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The economics of a US civilian nuclear phase-out

By Amory B. Lovins

Abstract

In the United States, which trades three-fifths of its electricity in competitive markets, the prohibitive capital cost of new nuclear power plants ensures that only a handful will be built. Nonetheless, with 40-year licenses being extended to 60 years, the 104 existing reactors' relatively low generating costs are widely expected to justify decades of continued operation. But the generating costs of aging reactors have been rising, while competitors, including modern renewables, show rapidly falling total costs—and those opposed cost curves have begun to intersect. An expanding fraction of well-running nuclear plants is now challenged to compete with moderating wholesale power prices, while plants needing major repairs or located in regions rich in wind power increasingly face difficult choices of whether to run or close. Thus, even without events that might accelerate nuclear phase-out, as the Fukushima disaster did in Germany, shifting competitive conditions have begun to drive a gradual US nuclear phase-out. Its economics are illuminated by a detailed energy scenario that needs no nuclear energy, coal, or oil and one-third less natural gas to run a 158 percent bigger US economy in 2050—but cuts carbon emissions by 82 to 86 percent and costs $5 trillion less. That scenario's 80-percent-renewable, 50-percent-distributed, equally reliable, and more resilient electricity system would cost essentially the same as a business-as-usual version that sustains nuclear and coal power, but it would better manage all the system's risks. Similarly comprehensive modeling could also analyze faster nuclear phase-out if desired.

Keywords
phase-out, nuclear exit, renewable energy

Nuclear power[i] in the United States, long considered the durably low-cost generator of electricity, faces intensifying competitive risks: New reactors are far too costly to replace the aging fleet of existing reactors, which in turn face rising pressure from even cheaper-to-operate ways to save or make electricity. For economic or other reasons, the gradual phase-out of unprofitable nuclear power plants, already quietly underway, may accelerate. Transparent empirical data and orthodox analytical techniques can illustrate the economics of this American nuclear energy transition—a complex transition embedded in a context that extends far beyond nuclear power.

The US electricity system is aging, dirty, and insecure, so almost all of it must be replaced by 2050, just to offset retiring generation and grid assets. This will cost approximately $6 trillion in net present value, whether the electricity industry builds more of the same infrastructure, new nuclear power plants and "clean coal" facilities, or centralized or distributed renewable plants (Lovins and RMI, 2011: 164–225). But these divergent possible futures differ profoundly in *risks*—related to security, safety, finance, technology, fuel, water, climate, and health—and in how they would affect innovation, entrepreneurship, and customer choice.

Nuclear power's public risks depend on many uncertain factors, including how well and long existing US nuclear plants are run, whether more are built (and if so, which kinds, how big, where, and by whom), and how much they are exposed to and how well they withstand natural disaster, technical mishap, or attack. Risk choices are highly political, influenced by public perceptions and by competitive forces and offerings. Energy—especially nuclear energy—has long been a uniquely subsidized, regulated, politicized, and powerful US industrial sector, so nuclear power's economics form only one thread in a complex tapestry of influences on its use. Recent shifts in the economics of both nuclear power and its competitors are overturning some long-held assumptions. These shifts shed light on how quickly nuclear power may or should phase out and what may or should replace it.

The competition problem

The 104 nuclear power plants operating in the United States—totaling 102 gigawatts of capacity and long assumed to run so cheaply that they could always make economic sense—now face competitive risks less obvious than those bedeviling new plants, but no less real. The most recent reliably operating US nuclear plant to be written off as uneconomic—the 38-year-old, small (566-megawatt), single-unit Kewaunee pressurized water reactor in Wisconsin, which has been relicensed to operate until 2033—will instead close in 2013, because its owner could neither sell it nor make it compete with natural-gas-fired electricity (DiSavino, 2012; Dominion, 2012). Once closed, the plant is extremely unlikely to reopen even if gas prices rise again. But gas isn't nuclear power's only competitive threat.

With the benefit of the production tax credit, a federal subsidy for wind and other renewable energy installations, new wind farms in the High Plains wind belt are highly competitive with both wholesale power prices (Wiser and Bolinger, 2012: 52)[ii] and typical nuclear operating costs, and wind power's costs continue to fall. The tax credit, which partly offsets nonrenewable generators' permanent and generally larger subsidies (Koplow, 2011), is set to expire for wind farms whose construction doesn't start by the end of 2013. But even after the credit's ultimate expiration—the wind industry has proposed a six-year phase-down to zero (Trabish, 2012)—wind's very low generating cost (Wiser and Bolinger, 2012: 37–40) will still beat the best nuclear plants' generating cost, despite continuing nuclear operating subsidies[iii] and despite costs for grid integration to address wind power's distinctive operating characteristics.[iv]

Of course, each nuclear reactor's competitiveness depends on a complex and shifting set of both market and plant-specific considerations, so no comparison of average conditions in a specific year can support conclusions about any individual plant. But it is safe to say that reactors that are sited in wind-rich regions or have relatively high generating costs confront increasing economic challenges (Wald, 2012a; Williams, 2012). Most distressed are reactors facing major repairs. Three examples, all with large and capable operators, are San Onofre in southern California, shut down when replacements for 28-year-old steam generators failed within two years (Associated Press, 2012); Crystal River 3 in Florida, with a repair bill exceeding its insurer's roughly $3.5 billion reserves (Penn, 2012), abandoned in February 2013 while this article was in press; and Oyster Creek in New Jersey, America's oldest reactor, which its owner plans to close in 2019 at age 50 rather than spend $750 million to add state-ordered cooling towers for a subsequent decade of operation.

The consequences of uncompetitiveness

From 2005 to 2012, coal lost one-third of its US market share to competition from natural gas, renewables, and efficiency.[v] Could existing nuclear plants be the next victim of shifting energy economics? The answer to that question depends not only on how competitive each plant appears on paper, but also who owns it. Many US reactors are owned by regulated utilities, whose recovery incentives and perceived regulatory risk of deviating from industry norms can sometimes bias performance toward "industry average." Merchant nuclear plants are often spurred by keener market incentives and their greater exposure to market volatilities to run better and cheaper. It is nonetheless instructive to consider the operational profitability of an "industry average" nuclear plant to get a sense of the emerging economic dilemma confronting some operators. This unit-based profitability differs from the asset's ownership profitability, which depends on its specific regulatory environment.

Nuclear plants are normally considered "must-run" assets. With substantial fixed operating and maintenance costs and little flexibility to follow varying loads, these units are built to run at a high and consistent output when they can and are increasingly forced to achieve rapid turnaround of repairs and refueling when they can't. Once their initial construction costs are sunk, nuclear plants must compete on their average running cost relative to electricity's wholesale market prices over an extended period. That incremental running cost has five elements that fall into two groups.

Operating costs. This first group sustains, and scales directly with, the plant's day-to-day operation. While one can argue that few costs in a nuclear plant are truly variable—its skilled staff, for example, can hardly be furloughed in a skill-short market and then rehired—these costs nonetheless are treated as variable because they approximate the plant's marginal cost of sending out electricity over time. The operators' 2010 reports to the Federal Energy Regulatory Commission on its required "Form FERC-1" show that operating costs averaged $26[vi] per megawatt-hour of output to the grid, including about $17 for routine operation and maintenance,[vii] $1 for the statutory federal nuclear-waste-management fee, and almost $7 for fuel,[viii] plus an unreported and highly discounted cost of operation[ix]—nearly $1 to cover future decommissioning, for which operators must book a reserve fund on their balance sheet.

Net capital additions. The second group comprises two kinds of post-construction capital investments (so big and durable that they're capitalized rather than expensed) that may overlap: major capital maintenance and upgrading to address issues of aging and reliability, and equipping a plant, with Nuclear Regulatory Commission approval, to produce more power than its original license allowed.[x] Net capital additions averaged $4.2 per megawatt-hour in 1993,[xi] when last assessed by government analysts, but have more than doubled since,[xii] and are highly erratic and unpredictable.

Adding $26 per megawatt-hour for operating costs to at least $4 per megawatt-hour for net capital additions yields a total generating cost that averaged at least $30 per megawatt-hour in 2010. In comparison, and in the same 2010 dollars, US wholesale electric energy prices in 2011 averaged $36 per megawatt-hour and normally[xiii] ranged from around $24 to $45. If an industry value (below) were used for today's typical net capital additions, the average 2010 nuclear generating cost would match the grid's $36 average 2011 wholesale price. Moreover, that price fell even further in 2012 (DOE/EIA, 2013b) than the year before (DOE/EIA, 2012f), so competition against 2010's average nuclear generating costs is tightening.

Even though each nuclear plant is unique, this parity of average costs suggests that the industry should be experiencing heightened competitive pressures, to which operators must and will respond. But the full picture is more complex. The wholesale electricity price range varies widely, both across the country and over time (Wald, 2012b). Wholesale prices also reflect the existing generating mix, and could shift—whether higher or lower is unclear—with less or no nuclear generation. And it is fair to include capacity prices as well as energy prices. Nuclear plants' high average capacity factor (around 90 percent) and relatively low variability earn bigger capacity credits than such competitors as gas, solar, and wind power. This nuclear advantage can range from zero (in markets that pay no capacity credit) to about $4 per megawatt-hour[xiv]—useful for operators, but still not enough to put many nuclear plants safely clear of the lower end of the average wholesale energy-price band. In fact, that $4 equals the real increase in average operating costs from 2010 to 2011 (EUCG, 2012), the biggest annual rise in a decade.

The implication is profound: Nuclear power plants, long thought to be very cheap to run once constructed, are under increasing competitive pressure—more immediately for some reactors than others, as new industry data reveal next.

Figure 1 compares the 2010 average generating costs derived above with a recent proprietary analysis[xv] by the operators' Electric Utility Cost Group (EUCG, 2012); those industry data illustrate how nuclear generating costs, like power prices, vary among plants and over time. Figure 1 sorts the generating costs of the 104 operating US reactors into four "quartiles" of 26 reactors each, ranked from the lowest-cost fourth (1st quartile) to the highest (4th quartile). From 2009 to 2011, Figure 1 shows a 2.4-fold range of average generating costs between the quartiles (hence an even wider range between outlier plants within the quartiles), and a nearly six-fold range of net capital additions. So why such wide cost variations?

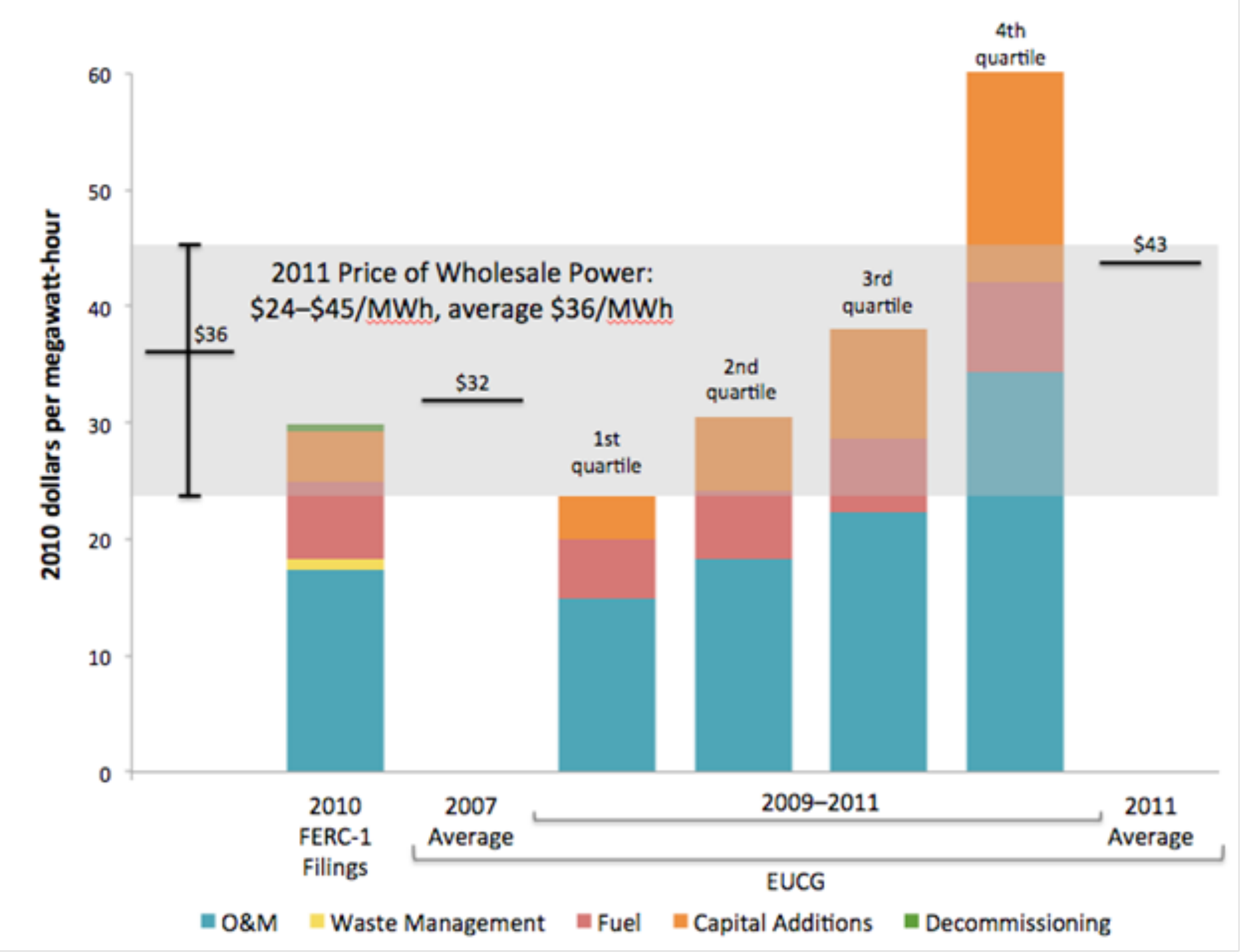

Figure Title: Nuclear power's price problem

Caption: The illustration compares (i) the 2011 normal energy price range and average (left vertical bar, in black, without capacity credits) for wholesale US electricity to (ii) four snapshots of average US nuclear generating costs. The four snapshots are: (a) the 2010 average, based on costs reported to FERC (author's analysis), and (b) the nuclear industry's analysis of its own average costs (EUCG, 2012) in three time periods: 2007, 2009 to 2011 by quartile, and 2011. The industry figures omit decommissioning costs but include waste management in fuel cost. All values shown are in 2010 dollars.

Most if not all of the high-net-capital-addition plants are said to have suffered extraordinary repair costs or invested in major upgrades to increase capacity and extend lifetimes—valuable benefits, but with significant costs. Such upgrades correct, anticipate, or forestall the effects of age: wear, corrosion, fatigue, leaks, cracks, contamination, and thermal and radiation embrittlement inexorably damage materials and degrade technical systems. Such deterioration presumably makes major repairs, prolonged outages, and potential accidents more likely and frequent, maintenance costlier, and profits lower. Operators therefore seek to minimize future regret. Renewing old components can indeed extend operating life if nothing else breaks first—it's a bet, like putting a new engine in an old car. But the required investment is as much a cost of continued operation now as a future repair would be later. Either way, rising capital additions like these may belie the assumption that nuclear plants will enjoy low future generating costs.

According to the Electric Utility Cost Group's analysis, the average nuclear total generating cost rose by one-third between 2007 and 2011 (especially in 2011) to $43 per megawatt-hour—two-fifths higher than my FERC 2010 estimate.[xvi] The biggest cause: 18 percent *annual* real escalation in net capital additions. That spending occurred chiefly in a modest number of high-cost units that bought power upratings or life extensions or both, or needed major repairs.

The 104 US reactors are diverse. With some exceptions, the units that are single or isolated, small, or trouble-prone may be harder to keep competitive. Yet other units could face greater pressure later, as nonnuclear competitors, especially renewable generators, become cheaper with mass production; as aging potentially raises nuclear generating costs and lowers capacity factors; as already-scarce spare parts for old equipment become less available from vanishing vendors in a dwindling market; and as imminent retirements from the rather aged staff population erode institutional memory and potentially weaken some operators' skill or focus.

Deciding whether to repair or shut down a nuclear unit will often depend less on its average generating cost than on its unpredictable, spiky, and large major-repair costs, like some of those units illustrated in the fourth quartile in Figure 1. As with fixing an old car, a reactor's owner must bet whether the investment will be justified by sufficiently long, cheap, and reliable future operation. A nuclear plant will be lucky to run for 40 to 60 years without facing a fix-or-close decision at least once: Of the 132 US power reactors ever licensed, by 2008, only 68 were still operating without having suffered at least one shutdown of a year or more (Lochbaum, 2008), and their clocks are ticking, too. Historic average costs, however, include *no* aging effects, making them a risky guide to the future in light of the emerging age-related trends that the Electric Utility Cost Group data in Figure 1 appear to imply.

The 2011 Fukushima Daiichi disaster intensified nuclear power's capital burdens worldwide. European reactors now face costs up to $33 billion for post-Fukushima safety retrofits (Kanter, 2012), while Électricité de France alone, operating an aging 58 of Europe's 134 reactors, estimates it will need as much as $46 billion to keep them in working order (Patel and de Beaupuy, 2010). US units too may face unpredictable ratcheting of regulatory requirements, and the few recently licensed new reactors, if completed, may need design changes as post-Fukushima safety reforms are defined.

"No [US] nuclear plant I know of," said former Nuclear Regulatory Commissioner[xvii] Peter Bradford, "has ever closed because it hit the end of its license" (Wald, 2012b). To be sure, license extensions have lately moved the goalpost and put the game into 20 years of overtime, but 28 US nuclear facilities closed between 1963 and 1998 (DOE/EIA, 2012a: 271) because they lost their cost-competitiveness, including one that melted down. While this primacy of operating economics may well persist, other reasons for closing nuclear plants may also emerge. Nobody can foresee how shutdown decisions might depend on such non-economic factors as political unease about old units near big cities, vulnerabilities to natural disaster or terrorism, another major accident anywhere in the world, or shifts from inflexible and vulnerable centralized units to flexible and resiliently linked distributed units.

The bleak competitive future for new nuclear plants

New nuclear plants face daunting economic and financial challenges rooted in recurrent history. From the early 1960s to 1978, when the first US nuclear boom stalled before the 1979 Three Mile Island accident[xviii], US utilities ordered 253 reactors. Three-fifths were abandoned or prematurely closed as lemons (Lochbaum, 2008). The completed units averaged threefold construction-cost overruns (Koomey and Hultman, 2007), due mainly to evolving safety regulations, unstandardized and unstable designs, challenges in managing big complex projects, and deteriorating finances as demand growth slackened and costs soared (Moody's Investor Service, 2009).[xix] Owners, paying hundreds of billions more than expected, averaged four-notch downgrades on 40 of 48 debt issuances (Moody's Investor Service, 2009: 3). Then in the 2000s, proposed next-generation US reactors suffered even steeper cost escalation (Lovins and RMI, 2011: 183).

The past decade saw another "nuclear renaissance" that economics choked off well before Fukushima. Starting in August 2005, US nuclear power enjoyed four years of the strongest political and policy support and the most robust capital markets in history, plus three years of high natural gas prices.[xx] Yet none of the 34 reactors then proposed could raise normal project financing, despite federal subsidies rivaling or exceeding their construction cost (Koplow, 2011; Lovins, 2010b).[xxi] Only a few projects survived. Two new reactors under construction in Georgia attracted private bond financing only after they were sufficiently de-risked by an $8.33 billion conditional federal loan guarantee projected to close in 2013, plus an unusual state law mandating customer financing in advance and guaranteeing full cost recovery even if the plant never runs.[xxii] In 2011, Moody's Investors Service downgraded similar bonds over concerns about analogously customer-financed South Carolina reactors (Bagley, 2011). Such financial structures lost bondholders up to $4 billion when a nuclear financing vehicle called the Washington Public Power Supply System collapsed in history's biggest municipal bond default (Lovins, 2010b).

Independent analysts estimate that new US nuclear plants would produce electricity at a total cost of roughly $110 to $342 per megawatt-hour.[xxiii] Not only is that uncompetitive with new or old gas-fired electricity; it can't even beat the construction *plus* operating cost of four abundant, widespread, and carbon-free options, *each* of which could readily displace all US nuclear output:

- Utilities' end-use efficiency programs, which help customers adopt equipment that converts less electricity into more and better services, cost about $17 to $34 per megawatt-hour or roughly $26 on average (Friedrich, 2009)—often less in factories and big buildings. Integrative design can make efficiency much cheaper still, with expanding rather than diminishing returns (Lovins et al, 2010; Lovins, 2010e; Lovins and RMI, 2011).
- Cogeneration, which produces electricity together with useful heat, often costs around $13 to $30 per megawatt-hour in industry and scarcely more in buildings, net of credit for its useful heat.[xxiv]
- New wind farms in the wind belt, during 2011 and 2012, sold power long-term for $25 to $40 per megawatt-hour, and prices are trending downwards (Wiser and Bolinger, 2012: 52).[xxv]
- Utility-scale[xxvi] photovoltaics cleared California's April 2012 public auction for new power supplies at an average price of $86 per megawatt-hour[xxvii]—cheaper than a new combined-cycle gas plant—and their prices are also trending downwards.

These comparisons conservatively omit many lesser but collectively important renewable options, valuable “distributed benefits” that can enormously increase the value of decentralized resources (Lovins et al, 2002), efficiency and renewables’ protection from volatile natural-gas prices (a free “price hedge” worth tens of dollars per megawatt-hour), and avoided delivery costs (which average about $40 per megawatt-hour) when electricity is saved or made at or near the customer.

Shale gas, too, is often said to ensure that gas-fired plants will beat new nuclear plants for decades[xxviii] on operating costs, despite gas’s rising and volatile US prices (Lovins and Creyts, 2012), which doubled in seven months after their April 2012 low. Yet the most durable, benign, and abundant competitors to new nuclear plants—efficiency and renewables—have falling costs and no fuel and would be equally advantaged by pricing carbon emissions.

Old reactors’ generating cost alone is increasingly challenged to compete with new carbon-free alternatives, but *new* reactors would add the crushing burden of construction costs an order of magnitude larger yet. On a pure microeconomic basis, few can claim a plausible business case for replacing retiring reactors with new reactors, leaving even one-time industry champions of nuclear energy skeptical of prospects for new construction.[xxix] A US nuclear phase-out will occur and indeed has been quietly underway for many years;[xxx] only the timing of its endgame is in question.

Paths to US nuclear phase-out

So what are the economic implications of the seemingly inevitable US exit from commercial nuclear generation? America’s 104 operating reactors average 32 years of age, and range in age from 16 to 43. They were originally licensed for 40 years, but 68 percent have been routinely extended to 60 years, another 14 percent have sought extension with equally strong prospects, and 16 percent plan to ask for extensions. Retirements have been buffered by Nuclear Regulatory Commission approval for 6.5 gigawatts of increased power ratings at existing plants, with another 7.6 gigawatts proposed (DOE/EIA, 2012g; DOE/EIA, 2013a). After that, the key question will be how long existing reactors will run—not how long their licenses last—before they’re replaced by non-nuclear resources.

Properly analyzing the elimination of nearly one-fifth of the country’s electricity production requires detailed and rigorous study, not only of the extremely complex electricity system, but also of the sectors that depend on it. Buildings use three-fourths of US electricity; industry uses one-fourth; both can profitably become far more efficient.[xxxi] In transportation, too, recent design and manufacturing innovations could advantageously electrify automobiles (Lovins and RMI, 2011), adding flexible loads and distributed storage that can help the grid accept variable supplies. Even partial capture of these lucrative opportunities could well stabilize or even decrease long-term electricity needs (Faruqui and Shultz, 2012).

In a 2011 whole-system analysis (Lovins and RMI, 2011), 61 independent nonprofit practitioners, helped by dozens of industry experts, showed how to run a US economy 2.6-fold larger in 2050 than in 2010, but with no oil, coal, or nuclear energy, one-third less natural gas, tripled energy efficiency, 74 percent renewable primary energy supply (up from 8 percent in 2010), 82 to

86 percent lower fossil carbon emissions, a $5 trillion lower net-present-valued cost than an extension of the status quo (pricing climate risks and all other external or hidden costs at zero), and no new inventions or acts of Congress. This transition could be led by business for profit.

That study, *Reinventing Fire*, compared four electricity scenarios: Maintain, which follows official forecasts; Migrate, a low-carbon new-nuclear-and-“clean-coal” case; Renew, a centralized 80-percent-renewable case; and Transform, a half-distributed, 80-percent-renewable case.

By choosing nuclear phase-out trajectories similar to the Maintain and Transform scenarios, *Reinventing Fire*’s in-depth analysis and modeling can be applied to three illustrative phase-out paths (Figure 2) that are by no means the fastest plausible ones:

- **Base Case.** The US Energy Information Administration’s 2013 Reference Case (DOE/EIA, 2012b) assumes 6.1 gigawatts of existing nuclear capacity retires before 2035, 8.5 gigawatts will be built (about 1.3 gigawatts more than currently underway), and 7.3 gigawatts of uprating will be approved at existing plants. Linearly extrapolating this forecast to 2050 yields a scenario comparable to the Maintain scenario.
- **Scheduled Retirement.** Using the Nuclear Regulatory Commission’s 2012–2013 Information Digest report on current plant licenses and generation capacity, this path assumes that no further uprates will be approved or further licenses renewed. It assumes completion of the four new units mentioned above, plus two Tennessee Valley Authority units that began construction in 1972 and 1974.
- **Transform.** The entire US nuclear fleet would retire by 2050 as all plants are closed at age 60 and the final 2 gigawatts are retired in 2050.

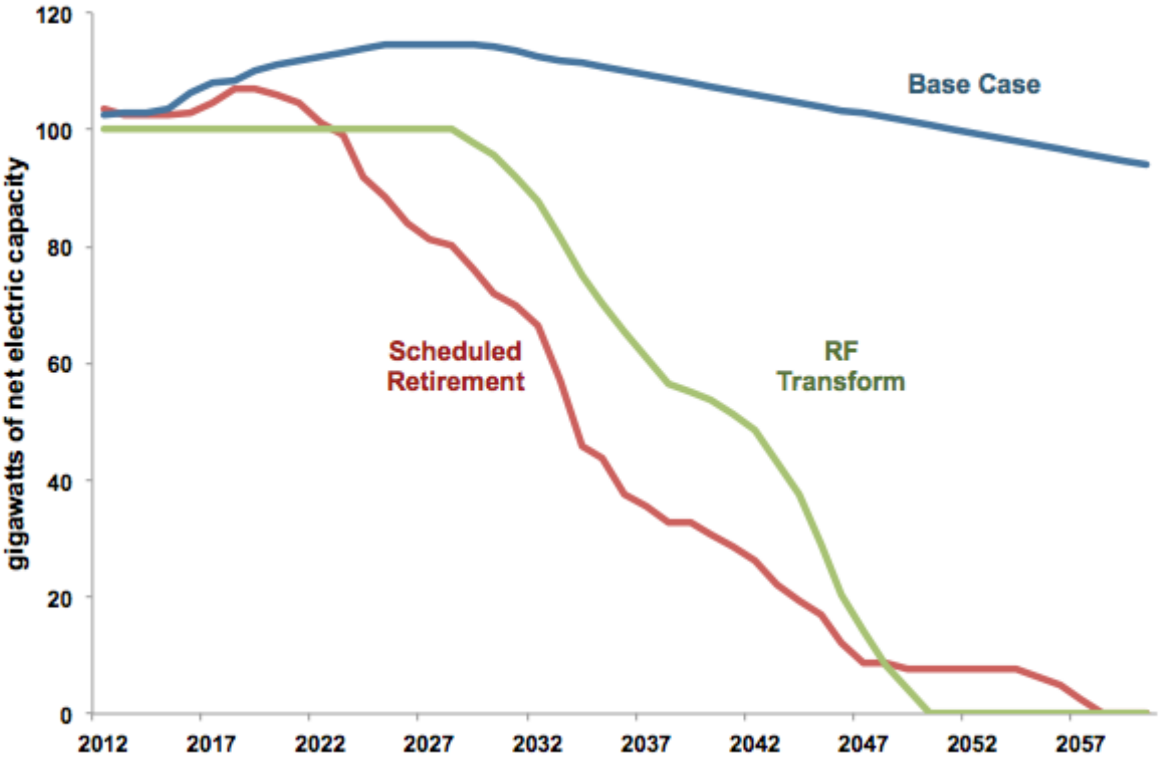

Figure Title: US nuclear phase-out paths
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Of course, when a reactor closes will depend not just on its age, but also on many other site- and system-specific factors. But average figures suffice to explore two linked economic questions: What economic costs could be avoided by phasing out nuclear power? And what economic costs would be incurred by replacing nuclear with other resources?

Avoided costs
Phasing out existing nuclear plants as just sketched could potentially avoid many costs. Some of those costs will exceed historic averages if aging effects, not yet fully understood, prove real. Subject to that uncertainty, not running nuclear plants can avoid fuel purchases, routine operation and maintenance costs, major repairs or retrofits (net capital additions), and paying to relicense plants not yet approved to run for an extra 20 years. Phase-out also proportionately reduces waste-management burdens[xxxii] and somewhat reduces decommissioning costs (but may increase their present value by incurring them sooner). Figure 3 summarizes these potential gross savings, which total on the order of $0.4 trillion to $0.5 trillion.

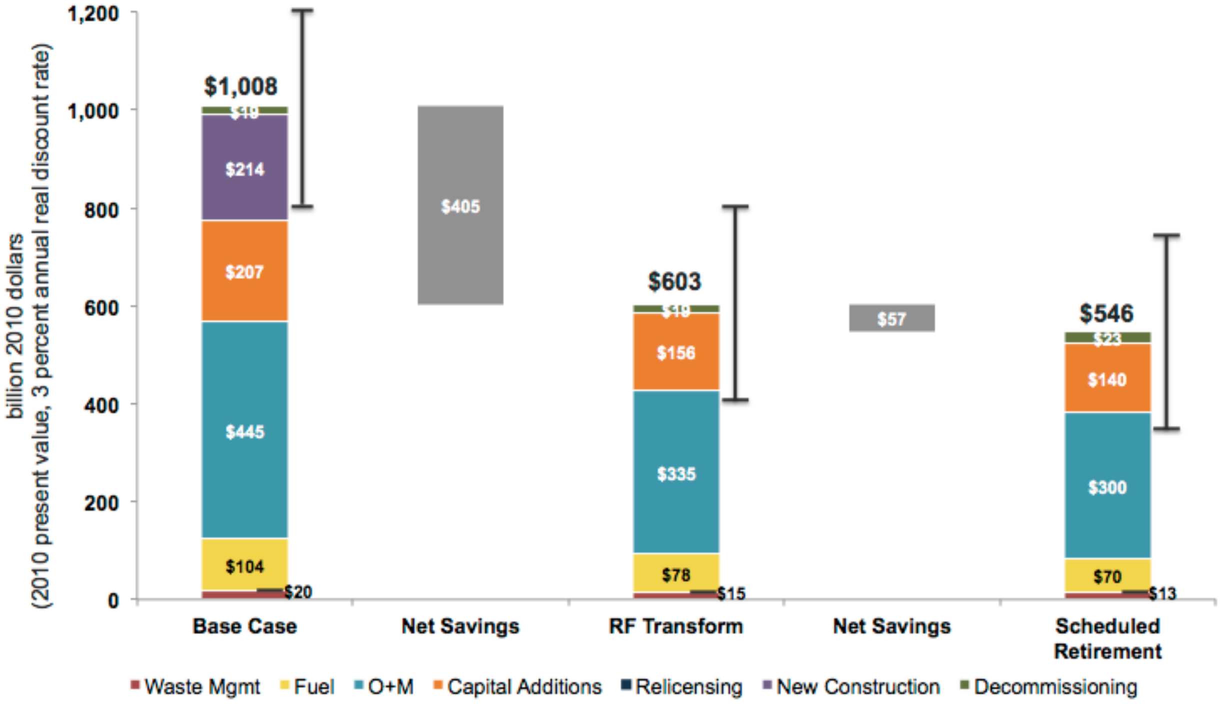

Figure Title: Could a phase-out save money?
Caption: Avoided costs from 2010 to 2050 in two scenarios that gradually phase out nuclear power rather than nearly sustaining it (Figure 2). All scenarios use 2009 to 2011 average nuclear generating costs (EUCG, 2012) and show as black error bars their cost range across the quartiles shown in Figure 1.

Replacement costs

The electricity production foregone by nuclear phase-out can be replaced by many different energy options. Properly assessing such systemic changes, especially to renewable and distributed options, requires an integrated whole-system analysis that continuously balances electricity supply and demand to provide reliable supply over time and space, subject to grid constraints. The *Reinventing Fire* analysis therefore used the National Renewable Energy Laboratory's state-of-the-art Renewable Energy Deployment System (ReEDS) linear programming model, which assesses grid balancing, transmission needs, and annual planning requirements over 134 balancing areas and 356 renewable resource regions throughout the lower 48 states.

The economic results will surprise many. Despite the Maintain and Transform scenarios' very different technologies, cost structures, and operating characteristics (Lovins and RMI, 2011: 203–204**)**, the net present value of their total system costs differs by only 2 percent. That is, the cost of a gradual nuclear phase-out in favor of modern carbon-free alternatives is negligible. Of course, actual resource portfolios and costs will depend strongly on local conditions.

The output of wind farms and photovoltaics fluctuates with the wind and sun, so upholding strict grid reliability standards requires new approaches to operating the system. Grid operators already have considerable experience managing grid variability and uncertainty. The *Reinventing Fire* analysis shows that reliable operation with 80 percent (or greater) renewable generation can be achieved by integrating a diversified portfolio of flexible supply- and demand-side resources. These include demand response (which unobtrusively shifts loads off-peak, partly via ice-storage air conditioning and smart charging of electric vehicles), electrical energy storage (more than one-third of it distributed in vehicles), increased and optimized transmission and interconnection capacity, and better coordination of regional electricity supply and demand through wider balancing areas and more frequent market clearance.[xxxiii] Such integration into a larger, more diverse grid is how Denmark gained the capacity to produce, in an average wind year, 36 percent of its electricity from renewables in 2010, including 26 percent from wind (Lovins and RMI, 2011: 199, 209). It's also how four German states ranged from 43 to 52 percent wind-powered in 2010 (Molly, 2011: 16), how Germany was making 25 percent of its annual electricity from renewables by mid-2012 (BDEW, 2012)—up to half at times in spring 2012 (Kirschbaum, 2012)—and how the power pool supplying 85 percent of the electricity in Texas was 26 percent wind-powered in November 2012 (Mirzatuny, 2012).

US and European studies have shown (NREL, 2012; European Climate Foundation, 2010) how, by similar techniques, even whole continents could make 80 percent or more of their electricity renewably by 2050. This may require far less bulk electricity storage than commonly assumed[xxxiv], if the two variable renewables, wind and photovoltaics, are properly diversified by type and location, forecasted, and integrated with flexible demand- and supply-side resources on the grid.

Some of the best US wind sites are remotely located in the High Plains, and the best solar sites lie in the desert Southwest, so moving those plentiful, low-cost resources to faraway load centers would need costly new transmission lines. An all-centralized, 80-percent-renewable US electricity system could need 220 to 370 percent higher transmission investment through 2050 (NREL, 2012). It may, however, cost more to exploit the best renewable resources if they are remote, compared to using merely good ones that are closer: For example, might Dakotas wind power cost more delivered to Chicago than the excellent wind resource in Lake Michigan? Such regionalization helps RMI's half-distributed Transform scenario reduce transmission costs (though distribution investment rises). And how much new transmission could be profitably displaced by three potentially cheaper alternatives at or near the customers—efficiency, demand response, and distributed generation? Regulators and investors will increasingly compare these options, and many transmission proposals may flunk that test. Any conclusions today about extra transmission's necessity and cost would thus be premature.

The Transform scenario's diverse, dispersed, renewable architecture could also be far more resilient than the base case. Lawrence Berkeley National Laboratory has estimated that blackouts already cost the US economy up to $160 billion annually (Hamachi LaCommare and Eto, 2004). Centralized grids are vulnerable to cascading blackouts—caused by natural disaster, accident, or malice—that could be even larger, longer, and in some cases irreparable. But grid reorganizations being piloted abroad (Ackerman et al, 2008; Lovins, 2010a) have shown a path to making prolonged regional blackouts impossible when distributed renewables, bypassing the vulnerable power lines where most failures start, feed local "microgrids" that can stand alone to support critical loads if needed. The US Department of Defense has adopted this approach to ensure its own mission continuity. So should the citizens the department is defending, who need their devices to work, too.

Finally, the Transform scenario demonstrates that phasing out nuclear power as part of a larger system transformation need not raise carbon emissions: They could fall by 82 to 86 percent at a $5-trillion net saving. Using zero-carbon renewables[xxxv] to displace nuclear and coal power would accelerate scaling renewables and reducing their costs, much as Germany's photovoltaic scaling has already cut its installed solar-system costs to half the US average (Wesoff, 2012). But what about the *total* cost of such a post-nuclear transformation?

The economic implications of nuclear phase-out

Reinventing Fire's scenarios explore, among other changes, phasing out nuclear and coal power plants in the United States by 2050 by integrating advanced end-use efficiency, 80-percent-renewable electricity supply from both centralized and distributed resources, and a diversified portfolio of flexible resources including demand response, electric vehicle integration, energy storage, and better operational integration of the whole electricity system. The result could be operationally secure, economically competitive with continued nuclear (or coal-plant) operation, and lower in waste generation, water use, and many risks. This strategy could also advance nonproliferation and global development (Lovins, 2010c; Lovins, 2010d) in concert with profitable climate protection (Lovins, 2005; Lovins, Sheikh, and Markevich, 2009).

A US nuclear phase-out could occur on many possible timelines. Post-Fukushima Germany changed a slowdown of its 2002 phase-out plan into a two- to three-year acceleration, led by the country's most pro-nuclear party, and with no political party dissenting. Remarkably, the 41 percent of German nuclear output shut down in August 2011 was replaced *during 2011*, over three-fifths by new renewable generation—while wholesale electricity prices and carbon emissions fell, employment and economic activity grew, and the country remained a net power exporter (Gipe, 2012; Carrington, 2012). Repeating 2011's pace of renewable expansion for three more years *could replace Germany's entire pre-Fukushima nuclear output before 2015* while meeting, in concert with comprehensive efficiency efforts, ambitious economic and environmental goals.

Might a US nuclear phase-out comparable to Germany's decade-long timetable cost more or less than the Transform scenario's 40-year phase-out? A proper answer to that question needs not just microeconomic comparisons between technologies, but rigorous simulation of nationwide shifts that ensure loadshape-matching, regional adequacy, grid stability, and reliable integration of variable renewables. In principle, modeling tools like those used in *Reinventing Fire*'s Transform scenario could yield an approximate answer.

Alternatively, greater use of existing combined-cycle gas plants could buffer a more leisurely deployment of renewables, efficiency, and cogeneration. Costs would depend on natural gas prices, which would react to such a demand surge, and on any carbon prices. If overall costs did fall, that could heighten the economic case for a faster nuclear phase-out. Carbon implications would need modeling too: Substituting gas for nuclear rather than for coal could delay a coal phase-out, but faster complementary shifts to efficiency and renewables could make both coal and nuclear phase-outs faster and cheaper.

As rigorous analysis explores the economic costs and benefits of different ways to provide electricity services on a local and regional basis, where and when renewables and efficiency present a "winning hand" compared with nuclear operation will depend on a host of local resource, grid, demand, loadshape, and dispatch issues. But whenever a nuclear plant must be either fixed or closed, regulators should insist on such a thorough whole-system analysis of alternative portfolios and their risks.

In many parts of the country, though, utility business models and electric utility regulation and public policy are not yet fully aligned to allow proper competition between nuclear generation, end-use efficiency, demand response, and distributed generation. Federal subsidies advantage nuclear power (Koplow, 2011) and often, to a lesser and less-analyzed degree, fossil-fuel generation. But there are other major distortions, too. Sometimes prices are opaque and purchasing biased. In 36 US states, regulated utilities earn more profit by selling more electricity but less profit if customers' bills fall, disadvantaging efficiency. In 31 states, regional auctions do not yet allow companies that save electricity to bid against new power supplies. Many arcane and archaic rules inhibit cogeneration, competition, and interconnection.[xxxvi] In most if not all states, impediments to full and fair competition among all ways to save or provide electricity persist. Wherever such impediments are removed, efficiency and renewables will compete more effectively, and customers and national security will benefit.

Nuclear power enjoys the advantages of comprehensive and durable[xxxvii] subsidization, supportive regulation and public policy, a grid designed around it, and operational practices and organizational structures that favor predictability over flexibility and centralized brittleness over distributed resilience. However, the emerging and far more dynamic marketplace, permeated with information and new players, is rapidly creating new business and regulatory models that enhance flexibility, diversity, customer choice, innovation, and entrepreneurial opportunity (Lovins and RMI, 2011). Nuclear power faces complex and ultimately existential challenges in adapting to stiff competition from efficient, diverse, distributed, renewable alternatives. The inevitable US nuclear phase-out, whatever its speed, is therefore just part of a far broader and deeper evolution from the remarkable electricity system that has served the nation so well to an even better successor now being created.

Author Biography

Amory Lovins is chairman and chief scientist of Rocky Mountain Institute (www.rmi.org)—an independent, apolitical, nonprofit think-and-do tank that drives the efficient and restorative use of resources. Lovins, originally an experimental physicist, has led energy innovations for four decades (chiefly with the private sector), written 31 books and more than 470 papers, and taught at 10 universities, most recently Stanford's School of Engineering and currently the Naval Postgraduate School. The views expressed here are solely those of the author and do not represent any government agency, particularly the US Department of Defense.

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References

Ackermann T, Lund P, Martensen N, et al. (2008) Overview of the Danish Cell Project. In: 7th International Workshop on Large Scale Integration of Wind Power and on Transmission Networks for Offshore Wind Farms. Available at: http://www.energynautics.com/downloads/publikationen/Paper_Energynautics_Overview_Danish_Cell_Project.pdf

Associated Press (2012) Nuclear Regulatory Commission wants more analysis at troubled San Onofre nuke plant. Southern California Public Radio. December 26. Available at: http://www.scpr.org/news/2012/12/26/35404/nuclear-regulatory-commission-wants-more-analysis-/

Bagley C (2011) SCANA Corp. hit with debt downgrades by Moody's. *Triangle Business Journal.* September 20. Available at: http://www.bizjournals.com/triangle/news/2011/09/20/scana-corp-hit-with-debt-downgrades.html

BDEW (Bundesverband der Energie und Wasserwirtschaft) (2012) Erneuerbare Energien liefern mehr als ein Vertel des Stroms. July 26. Available at: http://www.bdew.de/internet.nsf/id/20120726-pi-erneuerbare-energien-liefern-mehr-als-ein-viertel-des-stroms-de

Bony L, Doig S, Hart C, et al. (2010) Solar PV Balance of System. Rocky Mountain Institute. Available at: http://www.rmi.org/SolarPVBOS

Bupp IC and Derian J-C (1978) *Light Water: How the Nuclear Dream Dissolved*. New York: Basic Books.

Business Week (1978) Nuclear Dilemma: The atom's fizzle in an energy-short world. December 25. Available at: http://thinkprogress.org/wp-content/uploads/2011/06/BW-1978-1.gif

California Energy Commission (2010) Comparative Costs of California Central Station Electricity Generation. January. Available at: http://www.energy.ca.gov/2009publications/CEC-200-2009-017/CEC-200-2009-017-SF.PDF

Carrington D (2012) Busting the carbon and cost myths of German's nuclear exit. *Guardian*, May 23. Available at: http://www.guardian.co.uk/environment/damian-carrington-blog/2012/may/23/energy-nuclear-power-germany

Center for Climate and Energy Solutions (2012) Cogeneration / Combined Heat and Power (CHP). Available at: http://www.c2es.org/technology/factsheet/CogenerationCHP

Chazan C and Boxell J (2012) EDF plant cost rises damp nuclear hopes. *Financial Times,* December 3.

Committee on America's Energy Future. (2009) *America's Energy Future: Technology and Transformation.* Washington, D.C.: The National Academies Press. Available at: http://books.nap.edu/openbook.php?record_id=12710&page=R2

CPS Energy (2010) Corporate Sustainability Report 2010. Available at: http://www.cpsenergy.com/files/Sustainability_Report.pdf

DiSavino S (2012) US natural gas boom claims first nuclear plant. Reuters, October 22. Available at: http://www.reuters.com/article/2012/10/22/dominionresources-idUSL3E8LM6J420121022

DOE/EIA (US Department of Energy / Energy Information Administration) (1989) Commercial Nuclear Power 1989, Prospects for the United States and the World. DOE/EIA-0438(89).

DOE/EIA (1995) Analysis of Nuclear Plant Operating Costs: A 1995 Update. Available at: ftp://tonto.eia.doe.gov/service/oiaf9501.pdf

DOE/EIA (2010) Annual Energy Outlook 2010. Available at: http://www.eia.gov/oiaf/aeo/pdf/0383(2010).pdf

DOE/EIA (2011a) Electricity resource planners credit only a fraction of potential wind capacity. May 13. Available at: http://www.eia.gov/todayinenergy/detail.cfm?id=1370

DOE/EIA (2011b) Average utilization of the nation's natural gas combined-cycle power plant fleet is rising. June 9. Available at: http://www.eia.gov/todayinenergy/detail.cfm?id=1730

DOE/EIA (2012a) Annual Energy Review 2011. September. Available at: http://www.eia.gov/totalenergy/data/annual/pdf/aer.pdf

DOE/EIA (2012b) Annual Energy Outlook 2013 Early Release Report. Available at: www.eia.gov/forecasts/aeo/er/index.cfm

DOE/EIA (2012c) Monthly Energy Review—November 2012. Available at: http://www.eia.gov/totalenergy/data/monthly/archive/00351302.pdf

DOE/EIA (2012d) Wholesale Market Data. December 27. Available at: http://www.eia.gov/electricity/wholesale/index.cfm

DOE/EIA (2012e) Electricity Monthly Update. Regional Wholesale Markets: October 2012. 21 December. Available at: http://www.eia.gov/electricity/monthly/update/archive/december2012/wholesale_markets.cfm

DOE/EIA (2012f) 2011 Brief: Wholesale electricity prices mostly lower in 2011. January 11. Available at: http://www.eia.gov/todayinenergy/detail.cfm?id=4530

DOE/EIA (2012g) Uprates can increase US nuclear capacity substantially without building new reactors. July 17. Available at: http://www.eia.gov/todayinenergy/detail.cfm?id=7130

DOE/EIA (2013a) Uprates can increase U.S. nuclear capacity substantially without building new reactors. January 2. Available at: http://www.eia.gov/todayinenergy/detail.cfm?id=9410

DOE/EIA (2013b) 2012 Brief: Average wholesale electricity prices down compared to last year. January 9. Available at: http://www.eia.gov/todayinenergy/detail.cfm?id=9510

Dominion (2012) Dominion to close, decommission Kewaunee Power Station. October 22. Available at: http://dom.mediaroom.com/2012-10-22-Dominion-To-Close-Decommission-Kewaunee-Power-Station

Economist (2012) Nuclear power: the dream that failed. March 10 leader and cover story. Available at: http://www.economist.com/node/21549936 and http://www.economist.com/node/21549098

EUCG (2012) Electric Utility Cost Group, Nuclear Committee Data, summary used by kind permission. Full database available to members at: http://www.eucg.org

European Climate Foundation (2010) Roadmap 2050: A Practical Guide to a Prosperous, Low Carbon Europe. Available at: http://www.roadmap2050.eu/

Faruqui A and Shultz E (2012) Demand Growth and the New Normal. *Public Utilities Fortnightly*, December, pp. 22–28.

FERC (Federal Energy Regulatory Commission) (2010) National Assessment & Action Plan for Demand Response. Available at: http://www.ferc.gov/legal/staff-reports/06-17-10-demand-response.pdf

Financial Times (2012) Nuclear Winter. August 3. Available at: http://www.ft.com/intl/cms/s/0/0bc5c4be-dd7c-11e1-8be2-00144feab49a.html#axzz2HADRkQQ6

Friedrich K, Eldridge M, York D, et al. (2009) Saving Energy Cost-Effectively: A National Review of the Cost of Energy Saved Through Utility-Sector Energy Efficiency Programs. *American Council for an Energy-Efficient Economy (ACEEE),* September. Available at: http://www.aceee.org/research-report/u092

Gipe P (2012) German Coal-Fired Generation of Electricity Falls While Renewable Generation Rises. October 3. Available at: http://www.renewableenergyworld.com/rea/news/article/2012/10/german-coal-fired-generation-of-electricity-falls-while-renewable-generation-rises

Grübler A (2009) An assessment of the costs of the French nuclear PWR program 1970–2000. *International Institute for Applied Systems Analysis,* October 6. Available at: http://webarchive.iiasa.ac.at/Admin/PUB/Documents/IR-09-036.pdf

Grübler A (2010) The costs of the French nuclear scale-up: A case of negative learning by doing. *Energy Policy,* 38(9): 5174–5188. Available at: http://dx.doi.org/10.1016/j.enpol.2010.05.003

Hamachi LaCommare K and Eto JH. (2004) Understanding the Cost of Power Interruptions to US Electricity Consumers. Lawrence Berkeley National Laboratory*,* September. Available at: http://certs.lbl.gov/pdf/55718.pdf

Harding J (2007) Economics of Nuclear Power and Proliferation Risks in a Carbon Constrained World. Proceedings from June 28 symposium at the Nonproliferation Policy Education

Center, Washington, D.C. Available at: http://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

Harman G (2010) Operation: CPS—The mysterious death of a done nuclear deal. *Current,* January 6. Available at: http://www2.sacurrent.com/news/story.asp?id=70826

Hoste G (2012). San Antonio's Goal to be "New Energy Capital" Pays Off With Jobs, Investment. *RMI Outlet,* March 12. Available at: http://blog.rmi.org/san_antonio_goal_to_be_new_energy_capital_pays_off_with_jobs_and_investment

Kanter J (2012) Europe's Nuclear Reactors Need Repair or Upgrades. *New York Times,* October 3. Available at: http://www.nytimes.com/2012/10/04/world/europe/safety-review-says-europes-nuclear-reactors-need-repair.html

Keystone Center (2007) Nuclear Power Joint Fact-Finding. June. Available at: http://www.nuclear.gov/pdfFiles/rpt_KeystoneReportNuclearPowerJointFactFinding_2007.pdf

Kidd S. (2008) Escalating costs of new build: what does it mean? *Nucl. Eng. Intl.* 22 Aug. Available at: http://www.neimagazine.com/opinion/opinionescalating-costs-of-new-build-what-does-it-mean/

Kirschbaum E (2012) Germany sets new solar power record, institute says. *Reuters.* May 26. Available at: www.reuters.com/assets/print?aid=USBRE84P0FI20120526

Koomey JG. (2011) Was the Three Mile Island accident in 1979 the main cause of US nuclear power's woes? June 24. Available at: http://www.koomey.com/post/6868835852

Koomey J and Hultman N (2007) A Reactor Level Analysis of Busbar Costs for US Nuclear Plants, 1970–2005. *Energy Policy,* 35(11): 5630–5642. Available at: http://dx.doi.org/10.1016/j.enpol.2007.06.005

Koplow D (2011) Nuclear Power: Still Not Viable Without Subsidies. Union of Concerned Scientists, February. Available at: http://www.ucsusa.org/assets/documents/nuclear_power/nuclear_subsidies_report.pdf

Lochbaum D (2008) Energy Independence and Global Warming. Testimony to the US House of Representatives, Washington, D.C., 12 March. Available at: http://www.ucsusa.org/assets/documents/nuclear_power/20080312-ucs-house-nuclear-climate-testimony.pdf

Lovins AB (1986) The Origins of the Nuclear Power Fiasco. In: *Energy Policy Studies.* University of Delaware. 3:7–34. Available at: http://www.rmi.org/Knowledge-Center/Library/1986-01_OriginsNuclearPowerFiasco

Lovins AB (2005) Nuclear Power: Economics and Climate-Protection Potential. Rocky Mountain Institute. Available at: http://www.rmi.org/Knowledge-Center/Library/E05-14_NuclearPowerEconomicsClimateProtection

Lovins AB (2009) "New" Nuclear Reactors, Same Old Story. Rocky Mountain Institute. Available at: http://www.rmi.org/Knowledge-Center/Library/2009-07_NuclearSameOldStory

Lovins AB (2010a) Efficiency and Micropower for Reliable and Resilient Electricity Service: An Intriguing Case-Study from Cuba. Rocky Mountain Institute. Available at: http://www.rmi.org/Knowledge-Center/Library/2010-23_CubaElectricity

Lovins AB (2010b) Nuclear Socialism. *The Weekly Standard,* October 25. Available at: http://www.weeklystandard.com/articles/nuclear-socialism_508830.html

Lovins AB (2010c) On Proliferation, Climate, and Oil. *Foreign Policy,* January 21. Available at: http://www.rmi.org/Knowledge-Center/Library/2010-03_ForeignPolicyProliferationClimateOilPattern

Lovins AB (2010d) Proliferation, Oil, and Climate: Solving for Pattern. Rocky Montain Institute. Available at: http://www.rmi.org/Knowledge-Center/Library/2010-02_ProliferationOilClimatePattern

Lovins AB (2010e). Integrative Design: A Disruptive Source of Expanding Returns to Investments in Energy Efficiency. Rocky Mountain Institute. Available at: http://www.rmi.org/Knowledge-Center/Library/2010-09_IntegrativeDesign

Lovins AB et al. (2002) Small Is Profitable: The Hidden Economic Benefits of Making Electrical Resources the Right Size. Rocky Mountain Institute. Available at: http://www.smallisprofitable.org

Lovins AB et al. (2010) Factor Ten Engineering Design Principles. Rocky Mountain Institute. Available at: http://www.rmi.org/Knowledge-Center/Library/2010-10_10xEPrinciples

Lovins AB and Creyts J (2012) Hot Air About Cheap Natural Gas. *RMI Outlet,* September 6. Available at: http://blog.rmi.org/blog_hot_air_about_cheap_natural_gas

Lovins AB and Rocky Mountain Institute (2011) *Reinventing Fire: Bold Business Solutions for the New Energy Era.* White River Junction, Vermont: Chelsea Green Publishing. Information at: http://www.reinventingfire.com.

Lovins AB and Sheikh I (2008) The Nuclear Illusion. Rocky Mountain Institute. Available at: http://www.rmi.org/Knowledge-Center/Library/E08-01_NuclearIllusion

Lovins AB Sheikh I, and Markevich A (2009) Nuclear Power: Climate Fix or Folly? Rocky Mountain Institute. Available at: http://www.rmi.org/Knowledge-Center/Library/E09-01_NuclearPowerClimateFixOrFolly

McMahon J (2012) Exelon's "Nuclear Guy": No New Nukes. *Forbes,* March 29. Available at: http://www.forbes.com/sites/jeffmcmahon/2012/03/29/exelons-nuclear-guy-no-new-nukes/

Mirzatuny M (2012) Wind Makes Up 26% Of ERCOT Load In November, New Record. *Environmental Defense Fund: Energy Exchange*. November 26. Available at: http://blogs.edf.org/energyexchange/2012/11/26/wind-makes-up-26-of-ercot-load-in-november-new-record/

Molly JP (2011) *Status der Windenergienutzung in Deutschland—Stand 31.12.2010.* DEWI GmbH. Available at: http://www.dewi.de/dewi/fileadmin/pdf/publications/Statistics Pressemitteilungen/31.12.10/Foliensatz_2010.pdf

Moody's Investor Service (2008) New Nuclear Generating Capacity: Potential Credit Implications for US Investor Owned Utilities. May.

Moody's Investor Service (2009) New Nuclear Generation: Ratings Pressure Increasing. June. Available at: http://tinyurl.com/3cbplsd

NREL (National Renewable Energy Laboratory) (2012) Renewable Electricity Futures Study. Available at: http://www.nrel.gov/analysis/re_futures/

Nuclear Energy Institute. (2012) The Cost of New Generating Capacity in Perspective. February. Available at: http://www.nei.org/corporatesite/media/filefolder/WHITE-PAPER-Cost-of-New-Generating-Capacity-in-Perspective.pdf

OECD NEA. (2003) Report on Decommissioning Nuclear Plant: Policies, Strategies, Costs. Nuclear Energy Agency of the OECD, Paris. Available at: http://www-ns.iaea.org/downloads/rw/projects/r2d2/workshop6/references/others/oecd-nea-decom-npps-eng-2003.pdf

ORNL (Oak Ridge National Laboratory) (2000) US Nuclear Power Plant Operating Cost and Experience. Available at: http://pbadupws.nrc.gov/docs/ML0101/ML010120458.pdf

ORNL (2003) US Nuclear Power Plant Operating Cost and Experience. Available at: http://www.ornl.gov/~webworks/cppr/y2001/rpt/118301.pdf

Palmintier B, Hansen L, and Levine J (2008) Spatial and Temporal Interactions of Solar and Wind Resources in the Next Generation Utility. Presented at SOLAR 2008, San Diego, May 3-8. Rocky Mountain Institute. Available at: http://www.rmi.org/rmi/Library/2008-21_SolarWindNGU

Patel T and de Beaupuy F (2010) EDF's French nuclear spending plans face government scrutiny. July 2. *Bloomberg Business News.* Available at: http://www.bloomberg.com/news/2010-07-02/electricite-de-france-s-french-nuclear-spending-plans-face-state-scrutiny.html

Penn, I. (2012) Utilities nationwide could share the financial pain of the idled Crystal River nuclear plant. *Tampa Bay Times*. December 30. Available at: http://www.tampabay.com/news/business/energy/utilities-nationwide-could-share-the-financial-pain-of-the-idled-crystal/1268290

Pfeifenberger J (2012) Resource Adequacy. Presentation to IRC Board Conference, Dallas. The Brattle Group, May 23. Available at: http://www.brattle.com/_documents/UploadLibrary/Upload1043.pdf

Romm J (2011) No, the Three Mile Island Accident in 1979 Was Not a Major Cause of US Nuclear Power's Woes. *Climate Progress,* June 25. Available at: http://thinkprogress.org/climate/2011/06/25/244122/three-mile-island-accident-nuclear-power

Rothwell G (2004) Nuclear Power Economics. In: Cleveland C.J., Ed., *Encyclopedia of Energy*, **4**:383–394, Elsevier.

San Antonio Business Journal (2009) CPS Energy sends team to Japan to negotiate cut in nuclear power costs. November 9. Available at: http://www.bizjournals.com/sanantonio/stories/2009/11/09/daily7.html

Schneider M, Froggatt A, and Hazemann J (2012) World Nuclear Industry Status Report 2012. July. Available at: http://www.worldnuclearreport.org/IMG/pdf/2012MSC-WorldNuclearReport-EN-V2.pdf

Sciortino M, Nowak S, Witte P, et al. (2011) Energy Efficiency Resource Standards: A Progress Report on State Experience. Washington, DC: American Council for an Energy Efficient Economy (ACEEE).

Seel J, Barbose G, and Wiser R (2012) Why Are Residential PV Prices in Germany So Much Lower Than in the United States? Lawrence Berkeley National Laboratory, September. Available at: http://eetd.lbl.gov/ea/emp/reports/german-us-pv-price-ppt.pdf

Seeley T and Chang G (2007) NRG Files First Full Application for US Reactor. *Bloomberg,* September 24. Available at: http://www.bloomberg.com/apps/news?pid=newsarchive&sid=a_Kp1BDPL6ZE

Smith R (2012) Cheap Natural Gas Unplugs US Nuclear-Power Revival. *Wall Street Journal,* March 15. Available at: http://online.wsj.com/article/SB10001424052702304459804577281490129153610.html

Trabish HK (2012) Wind Industry Calls for 6-Year Phaseout of Production Tax Credit Subsidy. greentechmedia. December 13. Available at: http://www.greentechmedia.com/articles/read/Wind-Industry-Calls-for-6-Year-Phase-Out-of-PTC-Subsidy

Wald M (2012a) Aging and Expensive, Reactors Face Mothballs. *New York Times,* October 23. Available at: http://www.nytimes.com/2012/10/24/business/energy-environment/economics-forcing-some-nuclear-plants-into-retirement.html

Wald M (2012b) Wisconsin Nuclear Reactor to be Closed. *New York Times,* 22 October. Available at: http://www.nytimes.com/2012/10/23/business/energy-environment/dominion-to-close-wisconsin-nuclear-plant.html

Wesoff E (2012). German Solar Installations Coming In at $2.24 per Watt Installed, US at $4.44. greentechmedia, June 19. Available at: http://www.greentechmedia.com/articles/read/German-Solar-Installations-Coming-in-at-2.24-Per-Watt-Installed-U.S-at-4/

Williams GSK (2012) Nuclear Plants Are Nuked. AOL Energy for Greentech Media. December 21. Available at: http://www.greentechmedia.com/articles/read/the-nations-nuclear-plants-are-nuked

Wiser R and Bolinger M (2012) 2011 Wind Technologies Market Report. US Department of Energy, August. Available at: http://eetd.lbl.gov/ea/emp/reports/lbnl-5559e.pdf

Woolf T, Whited M, Vitolo T, et al. (2012) Indian Point Replacement Analysis: A Clean Energy Roadmap—A Proposal for Replacing the Nuclear Plant with Clean, Sustainable Energy Sources. Synapse Energy Economics, Inc., October 11. Available at: http://www.riverkeeper.org/wp-content/uploads/2012/10/Synapse-Indian-Point-Replacement-Study-10-11.pdf

World Nuclear Association (2012) Nuclear power in the USA. Available at: http://www.world-nuclear.org/info/inf41.html#New_build

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[i] This article considers and applies to civilian power reactors only, not the more numerous US naval reactors, research reactors, or other reactor types.

[ii] New 2011 wind belt wind farms' Power Purchase Agreement levelized prices, net of the production tax credit, ranged from $20-odd to about $40 per megawatt-hour per megawatt-hour, averaging $32 and trending downwards (Wiser and Bolinger 2012:52). The Production Tax Credit's initial $22 per megawatt-hour subsidy lasts only 10 years, so its levelized value at a 3 percent per year societal real discount rate, a 40 percent marginal tax rate, and a 25-year operating life is approximately $18 per megawatt-hour before tax. An investor might assume a 15 percent annual real hurdle rate, raising the pretax levelized value to $28 per megawatt-hour.

[iii] Koplow (2011) estimated these at $3 to $8 per megawatt-hour in 2009, and they're rolled into the reported operating costs in Figure 1. In addition, likewise with no expiration date, but not included in Figure 1, the *next* 6 gigawatts of nuclear plants built get an 8-year (versus 10 for wind), $22 per megawatt-hour (same as wind) Production Tax Credit worth $11 per megawatt-hour from a societal or $25 from an investor perspective (as in note 2). Thus the total new-nuclear operating subsidy exceeds new wind power's production tax credit, and it's inconsistent to analyze removing one without also removing the other.

[iv] Wind's grid integration (balancing) costs are less than $12 per megawatt-hour and often below $5 per megawatt-hour, even if wind generates 40 percent or more of a utility's electricity (Wiser and Bolinger 2012: 63–68). Grid-integration costs (such as the reserve margin and spinning reserve required to offset sudden failures in large units or lines) should also be counted for nonrenewable electricity generators, but usually aren't, and as a conservatism, aren't included

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here either. Yet diverse continental-US utilities have calculated that producing up to or beyond 50 percent of their electricity from wind power would need balancing reserves below 10 percent and often below 5 percent of wind capacity (Wiser and Bolinger 2012: 65). Both are less than the 15 to 20 percent reserve margins classically required to manage the intermittence of large thermal power stations.

[v] Author's analysis from data in DOE/EIA (2012c) for January 2005 through August 2012.

[vi] 2010 US dollars are used throughout this article, converted using the GDP Implicit Price Deflator.

[vii] As noted below, this operation and maintenance cost looks low in an aging fleet. The authoritative Keystone Center (2007) nuclear-power fact-finding report, nine of whose 11 sponsors sold or ran reactors, found a 2010-dollar prospective range of $5.3 per megawatt-hour variable plus $20.2 to $22.0 per megawatt-hour fixed operation and maintenance cost. The latter figure includes one-half to one times the fleet-average value for net capital additions, which MIT economist Paul Joskow estimates to total about half of original construction cost. Keystone's long-term forecast of operation and maintenance costs plus net capital additions approximates actual costs just 2 to 4 years later (EUCG, 2012) for reactors with somewhat *below*-average generating costs, so these costs are rising more quickly than those experts expected.

[viii] Utility accountants capitalize nuclear fuel because it provides more than a year's service, but its gradual use as the plant runs is an operating cost that needn't be incurred if the plant doesn't run, so operators report it as an operating cost on their Form FERC-1 filings. I so count it here, because this article is about economics, not accounting.

[ix] That's because even though many ultimate decommissioning costs are fixed after decades of operation, they also depend rather strongly on the total neutron flux that has irradiated the reactor's structures, and on time-dependent processes like corrosion. For this analysis, RMI engineers Leia Guccione and Ryan Matley estimated decommissioning would cost $406 million undiscounted per unit (OECD NEA, 2003), equivalent to $0.7 per megawatt-hour levelized. Other sources' differing variabilized cost estimates have similar present values after discounting over decades.

[x] All but six of the 104 units have sought uprates. Exelon Corp. has invested about $3.5 billion in uprates totaling 1.3 to 1.5 gigawatts (World Nuclear Association, 2012). I don't account here for resulting economic benefits to the operator, nor speculate on whether uprates might reduce reactors' operational lifetimes or safety margins by pushing equipment harder.

[xi] Net capital additions are not directly reported on Form FERC-1, but can be inferred from the total capitalized plant value reported there compared with the previous year (ORNL, 2000 and ORNL, 2003). Like DOE/EIA (1995: Table 1), I treat these capitalized additions as an operating cost avoidable by closing a plant and often important in such decisions. I use the average 1993 value (DOE/EIA, 1995) of $4.21 per megawatt-hour, close to other old estimates (ORNL, 2000; Rothwell, 2004). EUCG (2012) found a much higher 2009–11 average around $10.5, ranging by quartiles from $3.8 to $22.1.

[xii] The author conservatively assumes the lower value.

[xiii] The wholesale price band shown below in Figure 1 reflects all 2011 energy-weighted daily-average day-ahead prices in the 10 markets reported by Intercontinental Exchange (DOE/EIA, 2012d). The upper and lower edges of the band are energy-weighted averages of the 10 markets' annual high and low daily prices, smoothing out their extremes. However, the band shown

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excludes the costliest 10 percent of days in each market (peaking at $590 per megawatt-hour in ERCOT and $587 in Entergy Louisiana), and the cheapest 10 percent of Mid Columbia days (down to $5 per megawatt-hour during the Northwest's spring hydro runoff, but $21 without it). Without the first exclusion, the upper edge of the national wholesale price band would rise from $45 to $97 per megawatt-hour; without the second, the lower edge would fall from $24 to $17. The $36 per megawatt-hour average counts all days in all 10 markets. Other markets are similar (DOE/EIA, 2012e). Falling wholesale prices since 2008 haven't made most nuclear operators unprofitable but have hurt some.

[xiv] Based on six markets' average capacity prices between 2004 and 2014 (Pfeifenberger, 2012: 8, excluding New York City), a smoothed value shouldn't exceed $50 per kilowatt-year, which at 0.90 capacity factor yields $6 per megawatt-hour. Wind's 2011 average capacity factor of 0.33 (Wiser and Bolinger, 2012: vii) would leave a difference of about $4 per megawatt-hour. EIA reasonably assigns a 15 to 30 percent wind capacity value, more than many utilities (DOE/EIA, 2011a), and simply picking anti-correlated sites can double wind's firm output per installed kW (Palmintier, Hansen, and Levine, 2008).

[xv] Each FERC-1 respondent chooses its own rules, making the results less meaningful than with EUCG's (2012) rigorously uniform accounting basis. EUCG defines "total operating" cost as fuel plus operation and maintenance, and "total generating cost" as those costs plus net capital additions.

[xvi] The difference is due mainly to EUCG (2012)'s roughly $6 per megawatt-hour higher average net capital additions and nearly $6 higher average operating and maintenance cost, which one industry reviewer believes may be substantially inflated by allocating "non-dedicated" general and administrative costs (which continue even if the reactor closes) disproportionately to nuclear plants because they're more mature than some other kinds.

[xvii] Bradford also chaired the Maine and New York utility commissions and was president of the National Association of Regulatory Utility Commissioners.

[xviii] Bad economics made orders for nuclear power plants in the United States fall by 90 percent from 1973 to 1975 and cease in 1978 (*Business Week*, 1978; Bupp and Derian, 1978; Koomey, 2011; Romm, 2011). For raw data, see DOE/EIA (1989: table E1 [orders]), and DOE/EIA (2012: 271, table 9.1 ["Nuclear Generation Units, 1955–2009," Construction Permits Issued]).

[xix] Uninformed commentators often add opponents' interventions and litigation to the costs nuclear operators face, but nuclear orders collapsed very similarly in countries with little or no opposition or protest (Lovins, 1986).

[xx] In nominal dollars, US utilities paid $2 to $3 per million BTU for natural gas in the 1980s and '90s; that price rose to $4.30 in 2000, peaked at $9.01 in 2008, then only in 2009 plummeted to $4.74 and stayed around $5 through 2011.

[xxi] Lovins and Sheikh (2008) summarize how top financial firms insisted on ever-greater federal subsidies, got them, then spurned them as inadequate.

[xxii] Similarly abroad: Of the 64 nuclear power projects under construction globally, all are in centrally planned power systems, mainly run by authorities with a draw on the public purse, and none was fairly compared with or competed against available alternatives. With such a weak business case (*Economist*, 2012), reactors are increasingly bought and sold mainly by state-owned firms. ABB and Siemens have exited the nuclear market; Combustion Engineering sold its nuclear business to Westinghouse which sold to Toshiba; now Toshiba wants to cut its stake.

The global nuclear industry's troubles are now so big that new construction can't credibly offset, let alone reverse, nuclear retirements (Schneider et al, 2012).

[xxiii] All the estimates are "levelized," a conventional way to convert time-varying costs into one constant figure in 2010 dollars. Excluding very low estimates (Nuclear Energy Institute, 2012) that appear far "wide of the mark" (Kidd, 2008), those estimates are: The Energy Information Administration (DOE/EIA, 2010) said $111 to $122 per megawatt-hour. Keystone's 2007 fact-finding report (Keystone Center, 2007), perhaps the soundest independent work yet, estimated $87 to $114 per megawatt-hour using probably a low capital cost and perhaps high fuel costs. A National Research Council study (Committee on America's Energy Future, 2009) found about $136 per megawatt-hour without federal loan guarantees. Moody's Investor Service (2008) estimated $157. The chair and spokesman of the Keystone study's economics committee (Harding, 2007; Lovins and Sheikh, 2008) calculated $177 to $194. On the high end, California's 2010 Cost of Generation Model (California Energy Commission, 2010) calculated $342 per megawatt-hour for a merchant AP1000 reactor; $273 if the reactor were owned by a shareholder-owned utility; and $167 if owned by a public utility. These estimates generally do not apply nuclear power's operating or capital subsidies.

[xxiv] Lovins (2005) used empirical data from a leading developer to calculate levelized costs of $13 to $30 per megawatt-hour, perhaps up to $46, for cogeneration recovering waste heat, or $43 to $83 burning natural gas or biogas priced at $5.7 to $9.2 per thousand cubic feet, or about $15 to $34 for well-optimized gas-fired building cogeneration. Cogeneration (Center for Climate and Energy Solutions, 2012) has nearly as much US installed capacity as nuclear power, often runs as steadily, and is targeted to add another 40 gigawatts in US industry by 2020. Even if fueled with market natural gas (as nearly three-fourths is), cogeneration typically reduces total carbon emissions, compared with the separate power plant and boiler it displaces.

[xxv] Net of the production tax credit; without it, equivalent to about $54 to $69 per megawatt-hour from an investor perspective or $43 to $58 from a societal perspective, as in note 2.

[xxvi] US rooftop systems typically yield costlier electricity than utility-scale systems, but may be more profitable because they compete with retail prices on the customer's side of the meter.

[xxvii] This levelized photovoltaic price is net of the 30 percent federal solar tax credit, implying without it an unsubsidized price of around $127 per megawatt-hour in California—or about $70 to $90 per megawatt-hour at the halved system cost (Wesoff, 2012; Seel, Barbose, and Wiser, 2012; Bony et al, 2010) in Germany, which is cloudier than almost any part of the US.

[xxviii] See McMahon (2012) and Smith, 2012 (whose headline mischaracterizes the timing: the "nuclear renaissance" never began (*Economist*, 2012), and new-build prospects collapsed before gas prices sank).

[xxix] See McMahon (2012); *Financial Times* (2012). Proposed alternative kinds of reactors do not change the economics materially (Lovins, 2009), nor do small modular reactors. Nuclear reactors do not scale down well, and the economies sought from mass-producing hypothetical small reactors cannot overcome the decades of head start enjoyed by small modular renewables (which attracted $1 trillion of private investment from 2004 to 2011 and are investing another quarter-trillion dollars a year), not to mention cogeneration and efficient end-use.

[xxx] Although DiSavino (2012) describes Kewaunee as the first such economic shutdown, the World Nuclear Association (2012) says eight US premature reactor shutdowns between 1991 and

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2009 were “due to their having high operating costs.” The same appears to be true of the roughly 19 US units (other than Three Mile Island) shut down previously.

[xxxi] Tripled or quadrupled energy productivity in buildings, with a 33 percent internal rate of return, and doubled energy productivity in industry, with 21 percent, could be achieved by 2050 if their adoption ramped up over 20 years to the levels already achieved in the Pacific Northwest (Lovins and RMI, 2011).

[xxxii] By generating less waste and incurring lower federal fees. If those fees fall short of actual costs, as seems likely, the shortfall socialized to taxpayers could rise with faster phase-out.

[xxxiii] This paragraph is extensively documented elsewhere (Lovins and RMI, 2011; NREL, 2012). Note iv explains why counting grid integration costs could well advantage wind power.

[xxxiv] For example, RMI’s Transform scenario includes 44 gigawatts of battery storage in superefficient electric vehicles and 69 gigawatts of ice storage in air-conditioning. Centralized storage would comprise 22 gigawatts of existing pumped hydroelectric storage plus 53 gigawatts of new centralized hydroelectric or compressed air storage. The 75 gigawatts of total centralized storage would total just 5 percent of the scenario’s renewable capacity, which comprises 330 gigawatts of wind, 990 of photovoltaics (700 on rooftops), 50 of solar-thermal-electric with built-in thermal storage, 25 of biomass, and 10 of geothermal. A distributed-and-renewable scenario may need less electricity storage and backup than one reliant on central thermal stations, as the wind data in note iv illustrate.

[xxxv] Natural gas is currently abundant, and efficient combined-cycle-gas generating capacity averaged only about a 53 percent capacity factor in 2010 (DOE/EIA, 2011b). Thus early nuclear retirements could be replaced temporarily by gas-fired electricity until permanent zero-carbon capacity could be installed and grid-integrated. (The German experience shows how quickly that could happen.) To avoid guessing long-term natural-gas or carbon prices, I compared nuclear operating costs directly with zero-carbon alternatives, which typically have lower levelized cost,— --properly counting fuel-price volatility (Lovins and Creyts, 2012)—than new or often existing combined-cycle gas plants.

[xxxvi] Even under industry consensus standards that ensure lineworker and public safety, many utilities or states still forbid “islandable” interconnection—a key to resilient supply, as the “islands” of local electricity production can serve critical loads with or without connection to the wider grid.

[xxxvii] Subsidies to modern renewables typically expire every one to five years, but key nuclear subsidies—including a unique cap on accident liability (without which the industry says it can’t operate)—have been in force for more than 50 years (Koplow, 2011). That liability cap covers every operating reactor for its lifetime, even if the law expires; the rest never expire.