, the politically potent nuclear industry got those U.S. subsidies raised to ~5–9¢/kWh for new plants, or ~60–90 percent of their entire projected power cost, including new taxpayer-funded insurance against legal or regulatory delays. Wall Street still demurred. In 2007, the industry won relaxed government rules that made its 100 percent loan guarantees (for 80%-debt financing) even more valuable—worth, one utility's data revealed, about $13 billion for a single new plant, about equal to its entire capital cost. But rising costs had meanwhile made the $4 billion of new 2005 loan guarantees scarcely sufficient for a single reactor, so Congress raised taxpayers' guarantees to $18.5 billion. Congress will soon be asked for another $30+ billion in loan guarantees, or even for a blank check. Meanwhile, the nonpartisan Congressional Budget Office has concluded that defaults are likely.

Wall Street is ever more skeptical that nuclear power is as robustly competitive as claimed. Starting with Warren Buffet, who recently abandoned a nuclear project because "it does not make

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[33] Wiser & Bolinger, ref. 8, p. 27, document 11 recent U.S. utility studies showing that even variable-renewable penetrations up to 31% generally cost <0.5¢/kWh to "firm" to central-plant reliability standards. The two studies that found costs up to 0.8¢ didn't assume the sub-hourly market-clearing that most grid operators now use.

[34] The nuclear industry's claim that because a modern economy needs highly reliable electricity, it also needs "24/7" power *stations* of billion-watt scale is absurd. *No* power source is 100% reliable; that's why utilities must use redundancy and elaborate operating techniques to ensure reliable supply despite unpredictable failures, which are especially damaging when the failed units are large. The same proven techniques apply similarly, but more easily, to large numbers of diverse renewables whose variable elements can be readily forecast. Without exception, more than 200 international and 11 U.S. studies have found this (see ref. 1, pp. 22–27). Wind-rich regions of Germany, Spain, and Denmark have already proven it by meeting 20–39% of all annual electrical needs (and at times over 100% of regional needs) with variable renewables, without encountering instability nor significant integration costs.

economic sense," the smart money is heading for the exits. The Nuclear Energy Institute is therefore trying to damp down the rosy expectations it created. It now says U.S. nuclear orders will come not in a tidal wave but in two little ripples—a mere 5–8 units coming online in 2015–16, then more if those are on time and within budget. Even that sounds dubious, as many senior energy-industry figures privately agree. In today's capital market, governments can have at most about as many nuclear plants as they can force taxpayers to buy. Indeed, the big financial houses that lobbied to be the vehicles of those gigantic federal loan guarantees are now largely gone; a new Administration with many other priorities may be less supportive of such largesse; and the "significant" equity investment required to qualify for the loan guarantees seems even less likely to come from the same investors who declined to put their own capital at risk at the height of the capital bubble. The financial crisis has virtually eliminated private investment in big, slow, risky projects, while not materially decreasing investment in the small, fast, granular ones that were already walloping central plants in the global marketplace.

The Micropower Revolution

While nuclear power struggles in vain to attract private capital, investors have switched—and the financial crisis has accelerated their shift[35]—to cheaper, faster, less risky alternatives that *The Economist* calls "micropower"—distributed turbines and generators in factories or buildings (usually cogenerating useful heat), and all renewable sources of electricity *except* big hydro dams (those over ten megawatts). These alternatives surpassed nuclear's global capacity in 2002 and its electric output in 2006. Nuclear power now accounts for about 2 percent of worldwide electric capacity additions, *vs*. 28 percent for micropower (2004–07 average) and probably a good deal more in 2007–08.[36]

Despite subsidies generally smaller than nuclear's, and many barriers to fair market entry and competition[37], negawatts (electricity saved by using it more efficiently or timely) and micropower have lately turned in a stunning global market performance. Figure 5 shows how micropower's actual and industry-projected electricity production is running away from nuclear's, not even counting the roughly comparable additional growth in negawatts, nor any fossil-fuelled generators under 1 megawatt.[38]

The nuclear industry nonetheless claims its only serious competitors are big coal and gas plants. But the marketplace has already abandoned that outmoded battleground for two others: central thermal plants *vs.* micropower, and megawatts *vs.* negawatts. For example, the U.S. added more windpower capacity in 2007 than it added coal-fired capacity in the past five years combined. By beating *all* central thermal plants, micropower and negawatts together provide about half the world's new electrical services. Micropower alone now provides a sixth of the world's electricity, and from a sixth to more than half of all electricity in twelve industrial countries, though the U.S. lags with ~6%.

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[35] New Energy Finance found only a 4% drop in 3Q08 renewables financing, and recent data suggest a robust, even growing, solar sector despite grave financial distress and accelerating decline in the central-station business.
[36] A thorough database of industry and official data sources is posted and updated at www.rmi.org/sitepages/pid256.php#E05-04. Similar renewable energy data are at www.ren21.net.
[37] A policy agenda for removing many of these obstacles is in the last section of *Small Is Profitable* (ref. 31).
[38] Data for decentralized gas turbines and diesel generators exclude generators of less than 1 megawatt capacity.

In this broader competitive landscape, high carbon prices or taxes can't save nuclear power from its fate. If nuclear did compete only with coal, then far-above-market carbon prices might save it; but coal isn't the competitor to beat. Higher carbon prices will advantage all other zero-carbon resources—renewables, recovered-heat cogeneration, and negawatts—as much as nuclear, and will partly advantage fossil-fueled but low-carbon cogeneration as well. The nuclear industry doesn't understand this because it doesn't consider these competitors important or legitimate.

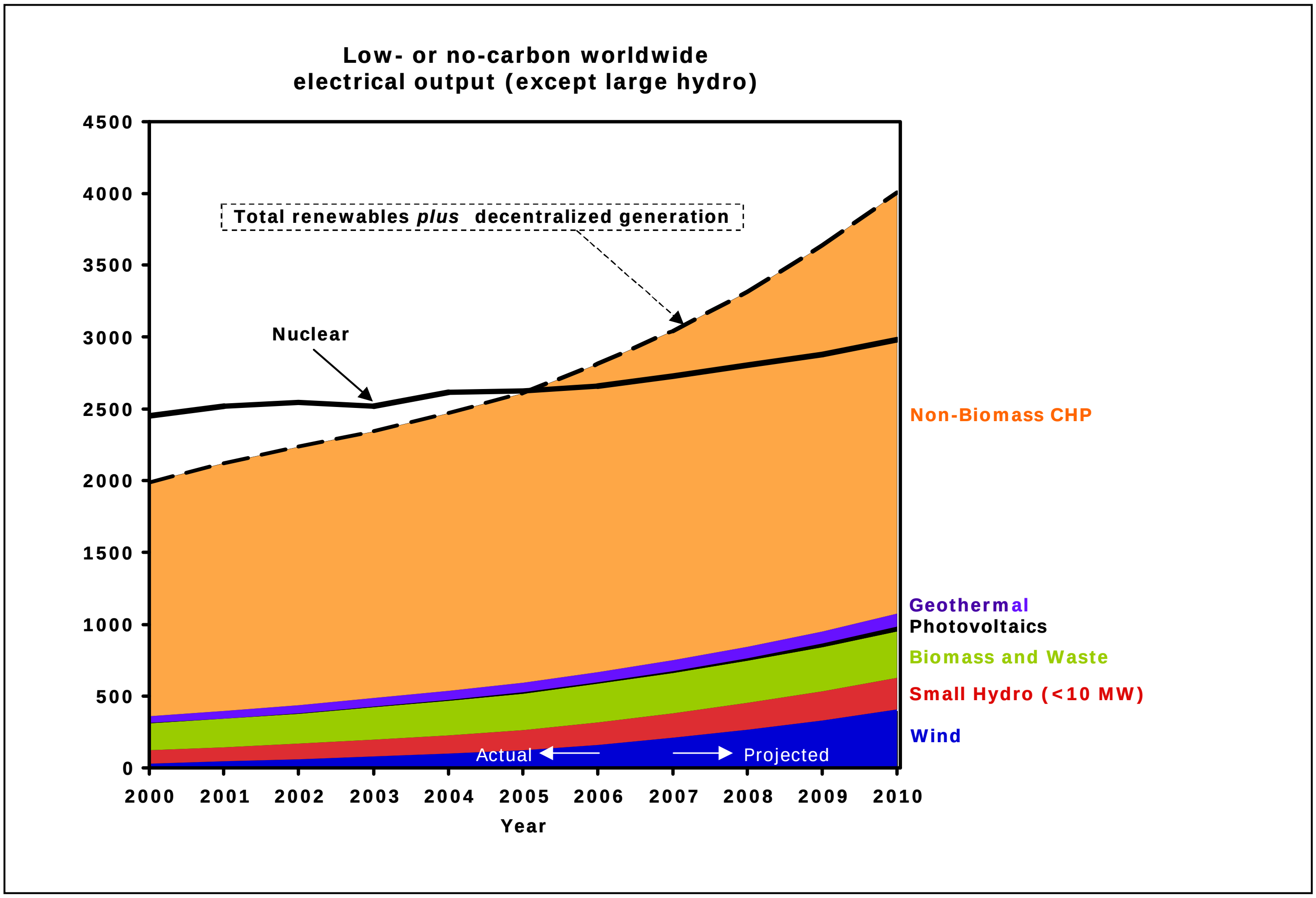

Figure 5. Global electricity produced, or projected by industry to be produced, by decentralized low- or no-carbon resources—cogeneration ("CHP"), mostly gas-fired, and "distributed" renewables (those other than big hydroelectric dams). Micropower got over $100 billion of new private capital in 2007—roughly an eighth of total global energy investment.

Small Is Fast, Low-Risk, and High in Total Potential

Small, quickly built units are faster to deploy for a given total effect than a few big, slowly built units. Widely accessible choices that sell like cellphones and PCs can add up to more, sooner, than ponderous plants that get built like cathedrals. And small units are much easier to match to the many small pieces of electrical demand. Even a multi-megawatt wind turbine can be built so quickly that the U.S. will probably have a hundred billion watts of them (matching its nuclear capacity) installed before it gets its first one billion watts of new nuclear capacity, if any. As noted earlier, this speed reduces financial risk and thus makes decentralized, short-lead-time projects more financeable, especially in hard times.

Despite their small individual size, and partly because of it, micropower generators and electrical savings are already adding up to huge totals. Indeed, over decades, negawatts and micropower can shoulder the entire burden of powering the economy. The Electric Power Research Institute (EPRI), the utilities' think-tank, has calculated the U.S. negawatt potential (cheaper than just running an existing nuclear plant and delivering its output) to be two to three times nuclear power's 19 percent share of the U.S. electricity market; RMI's more detailed analysis found even more. Cogeneration in factories can make as much U.S. electricity as nuclear does[39], plus more in buildings, which use 69 percent of U.S. electricity. Windpower at acceptable U.S. sites can cost-effectively produce several times the nation's total electricity use[40], and other renewables can make even more without significant land-use, variability, or other constraints. Thus just co-generation, windpower, and efficient use—all profitable today—can displace nuclear's current U.S. output ~6–14$^+$ times over. This ratio becomes arbitrarily large when photovoltaics are included.

Nuclear power, with its decade-long project cycles, difficult siting, and (above all) unattractiveness to private capital, simply cannot compete. In 2006, for example, it added less global capacity than photovoltaics did, or a tenth as much as windpower added, or 30–41 times less than micropower added. Renewables other than big hydro dams won $56 billion of private risk capital; nuclear, as usual, got zero. China's distributed renewable capacity reached seven times its nuclear capacity and grew seven times faster. And in 2007, China, Spain, and the U.S. each added more windpower capacity than the world added nuclear capacity. The nuclear industry does trumpet its growth, yet micropower is already bigger and is growing 18 times faster.[41]

Security Risks

President Bush has rightly identified the spread of nuclear weapons as the gravest threat to America. Yet that proliferation is largely driven and greatly facilitated by nuclear power's flow of materials, equipment, skills, and knowledge, all wrapped in an innocent-looking civilian disguise. (Reprocessing nuclear fuel, which President Bush tried to revive, greatly complicates waste management, increases cost, and boosts proliferation.) Yet acknowledging nuclear power's market failure and moving on to secure, least-cost energy options for global development would unmask and penalize proliferators by making bomb ingredients harder to get, more conspicuous to try to get, and politically costlier to be caught trying to get. This would make proliferation far more difficult, and easier to detect in time by focusing scarce intelligence resources on needles, not haystacks.[42] The new Administration has an extraordinary opportunity to turn the world away from its rush toward a "nuclear-armed crowd" by setting a good example in domestic energy pol-

[39] 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/.

[40] U.S. Department of Energy, *20% Wind Energy by 2030*, www.20percentwind.org/20p.aspx?page=Report, Ch. 2, p. 2.

[41] All documented in ref. 1.

[42] 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.

icy and by helping all developing countries with the nonviolent, cheaper, faster energy alternatives that are already winning in the market.[43]

Nuclear power has other unique challenges too, such as long-lived radioactive wastes, potential for catastrophic accidents, and vulnerability to terrorist attacks. But in a market economy, the technology couldn't proceed even if it lacked those issues, so we needn't consider them here.

[43] This would satisfy the intent of the "nuclear bargain" in Article IV of the Non-Proliferation Treaty. See also C.A. Ford (Hudson Institute), "Nuclear Technology Rights and Benefits: Risk, Cost, and Beneficial Use under the NPT's Article IV," Conference on "Comparing Electricity Costs," NPEC/Carnegie Corporation of New York, 1 Dec 2008.

Conclusion

So why do otherwise well-informed people still consider nuclear power a key element of a sound climate strategy? Not because that belief can withstand analytic scrutiny. Rather, it seems, because of a superficially attractive story, an immensely powerful and effective lobby, a new generation who forgot or never knew why nuclear power failed previously (almost nothing has changed), sympathetic leaders of nearly all main governments simultaneously, deeply rooted habits and rules that favor giant power plants over distributed solutions and enlarged supply over efficient use, the market winners' absence from many official databases (which often count only big plants owned by utilities), and lazy reporting by an unduly credulous press.

Isn't it time we forgot about nuclear power? Informed capitalists have. Politicians and pundits should too. After more than half a century of devoted effort and a half-trillion dollars of public subsidies, nuclear power still can't make its way in the market. If we accept that unequivocal verdict, we can at last get on with the best buys first: proven and ample ways to save more carbon per dollar, faster, more surely, more securely, and with wider consensus. As often before, the biggest key to a sound climate and security strategy is to take market economics seriously.

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Mr. Lovins, a physicist, is cofounder, Chairman, and Chief Scientist of Rocky Mountain Institute (www.rmi.org), where Mr. Sheikh, an engineer, was a Research Analyst (now a graduate student in the Energy and Resources Group at the University of California at Berkeley), and Dr. Markevich, a physicist and management consultant, was a Vice President until mid-2008. Mr. Lovins, a student of this subject for over four decades, has consulted for scores of electric utilities, many of them nuclear operators. Published in 29 books and hundreds of papers, his wide-ranging innovations in energy, security, environment, and development have been recognized by the Blue Planet, Volvo, Onassis, Nissan, Shingo, and Mitchell Prizes, a MacArthur Fellowship, the Benjamin Franklin and Happold Medals, ten honorary doctorates, an Hon. AIA and FRSA, Foreign Membership of the Royal Swedish Academy of Engineering Sciences, and the Heinz, Lindbergh, Right Livelihood, and World Technology Awards. He advises governments and major firms worldwide on advanced energy and resource efficiency and its integration with energy supply, and recently led the technical redesign of more than $30 billion worth of facilities in 29 sectors to achieve very large energy savings at typically lower capital cost.

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