CLIMATE CHANGE AND NUCLEAR POWER

THE STAKES

The threats to the biosphere and human prospect from Climate Change[978], increasingly termed Climate Emergency[979], demand six unprecedentedly rapid changes in the global economy:

- replace energy use with "passive" ways to deliver the same services[980];
- use energy[981] and energy-intensive materials[982] with dramatically greater efficiency to serve human needs by providing desired services in buildings, mobility, and industry;
- convert devices that provide heat and mobility from burning fossil fuels to using low-carbon energy carriers that can be made cleanly (electricity, hydrogen, renewable direct heat, etc.);
- drastically decarbonize energy supplies;
- remove excess carbon from the air, most readily by natural systems (forests, grasslands, croplands, wetlands, oceans, etc.), though engineered systems are being tried too; and
- reduce non-CO2 greenhouse gas emissions—particularly methane by drastically limiting flaring, leakage and venting in the oil and gas industries.

Of these, decarbonization is progressing fastest in generating electricity—formerly by replacing fossil-fueled with nuclear power plants, whose share then declined since 1996 (see **Figure 3**), and lately with even larger and faster-growing renewable generation. Experiments underway[983] may add the option of burning fossil fuels and capturing and storing their carbon (as waste or useful products) rather than emitting it.

Electricity is only about 20 percent of delivered energy[984], but that share is slowly rising. Making electricity emits 38 percent (2016)[985] of fossil carbon dioxide (CO_2), the most important greenhouse gas, so if existing nuclear generation (a tenth of global commercial electricity)

978 - IPCC, "Global Warming of 1.5°C", Intergovernmental Panel on Climate Change, Special Report, 2018, see https://www.ipcc.ch/sr15/.

979 - See The Climate Mobilization, "Climate Emergency Campaign", see https://www.theclimatemobilization.org/climate-emergency-campaign, accessed 3 August 2019.

980 - E.g. daylighting to provide light, insulation to provide thermal comfort, densifying local services to avoid transport and/or increase mobility options (walking, biking), etc.

981 - Amory B. Lovins, "How big is the energy efficiency resource?", *Environmental Research Letters*, 13:090401, 18 September 2018, see https://iopscience.iop.org/article/10.1088/1748-9326/aad965/pdf, 4-min video here https://iopscience.iop.org/article/10.1088/1748-9326/aad965, both accessed on 5 August 2019.

982 - Energy Transitions Commission, "Mission Possible", 19 November 2019, see www.energy-transitions.org/mission-possible, finds that industrial CO_2 emissions can be abated by mid-century at reasonable cost, two-fifths by "circular economy" measures that wring more work from fewer tons of cement, steel, aluminum, etc. Complementary further savings are being explored.

983 - Those mainly discussed chemically separate CO_2 from flue gas right after burning fuels. So far they appear costly and not available in the short term, except arguably the Allam cycle for oxygen-and-natural-gas generation by using hot CO_2 rather than steam as the working fluid: Sonal Patel, "Inside NET Power: Gas Power Goes Supercritical", 1 April 2019, *POWER Magazine*, see https://www.powermag.com/inside-net-power-gas-power-goes-supercritical/, accessed 30 August 2019.

984 - IEA, "Key World Energy Statistics—2016 simplified world energy balances, Mtoe", see https://www.iea.org/statistics/kwes/balances/, excluding feedstock uses.

985 - IEA, "Global Energy & CO2 Status Report", March 2019, p 21, see www.iea.org/geco/.

displaced an average mix of fossil-fueled power generation and nothing else, it would offset the equivalent of 4 percent of total global CO_2 emissions. Expanding nuclear power could displace other generators—fossil-fueled or renewable. Nuclear power is frequently promoted as a nearly carbon-free[986] substitute for electricity made from coal and natural gas (oil-fired electricity is negligible). Nuclear power is thus often presented as an essential part of the climate solution, deserving greater subsidy and policy support (called "not forcing nuclear out of the market" or "not taking nuclear off the table" or "keeping the nuclear option open")—either because climate protection is so hard and urgent that all options would be needed, or to protect existing jobs and infrastructures, or because other solutions would be too small, slow, costly, or impractical.

" we must pay attention to carbon, cost, and time, not to carbon alone "

Any claim that not expanding or sustaining nuclear power makes climate solutions "drastically harder and more costly"[987] must depend on comparing the nuclear option with other options. What criteria should such comparisons use? Past criteria have been incomplete. The coal-fired power plants that make 38 percent of the world's electricity and emit 30 percent of the world's total energy-related CO_2 were built by paying attention to cost but not carbon. The nuclear plants, which make just over one-fourth as much electricity but directly burn no fossil fuel, are defended by paying attention to carbon but not cost. Yet to protect the climate, we must abate the most carbon at the least cost—and in the least time—*so we must pay attention to carbon, cost, and time, not to carbon alone.* This chapter explores that logic. An analytic framework and metric to compare all options' "climate-effectiveness," including those with intermediate carbon emissions such as gas-fired generation or cogeneration (of electricity plus useful heat), is available elsewhere[988].

The more urgent climate protection becomes, the more vital it is to achieve *the greatest greenhouse gas reductions per dollar and per year.* Being virtually carbon-free is not sufficient; limited money and time also require "climate-effectiveness." Any solution that saves less greenhouse gas emission per dollar, or does so slower, than it could have will stabilize the Earth's climate less and later than it should have. That is, costly and slow options avoid less carbon per dollar and per year than cheaper and faster options could have, and thus make climate change worse than it should have been: even though they are low-carbon, they still reduce and retard achievable climate protection compared to what was achievable. Yet such common-sense comparisons are rarely discussed—leading to results akin to arguing that since people are hungry, hunger is urgent, and filet mignon and rice are both food, both are essential

986 - A complex literature points out that nuclear power is not strictly carbon-free, not only because of fossil-fuel energy embodied in its construction but also because of complex fuel-chain requirements: Benjamin K. Sovacool, "Valuing the greenhouse gas emissions from nuclear power: A critical survey", *Energy Policy*, August 2008, see https//:doi.org/10.1016/j.enpol.2008.04.017; and for comparison with other energy technologies, see Fig. 7.6, p. 539, in T. Bruckner et al., "Energy Systems," in O. Edenhofer et al., eds., "Climate Change 2014: Mitigation of Climate Change", Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, *Cambridge University Press*, 2014, see www.ipcc.ch. These indirect emissions linked to the nuclear system are far smaller than the direct CO_2 releases from burning fossil fuel, and will not be considered further here. We also do not assess here such other debated climate effects as krypton-85's causing atmospheric ionization, nuclear heat release, nuclear power's effect on water resources and atmospheric humidity, or other indirect effects.

987 - IEA, "Nuclear power in a clean energy system", 28 May 2019, see https://www.iea.org/publications/nuclear/.

988 - Amory B. Lovins, T. Palazzi, "Effectively decarbonizing the electricity system", 2019, see https://www.rmi.org/decarb.

to combatting hunger. Our priorities in feeding people or providing energy services must be informed by relative cost and speed.

NUCLEAR POWER DISPLACES OTHER CLIMATE SOLUTIONS

Nuclear power is obviously not the only way to displace fossil-fueled electricity generation. The past decade's electricity transformation has morphed what were once considered distinctive nuclear advantages—billion-watt scale, steady operation (most of the time), low operating cost—into the handicaps of gigantism and complexity, inflexibility, and greater dispatch cost than nearly free-to-run renewables and demand-side resources (using electricity more efficiently or more timely). Since each of these competing options can succeed only at the expense of the others, nuclear advocates increasingly seek to ensure that their favored technology replaces not only fossil fuels but also renewable power.

This might be rational if nuclear power were far more effective. For example, it might seem obvious that nuclear power has avoided huge CO_2 emissions from fossil-fueled power plants—63 $GTCO_2$ during 1971–2018 according to a new nuclear report by the OECD's International Energy Agency (IEA), which says

> Without nuclear power, emissions from electricity generation would have been almost 20% higher, and total energy-related emissions 6% higher, over that period.[989]

But that depends on what would have been bought in its place. IEA assumes mostly fossil-fueled power plants.[990] But if a portfolio of end-use efficiency or renewables or both had been backed, matured, and bought instead (as U.S. President Truman's Paley Commission recommended in 1953), they could have avoided as much or significantly more carbon emissions.[991]

Similarly, IEA states that

> For countries lacking their own domestic energy resources, reliance on nuclear power can reduce import dependence and enhance supply security. For example, in Japan, which must import all its fuels for nonrenewable power generation, it is estimated that fuel imports over the period 1965–2010 were reduced by at least 14.5 trillion yen (US$132 billion) due to the development of nuclear power.[992]

989 - IEA, "Nuclear power in a clean energy system", 28 May 2019, op. cit.

990 - IEA, "Nuclear power in a clean energy system", op. cit., p.9, Fig.4, Pp.53–4 show the assumed mix was about 44 percent gas, 12 percent coal, 44 percent renewable, and zero efficiency.

991 - What delayed the renewable revolution until the 2010s was not lack of technology or market opportunity but sparse attention, even outright opposition, by the same governments that instead lavished more than a trillion dollars of support on nuclear power. Indeed, an early spurt of efficiency and renewables adoption in the U.S. in the mid-1980s—until its success crashed energy prices—demonstrated their early ripeness.

992 - IEA, "Nuclear power in a clean energy system", 28 May 2019, op. cit.

However, fossil fuel saved by Japan's nuclear program came at a very high economic cost.[993] Building renewables instead, or providing more energy services by saving electricity, would have cost less (at international prices), fuel costs would be zero and other operating costs negligible, and accident costs practically zero, so those alternatives would have saved even more yen and no less carbon. Renewables and efficiency can thus "bolster energy security" at least as well as nuclear power. Actually, Japan is poor in domestic *fuels* but rich in a scarcely tapped renewable *energy* potential. Though energy trade and exchange are often advantageous, renewable resources are so abundant, diverse, and widespread that probably no nation lacks sufficient renewable potential to meet its people's needs efficiently.[994]

"Renewables and efficiency can thus "bolster energy security" at least as well as nuclear power"

This tension between nuclear power and other low-carbon resources is not just theoretical. They compete for the same markets, where efficiency and renewables, and often natural gas, outcompete new and even existing nuclear plants. The nuclear industry's unrivaled political power has therefore been applied, initially in six of the United States, to adding new operating subsidies for distressed nuclear plants (see **United States Focus**). These novel schemes generally substitute political deals for market choices, carve out long-term mandatory nuclear supply allotments not contestable by renewables, and in exchange offer renewable allotments arguably smaller than continued market competition would have yielded. At the same time, both nuclear and fossil-fuel industries and lobbyists press strongly at all policy levels to inhibit, disparage, and suppress renewables, both directly and more subtly. For example, every kWh of uncompetitive generation forced into the market by new subsidies or guaranteed to nuclear operators by preferential dispatch (like Japan's nuclear must-run rule) is a kWh for which renewables cannot compete; and by letting utilities block renewable energy from their grids at any time, for any reason or no reason, Japan makes renewable developers' revenues unpredictable and their projects very hard and costly to finance.

Such rivalry occurs in many countries. Globally, an important subset of the technical literature criticizing renewable energy is prepared and publicized by nuclear advocates to support campaigning by the industry and its allies. For understandable commercial reasons, the nuclear industry has become one of the +most potent obstacles to renewables' further progress, seeking to strangle a competitor to defend its own prospects by diverting demand and capital to itself. The nuclear industry may complain of a reciprocal effort by practitioners and advocates of renewable energy. This chapter examines that tangled competition of technologies, investments, and ideas.

993 - Building Japan's nuclear plants (at historic average costs around ¥$_{2014}$286/We, plus ~10 percent for construction financing) cost about as much as those fuel savings—plus their non-fuel operating costs and decommissioning, plus fuel-chain infrastructure (just the Rokkasho reprocessing plant has already cost ¥2.9 trillion (US$26.8 billion), not counting earlier reprocessing, enrichment and fuel fabrication facilities), plus the officially estimated cost of the Fukushima Daiichi accidents—¥22 trillion (US$203 billion) estimated by the government or ¥35–81 trillion (US$323–748 billion) estimated by Japan Center for Economic Research. Thus, it appears that so far, cumulative cost is several times cumulative benefit, leaving little prospect of covering total costs over the fleet's lifetime. As in the previous example, this raises the question whether fuel and carbon could have been saved more cost-effectively.

994 - See e.g. IRENA, "Global Atlas for Renewable Energy: Overview of Solar and Wind Maps", International Renewable Energy Agency, 2014, see www.irena.org/publications/2014/Jan/Global-Atlas-for-Renewable-Energy-Overview-of-Solar-and-Wind-Maps; IPCC, "Fifth Assessment Report", 2014, pp. 525–526.

NON-NUCLEAR OPTIONS SAVE MORE CARBON *PER DOLLAR*

New-build Costs

New nuclear plants, lacking a business case[995] (see **Nuclear Power vs. Renewable Energy Deployment**), have never been bid into competitive wholesale power markets as competing resources routinely are. Nearly all the nuclear plants under construction are transactions between governments or state-owned enterprises not subject to market discipline and generally unable to engage capital markets without sovereign guarantees. As the International Energy Agency (IEA) states:

> Because of the sheer scale of the investment required, all but 7 of the 54 nuclear power plants under construction globally [see Overview of Current New-Build] are owned by state-owned companies and all but one of the projects in private hands (all of which are in advanced economies) are subject to price regulation, which reduces risks to investors....This is unlikely to change soon. In the current policy and market environment, it is difficult to see any privately-owned utility embarking on a Generation III project in Europe or in North America without strong government support to minimize financial risks to investors. In developing countries, state-owned companies are responsible for all new nuclear investment.[996]

Table 19 | New-build Costs for Nuclear, Renewables and Efficiency

	Lazard Ltd. (2018)[a] (in $US\$_{2018}$/MWh)	BNEF[b] (in $US\$_{2019}$/MWh)	Market Actuals (in $US\$_{2018-2019}$/MWh)
Nuclear new-build	151	195–344 (US)	see country sections
Utility-scale solar	36–44	30–35	19 (Mexico)
Onshore wind power	29–56	27–32	22–26 (India), 17 (Mexico)
Electric end-use efficiency bought by utility programs	0–50	—	U.S. average 23–31[c] (2009–12)

Source: Lazard, BNEF, Market Actuals

Notes

a - Lazard, "Levelized Cost of Energy Analysis–Version 12.0", 8 November 2018, see www.lazard.com/media/450784/lazards-levelized-cost-of-energy-version-120-vfinal.pdf.

b - E. Giannakopoulou, T. Brandily, 1H 2019 LCOE Update, 26 March 2019, Bloomberg New Energy Finance subscriber database, see www.bnef.com, accessed 9 July 2019.

c - Megan A. Billingsley, Ian M. Hoffman, et al., "The program administrator Cost of Saved Energy for utility customer-funded energy efficiency programs", Lawrence Berkeley National Laboratory (LBNL), March 2014, see https://emp.lbl.gov/sites/all/files/lbnl-6595e.pdf; and Maggie Molina, "The best value for America's energy dollar: a national review of the cost of utility energy efficiency programs", American Council for an Energy-Efficient Economy, Research Report U1402, 25 March 2014, see http://aceee.org/research-report/u1402; also M. Wemple, "DSM Achievements and Expenditures 2013", see http://www.esource.com/members/DSM-INDBMK-Achievements-2013/DSM-Achievements-and-Expenditures-Study.

Even before the latest unhappy chapters such as Olkiluoto-3 (see **Finland Focus**) and Flamanville-3 (see **France Focus**), nuclear new-build's real levelized electricity costs were officially assessed as rising 130 percent in France during 2005–15, 29 percent in Japan, and

995 - Ben Wealer et al., "High-priced and dangerous: nuclear power is not an option for the climate-friendly energy mix", German Institute for Economic Research, July 2019, see www.diw.de/documents/publikationen/73/diw_01.c.670581.de/dwr-19-30-1.pdf.

996 - IEA, "Nuclear power in a clean energy system," 2019, op. cit., p. 19. P 5 recommends for new-build support "long-term contracts, price guarantees and direct state investments."

75 percent in the U.S.[997] Conversely, just in the past five years, U.S. solar and wind prices fell by two-thirds, putting new nuclear power out of the money by about 5–10-fold (see **Nuclear Power vs. Renewable Energy Deployment** for additional details):

Nuclear new-build thus costs many times more per kWh, so it buys many times less climate solution per dollar, than these major low-carbon competitors. That reality could usefully guide policy and investment decisions if the objective is to save money or the climate or both.

This gap is widening as nuclear costs keep rising and renewable costs falling. IEA agrees that

> Solar PV costs fell by 65 percent between 2012 and 2017, and are projected to fall by a further 50% by 2040; onshore wind costs fell by 15% over the same period and are projected to fall by another 10–20% to 2040.[998]

The National Renewable Energy Laboratory (NREL) expected in 2018[999] that onshore wind power would get 27 percent cheaper during 2016–50 and photovoltaics 60 percent, so by 2050 they should cost respectively around US$27/MWh and US$18/MWh in good sites. Yet those projections exceed Mexico's respective unsubsidized low prices of US$19 and US$17 bid *in the previous year*—33 years before 2050. The main outlier in acknowledging this pattern, the IEA, is struggling to improve its renewables forecasting: since 2002, it has raised wind power forecasts sixfold and solar forecasts 23-fold without ever catching up with reality, so installed solar capacity is now over 50 times the 2002 forecast. That's because IEA's renewable cost projections lag the market, and because its forecasting model, like other conventional economic models, is structurally unable to handle increasing returns—as Thomas Friedman says, "The more you buy, the cheaper it gets, so you buy more, so it gets cheaper."

“ installed solar capacity is now over 50 times the 2002 forecast ”

IEA publishes many excellent studies on diverse topics, but its May 2019 nuclear report, the first in nearly two decades, is only partly consistent with evidence offered here, so we highlight some points that are not. IEA shows a 2040 levelized new-nuclear cost of just US$$_{2018}$100/MWh (34–71 percent below the market prices in **Table 19**), yet agrees it exceeds solar and onshore wind power costs.[1000] However, IEA projects those renewables to exceed US$50/MWh through 2040 for Europe and North America "under the same financing conditions" as its nuclear analysis (8 percent weighted-average cost of capital, 10–20-year financing duration). Capital markets evidently do not consider the risks equivalent, so U.S. wind power, for example, currently pays <4.5 percent for its capital, and unsubsidized renewables from Mexico to India are bid at around US$17–26/MWh. By inappropriately applying short-term nuclear-upgrade financial assumptions to long-range renewable investments, IEA calculates renewable prices for 2040 that are about twice today's competitive renewable prices and exceed those observed in all major markets (except Japan) according to BNEF's authoritative assessment.

997 - IEA/NEA, "Projected Costs of Generating Electricity 2015", Nuclear Energy Agency, September 2015, see www.oecd-nea.org/ndd/pubs/2015/7057-proj-costs-electricity-2015.pdf.

998 - IEA, "Nuclear power in a clean energy system", 28 May 2019, op. cit.

999 - National Renewable Energy Laboratory, "Annual Technology Baseline: 2018 ATB Cost and Performance Summary", 2018, see https://atb.nrel.gov/electricity/2018/summary.html.

1000 - IEA, "Nuclear power in a clean energy system", 28 May 2019, op. cit.

The business case for modern renewables is so convincing to investors that the latest official U.S. forecast[1001] foresees 45 GW of renewable additions from mid-2019 to mid-2022, *vs.* 7 GW of net retirements for nuclear and 17 for coal. With modern renewables now supplying nearly two-thirds of the world's 2017–18 net additions to global generating capacity, the marketplace rout is nearly complete: non-hydro renewables in 2018 got eight times as much investment as nuclear power, nearly three times that of fossil-fueled generation.[1002] The nuclear industry's spectacular failures to deliver on its promises of a nuclear renaissance are "scaring off investors".[1003] But might they be drawn back by the latest round of claims that imminent new technologies will turn decades of rising nuclear costs into sharp declines?

> *" even free steam from any kind of fuel, fission, or fusion is not good enough, because the rest of the plant costs too much "*

A current fashion in nuclear advocacy is to admit today's reactors are uneconomic, then use the novel candor thus displayed to bolster the claim that new reactor types or fuel systems will make nuclear new-build competitive, so their development merits major public funding. That hope, however, is tempered by an awkward fact: of the prohibitive capital cost of Gen-III+ reactors, on the order of US$5,000–8,000+/ kW, ~78–87 percent is for *non*-nuclear costs.[1004] Thus, if the other ~13–22 percent—the "nuclear island" (Nuclear Steam Supply System)—were *free*, the rest of the plant would still be grossly uncompetitive with renewables or efficiency. That is, even *free* steam from any kind of fuel, fission, or fusion is not good enough, because the rest of the plant costs too much.

Equally simple logic clouds the economies of mass production hoped for from Small Modular Reactors (SMRs). As a matter of physics, reactors do not scale down well, so the more-careful analysts acknowledge SMRs—including in China—would initially cost significantly (often about twofold) more per kWh than today's gigawatt-scale reactors (see Small Modular Reactors). But, as shown above, today's new-build reactors already have ~5–10 times the levelized cost of modern renewables (let alone efficiency) per kWh. On durable observed learning curves (which nuclear power has never displayed), renewables will become another twofold cheaper by the time SMRs could be built, tested, and scaled. Two times 5–10 times two is a factor of 20–40—far beyond any plausible saving from mass production. No nuclear miracle is waiting to emerge. Small Modular Renewables, which do scale down well and whose economies of mass production have several decades' head start, have decisively won on cost.[1005]

1001 - Federal Energy Regulatory Commission, "Electricity Infrastructure Update for May 2019", see https://www.ferc.gov/legal/staff-reports/2019/may-energy-infrastructure.pdf.

1002 - REN21, "Global Status Report", Fig. 50, 2019, see https://www.ren21.net/gsr-2019/.

1003 - IEA, "Nuclear power in a clean energy system", 28 May 2019, op. cit., p. 22.

1004 - MIT Energy Initiative, "The Future of Nuclear Energy in a Carbon-Constrained World", 2018, see https://energy.mit.edu/wp-content/uploads/2018/09/The-Future-of-Nuclear-Energy-in-a-Carbon-Constrained-World.pdf, Table 2.2, p. 39, which also presents 10 percent typical and 16 percent best U.S. Light Water Reactor (LWR) cost fractions for the Nuclear Steam Supply System.

1005 - Or, as David Freeman said in his Foreword to WNISR2017: "The report makes clear, in telling detail, that the debate is over." See Mycle Schneider, Antony Froggatt, et al., "WNISR2017", 12 September 2017, see https://www.worldnuclearreport.org/The-World-Nuclear-Industry-Status-Report-2017-HTML.html#link0, accessed 22 July 2019.

Non-Economic Arguments for Nuclear Need

Objections to renewables other than cost-effectiveness are therefore often raised, whether expressed as technical issues or as hidden costs. These become ever less convincing as experience gives grid operators comfort with new ways of operating power systems, and as major heavy-electricals firms like General Electric, Siemens, Schneider and Asea Brown Boveri (ABB) refocus their skills from nuclear power to distributed and renewable energy systems. There are six main arguments:

- *Baseload:* The venerable "baseload" concept—that grid stability needs gigawatt-scale, steadily operating thermal (steam-raising) power plants—reflects the valid and vital economic practice of dispatching power at least operating cost, so resources with lowest operating costs are run most. This traditional role of giant thermal plants led many people to suppose that such plants are always needed. But now that renewables with no fuel cost are taking over the "baseload" role of being dispatched whenever available, those big thermal plants are relegated to fewer operating hours, making the term "baseload" an obsolete honorific. Thermal plants must now adapt to follow the net load left after cost-effective efficiency, demand response, and real-time "base-cost" renewable supply have been dispatched. Nuclear power's limited flexibility, and its technical and economic challenges when cycled, have thus become a handicap, complicating least-cost and stable grid operation with a rising share of zero-carbon, least-cost variable renewables.[1006] That is why Pacific Gas and Electric Company (PG&E) found that early closure of its well running Diablo Canyon reactors would save customers money and, by making the grid more flexible, raise renewables' share. Those reactors had become cheaper to close than to run: the power systems' shift to renewables had turned them from an asset to a liability[1007], so they'll be replaced by competitively procured low-carbon resources, saving both money and carbon.

- *Storage:* Keeping the grid reliable as solar photovoltaics and wind power (both with accurately forecastable but large variations in output) come to dominate electric generation requires changes in markets, institutions, operations, habits, and mental models. This has proven feasible in both theory and practice, as illustrated by national statistics' reports of 75 percent renewable coverage of annual electricity consumption in Scotland (2018), 72 percent in Denmark (2017, domestic production only), 67 percent in Portugal (2018), 40 percent in peninsular Spain (2018), and 38 percent in Germany (2018). Most such grids sometimes achieve over 100 percent renewable supply, just as Japan's southern island of Kyushu reported 76 percent peak solar coverage on 23 April 2017[1008], and Shikoku 102 percent on 3 May 2018[1009], despite Japanese utilities' insistence that far smaller renewable fractions will crash the grid. No "storage miracle" is needed, though some seem to be emerging. Whether solar, fossil-fueled, or nuclear, no generator needs 100 percent

1006 - Amory B. Lovins, "Do coal and nuclear generation deserve above-market prices?", *The Electricity Journal*, Vol.30, Issue 6, July 2017, see https://doi.org/10.1016/j.tej.2017.06.002, notes 58–68; and C. Morris, "Backing up Wind and Nuclear Power", 2015, see www.renewablesinternational.net/backing-up-wind-and-nuclear-power/150/537/86412/.

1007 - Amory B. Lovins, "Closing Diablo Canyon Nuclear Plant Will Save Money and Carbon", *Forbes*, 22 June 2016, see www.forbes.com/sites/amorylovins/2016/06/22/close-a-nuclear-plant-save-money-and-carbon-improve-the-grid-says-pge/, accessed 22 July 2019.

1008 - However, planned nuclear restarts would require such strong solar production to be curtailed under Japan's "uneconomic dispatch" rule.

1009 - Kazuhiko Miko, "Status and Challenges on the Power System in Japan", Smart Community Department, New Energy and Industrial Technology Development Organization, NEDO, IRED 2018 Session 1, 17 October 2018, see www.ired2018.at/Sessions/181017_IRED2018%20Session1_NEDOver.5.pdf, accessed 22 July 2019.

backup, because one generator does not serve one load; rather, all generators serve the grid, which in turn serves all loads. The grid is designed to back up failed plants with working plants, so varying solar and wind power output are backed up by a diversified portfolio of other variable renewables, dispatchable renewables, or other resources. Solar and wind power don't need massive batteries so they can produce power steadily like big thermal plants; rather, at least eight classes of grid flexibility resources[1010] besides bulk electrical storage and fossil-fueled backup are proven, available, cost-effective, and sufficient.[1011] We don't and needn't yet know all details of their ultimate mix as renewables rise toward 100 percent of generation; for now, we need only know that ample and affordable integration options exist.[1012] As climatologist Prof. Ken Caldeira says, "Controversies about how to handle the [electricity] endgame should not overly influence our opening moves."

- *Saturation*: The claim that high fractions of variable renewables suffer inevitable "value deflation" making them uncompetitive with thermal plants has turned out to be an artifact of models that exclude many available forms of effective mitigation.[1013] For example, in the ERCOT (Texas) power pool, thorough installation by 2050 of eight kinds of demand response can more than eliminate the supposedly problematic "duck curve" of steeply ramping net load as solar output declines and home loads rise late on hot summer days. Such a demand response strategy can also halve the summer daily load range, save one-fourth of nonrenewable capacity, make renewable energy one-third *more* valuable, and pay back in about five months.[1014]

> *"renewables generally have lower backup needs and costs than nuclear plants"*

- *Backup*: A related argument often claims that more renewables mean steeply rising grid integration costs. But such effects would be worse for nuclear-dominated grids because nuclear plants are bigger, more transmission-dependent, and more prone to sudden, lengthy, unpredictable failures (see **Belgium Focus** and **France Focus**). No kind of generator is 24/7/365—they all break—but failure is more consequential in big units. Variable renewables' "firming costs"—the cost of diversification (which may include network expansions), backup, storage, or other ways to ensure reliability standards are met even when sun and wind falter—remain low (generally under US$5/MWh, nearly always

1010 - 1. Efficient use; 2. unobtrusively flexible demand; 3. modern forecasting of variable renewables' output (often more accurately than demand); 4. diversifying those variable renewables—wind and solar PV—by type and location; 5. dispatchability—integrating wind and solar PV portfolios with the other renewables (not counting big hydropower, which could also be integrated more effectively than now and with cogeneration that must run anyhow to satisfy its thermal loads; 6. distributed thermal storage worth buying anyway, or managed thermal storage in buildings' existing thermal mass; 7. distributed electrical storage worth buying anyway (e.g. smart charging and discharging of electric vehicles bought to provide mobility); 8. hydrogen, now most likely from renewable electricity.

1011 - Amory B. Lovins, "Reliably integrating variable renewables: Moving grid flexibility resources from models to results", *The Electricity Journal*, Volume 30, Issue 10, December 2017, see https://doi.org/10.1016/j.tej.2017./11.006.

1012 - Tom W. Brown et al., "Response to 'Burden of proof: A comprehensive review of the feasibility of 100% renewable-electricity systems", *Renewable and Sustainable Energy Reviews*, Volume 92, 11 May 2018, see https://doi.org/10.1016/j.rser.2018.04.113.

1013 - Amory B. Lovins, "Do coal and nuclear generation deserve above-market prices?", *The Electricity Journa*l, Volume 30, July 2017, see https://doi.org/10.1016/j.tej.2017.06.002, and its note 81. An instructive four-part debate with two economists commissioned by nuclear owner Exelon, which objected to the article's §2 on climate-effective solutions, is in the October 2017 and December 2017 issues.

1014 - Cara Goldenberg et al., "Demand Flexibility", Insight Brief, Rocky Mountain Institute, February 2018, see www.rmi.org/wp-content/uploads/2018/02/Insight_Brief_Demand_Flexibility_2018.pdf.

under US$10[1015]) even at high renewable fractions.[1016] Indeed, evidence is emerging[1017] that the long-socialized but -unanalyzed corresponding firming costs to guard against the intermittence (forced outages) of large thermal plants are severalfold larger than for (say) wind farms but are not charged to those thermal projects as they are to variable renewables. Such costs can be major, as unbundled prices in ERCOT reveal[1018], because lumpy gigawatt-scale units require large reserve margin and spinning reserve, incurring corresponding part-load penalties and cycling costs. Thus balancing a soundly diversified portfolio of granular renewables may need severalfold fewer and cheaper resources than utilities have already bought to manage their big thermal plants' intermittence. If firming costs are ascribed to specific technologies or projects, then symmetrical comparison favors modern renewables; if firming costs are instead treated as inevitable system costs, as they always were for thermal plants, then they don't affect the choice of technologies. Either way, renewables generally have *lower* backup needs and costs than nuclear plants, despite solar and wind power's much lower capacity factors.

- *Ancillary services*: Large thermal plants provide vital "ancillary services" to the grid, such as frequency stability, voltage stability, short-circuit current, and fault management. However, the same services have turned out to be available at lower cost and higher quality from modern renewables' smart inverters and their virtual inertia, and from repurposing retired thermal plants' synchronous generators, without their prime movers, as synchronous condensers (also called synchronous compensators): these can provide the same services as a standard generator except active power, which can instead come from renewables or storage.[1019]

- *Resilience*: Nuclear power's claimed resilience benefits are compromised by many unpleasant attributes documented elsewhere.[1020] They also exhibit a high historical "dry-hole" risk of yielding no power or far less than expected. Of the 259 U.S. power reactors ordered during 1955–2016, just 28 (as of mid-2017), some slated for closure, remained competitive in their wholesale markets and had not yet suffered a year-plus safety-related outage.[1021] And in an

1015 - Ryan Wiser, Mark Bolinger, et al., "2017 Wind Technologies Market Report", Lawrence Berkeley National Laboratory (LBNL), published by the Office of Energy Efficiency, U.S.DOE, August 2018, p.70, see https://energy.gov/eere/wind.

1016 - Phil Heptonstall, Rob Gross, et al., "The costs and impacts of intermittency – 2016 update", UK Energy Research Centre, 21 February 2017, see http://www.ukerc.ac.uk/publications/the-costs-and-impacts-of-intermittency-2016-update.html, accessed 21 July 2019.

1017 - Amory B. Lovins, "Do coal and nuclear generation deserve above-market prices?", *The Electricity Journal*, July 2017, op. cit., notes 72–75.

1018 - American Wind Energy Association, "Wind energy helps build a more reliable and balanced electricity portfolio", 2015, see http://awea.files.cms-plus.com/AWEA%20Reliability%20White%20Paper%20-202-12-15.pdf.

1019 - Tom W. Brown, et al., "Response to 'Burden of proof: A comprehensive review of the feasibility of 100% renewable-electricity systems", *Renewable and Sustainable Energy Reviews*, Volume 92, September 2018, §3.5, see https://doi.org/10.1016/j.rser.2018.04.113; and Michael Milligan, "Sources of grid reliability services", Milligan Grid Solutions, *The Electricity Journal*, Volume 31, Issue 9, November 2018, see https://doi.org/10.1016/j.tej.2018.10.002.

1020 - Amory B. Lovins, "Do coal and nuclear generation deserve above-market prices?", *The Electricity Journal*, July 2017, §9 ("Fuel on hand"), elaborated in Amory B. Lovins, "Comments by Amory B. Lovins, Cofounder and Chief Scientist, Rocky Mountain Institute", FERC, Notice of Proposed Rulemaking, Grid Resiliency Pricing Rule, Submission 813728, Docket RM18-1-000, 23 October 2017, see https://elibrary.ferc.gov/idmws/file_list.asp?accession_num=20171023-5099; and Amory B. Lovins, "Errata—Correcting 23 October 2017 Comments (Submission 813728 by Amory B. Lovins", FERC, Submission 813743, see https://elibrary.ferc.gov/idmws/file_list.asp?accession_num=20171023-5109; both accessed 30 August 2019.

1021 - Amory B. Lovins, FERC comments, op. cit.

emergent risk, at least 100 reactors are reportedly in low-lying coastal sites vulnerable to sea-level rise that may occur during their lifetimes.[1022]

Costs of Lifetime-Extended Nuclear Plants

IEA's previously mentioned 2019 report admits new reactors can't compete in the market, but strongly encourages decades of lifetime extension for existing reactors to save both money and carbon. IEA says that will cost US$$_{2017}$40–55/MWh and will undercut US$50+/MWh renewables (calculated, as noted above, at about twice observed levels, let alone forecast levels, by assuming nuclear rather than actual renewable financing conditions). On its face, this comparison invites skepticism. If lifetime extension and continued operation can beat renewables through 2040, why will it need subsidies, and why won't all operators make that bet with their own money? In fact, many reactors, in particular in the U.S., cannot beat new renewables in day-to-day market competition, and are shutting down one or more decades before their licenses expire unless bailed out by new subsidies (see **United States Focus**). Wouldn't any reactors not yet upgraded become even less competitive after each is burdened by roughly US$0.5–1.1+ billion of backfitting/upgrade costs? And wouldn't their viability then erode further as renewables get cheaper, nuclear plants age, economic dispatch against growing renewable fleets reduces their run hours (spreading their fixed operating costs over smaller sales), and safety standards continue to ratchet?

Since new solar and wind power at market prices, though nearly pure capital costs, empirically undercut the upgrade cost plus operating cost of nuclear lifetime extensions, how does IEA conclude that foregoing those extensions would need a third of a trillion dollars more capital investment (over a third of it for grid expansions to reach "less accessible sites")? And why is IEA so concerned about the Nuclear Fade Case's raising wind and solar output[1023] in advanced economies by only one-fifth above the Sustainable Development Scenario—growing three rather than two times as fast as occurred during 2000–17, both well *below* respected market forecasts? IEA's excellent analysts may have answers, but their untransparent analysis raises doubts. We therefore explore next the most basic and intractable, yet often least noticed, cause of existing reactors' uncompetitiveness: the routine operating costs that according to IEA (p.4) put "most nuclear plants in advanced economies…at risk of closing prematurely."

Operating Costs of Existing Nuclear Plants

Even reactors that already implemented their lifetime-extension and safety-upgrade investments, or are excused by compliant regulators from making them, and whose original

1022 - J. Vidal, "What are coastal nuclear power plants doing to address climate threats?", 8 August 2018, see www.ensia.com/features/coastal-nuclear. Of 51 US nuclear sites, 55 were already found subject to beyond-design-basis flood hazards, but in January 2019, the U.S. Nuclear Regulatory Commission voted 3–2 not to require upgrades to address those identified hazards; see S.Q. Stranahan, "Why don't U.S. nuclear regulators acknowledge the dangers of climate change?", *The Washington Post*, 14 March 2019. In July 2019, NRC staff also proposed fewer safety inspections, fuzzier descriptions of problems, and other weakening of safety oversight. See S. Cooke, "Safety: NRC Proposes Reduced Inspection Effort", *NIW*, 19 July 2019.

1023 - IEA, "Nuclear power in a clean energy system", 28 May 2019, op. cit., p.63 uses implicit capacity factors of 25 percent for wind-plus-solar production. For comparison, the actual 2018 US averages were 37.4 percent for wind power, 26.1 percent for PVs, and 23.6 percent for solar thermal, compared with 73.3 percent for landfill gas and municipal solid waste, 49.3 percent for other biomass including wood, and 77.3 percent for geothermal; see U.S.EIA, "Electric Power Monthly—Table 6.7.B. Capacity Factors for Utility Scale Generators Not Primarily Using Fossil Fuels, January 2013–May 2019", 24 July 2019, see www.eia.gov/electricity/monthly/epm_table_grapher.php?t=epmt_6_07_b.

construction costs were already fully amortized, face normal operating costs. Once assumed too small to discuss, these have become a major obstacle to many plants' continued profitable operation, especially as their age increases the frequency and cost of major repairs. The US$2.9 billion annual losses *Bloomberg* reported in June 2017[1024], spread among 54 GW (over half of the U.S. nuclear installed capacity), probably remain unsustainable for units not yet retired or rescued for a few years by direct subsidies (see **United States Focus**). Their operating-cost data are often commercial secrets, but aggregated data reveal fundamental uncompetitiveness against most electric-efficiency investments and many modern renewables.

The "total generating cost" assessed here excludes initial construction and financing cost, and applies only to subsequent operations. It comprises three terms: fuel (including waste-management and decommissioning provisions), operation and maintenance ("O&M," including normal business costs like taxes and insurance), and Net Capital Additions (post-construction investments for repairs, upratings, or safety upgrades that are large enough that they are capitalized rather than expensed; they are poorly reported and often omitted, their boundary with fixed O&M is rather vague, and those two costs' sum rises nonlinearly with age). Closed plants do not continue to incur these operating costs.

United States

The Nuclear Energy Institute (NEI), the leading industry trade group in the U.S., has summarized in three-year averages the Electric Utility Cost Group's (EUCG) proprietary annual compilation of total generating cost. No list is available of exactly which units are included, hence whether any operating units are excluded, and at what stage a troubled or retired unit is removed from the database, but the broad pattern is clear, as illustrated in **Table 20**. Each quartile includes roughly 25 reactors.

Table 20 | Average Nuclear Generating Costs in the United States (by Quartile)

US$$_{2017}$ per busbar kWh	2012–14	2013–15	2014–16
Quartile 1	30.26	29.78	28.81
Quartile 2	35.50	34.97	34.40
Quartile 3	43.51	41.72	40.69
Quartile 4	62.17	55.42	51.57

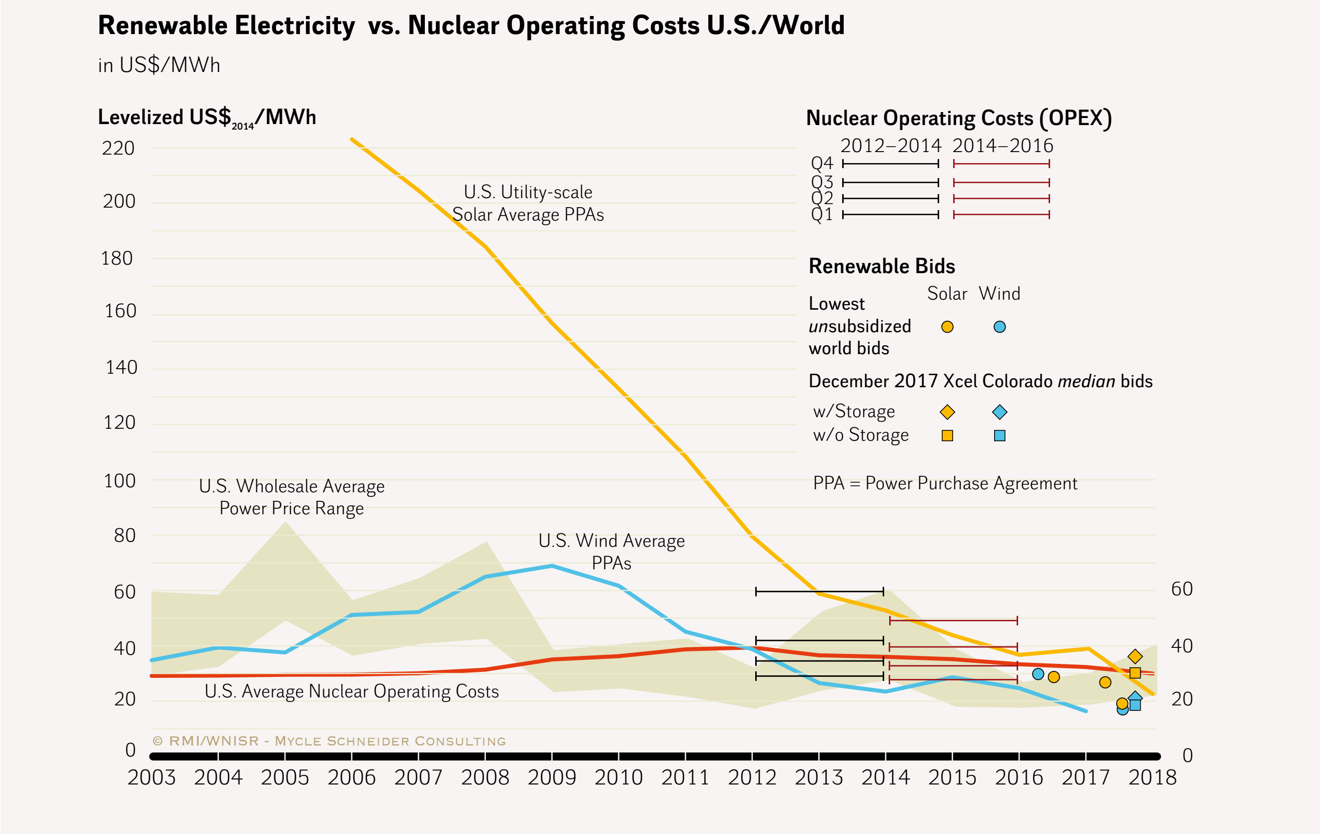
Source: Nuclear Energy Institute, private communication to Amory B. Lovins, 26 July 2018

How are these nuclear operating costs evolving? **Table 21** represents the same EUCG analysts' average generating costs by category and year (US$$_{2017}$/busbar MWh).[1025]

1024 - Jim Polson, "More Than Half of America's Nuclear Reactors Are Losing Money", *Bloomberg*, 14 June 2017, see www.bloomberg.com/news/articles/2017-06-14/half-of-america-s-nuclear-power-plants-seen-as-money-losers.

1025 - NEI, "Nuclear by the numbers", March 2019, see https://nei.org/CorporateSite/media/filefolder/resources/fact-sheets/nuclear-by-the-numbers.pdf, 2018 data from April 2019 edition converted to 2017 US$ using GDP Implicit Price Deflator, previous data from April 2018 edition. IEA, "Nuclear power in a clean energy system", 28 May 2019, op. cit., p. 34, confusingly equates variable cost with fuel cost, overlooking variable O&M cost.

Figure 51 | Cost Evolution of New Renewables vs. Operating Nuclear



Sources: various compiled by Amory Lovins, Rocky Mountain Institute, 2019[1026]

Notes

Wind and Solar PPAs: US generation-weighted-average Power Purchase Agreements prices, by year of signing.
Nuclear operating cost: fuel, operation and maintenance, and Net Capital Additions average and quartiles. See Table 20 and Table 21.

Figure 51 represents nuclear plants' total generating costs *vs.* competing costs during 2003–18. This reveals that although average U.S. nuclear operating costs have declined since 2012—especially in the costliest quartile, where the most distressed units have begun to retire—the *average* wholesale long-term Power Purchase Agreement (PPA) prices for both new wind power (blue curve) and new utility-scale solar power (gold curve) have declined even faster. This leaves most operating reactors and the 2018 average U.S. nuclear operating costs (red curve) uncompetitive by ~US$10+/MWh with those renewable sources (including wind power plus storage, the blue diamond), or even with the best *un*subsidized international renewable prices (blue and gold round dots), let alone with often-cheaper energy efficiency. Nuclear operating costs for the four-decade-old U.S. fleet probably have limited scope to fall further, but renewables have far more; they're a rapidly moving target that nuclear operating costs are unlikely ever to hit.

1026 - Updated through June 2018; August 2019 Lawrence Berkeley National Laboratory (LBNL) data show wind power PPAs below $20 and continuing their downward trend.
Solar world bids: Chile (US$29.1/MWh, August 2016) and Mexico (US$27 /MWh, February 2017; US$19.2/MWh, November 2017)
Wind world bids: Morocco (January 2016), Mexico (US$17/MWh, November 2017)
Xcel Energy December 2017 median levelized solar bids: US$36/MWh and US$30/MWh with and without storage—wind bids US$21/MWh and US$18/MWh with and without storage
U.S. Wind and Solar PPAs: LBNL
Wholesale price range: RMI Analysis of BNEF Prices, Tariffs and Auctions, US Power & Fuels from subscribers database.
Nuclear operating costs: NEI, "Nuclear by the Numbers", April 2018, plus April 2019 (for 2018 datum) using Electric Utility Cost Group data, converted to 2014 US$ using GDP Implicit Price Deflator.

Table 21 | Average Nuclear Generating Costs in the United States (by Category)

$US\$_{2017}$ per busbar kWh	Fuel	Operation & Maintenance	Net Capital Additions	Total
2012	7.77	11.21	22.37	41.35
2013	8.01	8.49	21.67	38.17
2014	7.47	8.47	21.67	37.60
2015	7.10	8.24	21.56	36.91
2016	6.90	6.89	20.87	34.65
2017	6.45	6.66	20.50	33.61
2018	5.86	6.01	19.30	31.17

Source: Nuclear Energy Institute, "Nuclear by the Numbers," 2018 and 2019

France

In the world's second-largest nuclear fleet, the world's largest nuclear operator Électricité de France's (EDF's) standard price for up to 100 TWh/y of electricity from fully amortized nuclear plants, equivalent to about a quarter of historic fleet production (ARENH[1027]), has been set since 2012 at €42/MWh[1028] ($US\$_{2012}$55.5/MWh). The public Court of Accounts (Cour des Comptes) assessed average nuclear generating costs[1029] at $€_{2019}$54/MWh ($US\$_{2019}$60.6/MWh) for 2010[1030], $€_{2019}$63/MWh (US$70.7/MWh) for 2013[1031], and $€_{2019}$66/MWh (US$74/MWh) for the second half of 2014[1032]; this 22-percent rise was due to higher maintenance costs, including Net Capital Additions for stricter post-Fukushima safety standards. However, the Court of Accounts stressed in its 2016 annual public report[1033] that the costs are even more sensitive to a potential drop in production. This is exactly what happened as generation dropped by 9 percent, from 417 TWh in 2015 to 379 in 2017, with a slight recovery to 393 TWh in 2018.

Romain Zissler, senior researcher at the Renewable Energy Institute in Tokyo, estimated 2017 French operating costs at $€_{2019}$81/MWh (US$91/MWh), based on lower generation[1034]. Published European Power Exchange (EPEX) baseload prices suggest many French reactors are losing money. These nuclear operating costs are less than half realistic new-build costs, yet are several times competitive new-renewables costs. In the second half of 2018, BNEF priced unsubsidized onshore wind power in France at US$67/MWh and solar at US$59/MWh[1035], putting unamortized nuclear plants under severe pressure now and even amortized units soon. No wonder the French Environment & Energy Management Agency concluded

1027 - ARENH = accès régulé à l'énergie nucléaire historique, or Regulated Access to Historic Nuclear Energy.

1028 - Commission de Régulation de l'Énergie, "ARENH", Undated (in French), see https://www.cre.fr/Pages-annexes/Glossaire/ARENH, accessed 18 July 2019.

1029 - Converted to $€/US\$_{2019}$ by WNISR.

1030 - Cour des Comptes, "The costs of the nuclear power sector", Press Release, 8 February 2012, see https://www.ccomptes.fr/sites/default/files/EzPublish/Costs_nuclear_power_sector_press_release.pdf, accessed 18 July 2019.

1031 - Cour des Comptes, "Le coût de production de l'électricité nucléaire—Actualisation 2014", Communication à la Commission d›Enquête de l›Assemblée Nationale, May 2014 (in French), see https://www.ccomptes.fr/sites/default/files/EzPublish/20140527_rapport_cout_production_electricite_nucleaire.pdf, accessed 18 July 2019.

1032 - Cour des Comptes, "Le Rapport Public Annuel 2016–Tome I: Les Observations", February 2016 (in French), see https://www.ccomptes.fr/sites/default/files/EzPublish/RPA2016-Tome-1-integral.pdf, accessed 18 July 2019.

1033 - Ibidem.

1034 - Romain Zissler et.al., "The Rise of Renewable Energy and Fall of Nuclear Power–Competition of Low Carbon Technologies", Renewable Energy Institute, 6 February 2019, see www.renewable-ei.org/en/activities/reports/20190206.php.

1035 - Ibidem.

in October 2018[1036]: "From an economic point of view, the development of a new generation nuclear technology would not be competitive for the French electricity system"—even at an assumed production cost of "a hypothetical €70/MWh" (US$79.5/MWh).

Germany

Detailed operating costs for German reactors appear not to be readily available, but applying 2018 European Commission generic assumptions[1037] to the seven operating reactors implies a 2020 snapshot value (probably below the levelized value) of $€_{2013}$22.5/MWh ($US\$_{2013}$31/MWh) for O&M alone, plus fuel, probably plus Net Capital Additions. The implied total does not look durably competitive with modern renewables.

Sweden

Swedish nuclear operating costs were estimated in 2016 by Vattenfall's head of generation at SEK250/MWh ($US\$_{2016}$29/MWh) excluding the SEK70/MWh ($US\$_{2016}$8/MWh) nuclear operating tax then in force)—above the SEK220/MWh ($US\$_{2016}$26/MWh) typical wholesale electricity price[1038], which was not expected to rise over the next 5–10 years[1039]. As operating costs were expected to durably exceed income, the Vattenfall manager concluded: "Nuclear is in trouble. Profitability needs to improve." Ringhals-1 and -2 are therefore being closed; Oskarshamn-1 and -2 and Barsebäck-1 and -2 already were.

Japan

Japan once had the world's third-largest nuclear fleet, but after the 2011 Fukushima Daiichi disaster started to unfold, all 54 reactors were shut down by 2014, and every year since, they've been outgenerated by solar power. By 2018, restarts left nine operating units generating about 50 TWh–243 TWh less than in 2010. Of that gap, ~75 percent was covered by energy savings plus renewable growth, or 82 percent when adjusted for economic growth so that efficiency gains are not understated.[1040] This is despite Japanese policy's comprehensive efforts to control solar expansion and suppress wind power growth—a regime aptly summarized as "a combination of barriers to access the grid, unfavorable treatment once connected, difficult technical requirements and tedious rather than effective environmental regulations"[1041] raising renewable costs to multiples of international levels. Thus more than four-fifths of the market

1036 - French original: "D'un point de vue économique, le développement d'une filière nucléaire de nouvelle génération ne serait pas compétitif pour le système électrique français", see ADEME, "Trajectoires d'évolution du mix électrique 2020–2060", October 2018.

1037 - P. Capros, E. Dimopoulou et al., "Technology pathways in decarbonisation scenarios", ASSET, Commissioned by the EU Commission, Directorate-General for Energy, July 2018, kindly compiled by Leonard Göke, TU-Berlin, pp. 45–47, see https://ec.europa.eu/energy/sites/ener/files/documents/2018_06_27/technology_pathways_-_finalreportmain2.pdf. The report does not specify what year's Euros it uses, but it solicited data on forms (pp 54–55) stating EUR_{2013}, as used in the EC's previous (2016) forecast.

1038 - Torbjörn Wahlborg, "Swedish nuclear power–Present status and outlook", Vattenfall, 3 March 2016, see https://wecfinland.fi/wp-content/uploads/2016/01/2016-03-03-Vattenfall-and-Fingrid-Final.pdf.

1039 - *WNN*, "Vattenfall seeks to return reactors to profitability", 8 January 2016, see www.world-nuclear-news.org/Articles/Vattenfall-seeks-to-return-reactors-to-profitabili. Actually, prices did then rise.

1040 - Prof. Kenichi Oshima, Personal Communications to Amory B. Lovins, 20 July 2019 and 1 , 3 and 7 August 2019; also 2018 update from REI's senior researcher Romain Zissler, Personal Communication to Amory B. Lovins, 4 July 2019.

1041 - Tomas Kåberger, Romain Zissler, "Solar PV cheaper than LNG-power in Japan makes massive deployment possible", Renewable Energy Institute, 26 May 2017, see www.renewable-ei.org/en/activities/column/20170526.html. REI's 2017 Expert Meeting dissected these policies.

previously served by nuclear power is already gone. If Japan didn't make nuclear units must-run, and began dispatching renewables in merit order, fossil-fueled generation would be largely squeezed out between efficiency and renewables. But are nuclear restarts even worthwhile? Only the owners know, but skepticism seems warranted.

A 2015 government study[1042] estimated average 2014 nuclear operating costs at ¥1,500/MWh (US$$_{2015}$12.6/MWh) for fuel including reprocessing, ¥3,500/MWh (US$$_{2015}$29.4/MWh) for O&M, and ¥400/MWh (US$$_{2015}$3.4/MWh) for additional safety measures (upgrades classifiable as Net Capital Additions). This total of ¥5,400/MWh (US$$_{2015}$45.4/MWh) excludes a further ¥1,300/MWh (US$$_{2015}$10.9/MWh) for policy measures (such as location grant and Monju surcharge) and ¥300/MWh (US$$_{2015}$2.5/MWh) for "costs for nuclear accident risk measures" (assuming an early Fukushima accident cost that was roughly half current estimates).

An 82-line-item compilation of the nuclear operating costs reported in the financial accounts of Japan's nine nuclear utilities for 2001–18[1043] is in reasonable agreement, averaging ¥6,350/MWh (in mixed nominal JPY)[1044] during 2001–10; whether that includes all net Capital Additions is unclear, but the total, more than US$$_{2015}$52/MWh, is similar to the operating costs for the costliest quartile of United States reactors documented in **Table 21**. After the Fukushima Daiichi accident began in 2011, Japanese operating costs soared to astronomical values due to low or zero output, then declined to a still-huge ¥25,000/MWh (US$$_{2018}$225/MWh) in 2018. In theory, that could scale back to roughly the pre-Fukushima ¥6,000/MWh (US$56/MWh) if Japan's nuclear share of total generation rebounded from 2018's 6 percent to the pre-Fukushima ~30 percent, but it can't, because about half of the units have been abandoned (see **Japan Focus** for details) and many durable new costs have been loaded onto the rest. The more units retire, the fewer will be left to share that burden—though the government will probably find ways to charge all electricity customers and taxpayers anyhow.

Leading Japanese experts also consider these cost estimates conservative, and note that Japanese utilities chose to close 12 reactors totaling almost 7 GW during 2015–19 (through April) as they faced safety-upgrade costs officially estimated to total just ¥60 billion (US$$_{2017}$0.5 billion) per reactor, equivalent to ¥600/MWh or ~US$5/MWh[1045]. Sure enough, a mid-2019 Japanese report[1046] based on surveys of the ten nuclear owners quintupled those safety upgrade costs from ¥0.9 trillion to ¥4.8 trillion (US$8.32 billion to US$44.2 billion)—on the order of US$1–1.5 billion per reactor.

Conversely, the same 2015 government study assumed utility-scale solar power costing ¥24,200/MWh (US$$_{2015}$200/MWh) in 2014 would cost ~¥14,000/MWh (US$$_{2015}$120) in 2030, while onshore wind power would fall from ¥21,600 to ~¥18,000/MWh (from US$$_{2015}$180 to ~US$$_{2015}$150/MWh); yet Japanese developers achieved those 2030 projections in 2019. Those prices are also manyfold higher than recent unsubsidized international bids that are now below

1042 - Power Generation Cost Analysis Working Group, "Report on Analysis of Generation Costs, Etc. for Subcommittee on Long-term Energy Supply-demand Outlook", Ministry of Economy, Trade and Industry, Provisional Translation, May 2015, see www.meti.go.jp/english/press/2015/pdf/0716_01b.pdf.

1043 - Using April–March Fiscal Years, Prof. Kenichi Oshima, Personal Communications to Amory B. Lovins, 1, 3 and 7 August 2019.

1044 - Considering the strong variation of the exchange rate over the period, a US$ value is not meaningful here.

1045 - Romain Zissler, "The Beginning of the End for Nuclear Power in France", Renewable Energy Institute, 16 November 2017, see www.renewable-ei.org/en/activities/column/20171116.html.

1046 - Suguru Kurimoto, "Nuclear safety costs in Japan surge to staggering heights", *Nikkei Asian Review*, 9 July 2019, see https://asia.nikkei.com/Business/Energy/Nuclear-safety-costs-in-Japan-surge-to-staggering-heights.

US$20/MWh or ¥2,100/MWh for both technologies, in resource zones not greatly inferior to Japan's (see **Figure 51** above and **Nuclear Power vs. Renewable Energy Deployment**). Thus even pre-Fukushima nuclear operating costs, let alone much higher post-Fukushima ones, can beat Japan's artificially inflated 2019 renewable prices, but would lose to globally competitive ones.

It would therefore appear that average Japanese nuclear operating costs are so uncompetitive with unconstrained solar and wind power that wide nuclear restarts would require intensified suppression of renewable development in Japan, contrary to the government's 2019 Basic Energy Plan, and reversal of current policies to promote free competition in liberalized power markets. This comparison does not count further repairs and upgrades likely to be needed to restart many plants that have been shut down for years, and it assumes that restarted plants will run reliably for decades more without significant mishaps.

South Korea

Though operating costs in Korea are not transparent, the EPSIS online database reports[1047] the regulated settlement prices that nuclear plants receive on the Korea Power Exchange—based not on competition but on annual reviews of fixed costs and monthly reviews of fuel costs by the Generation Cost Assessment Committee, comprising mainly interested parties, based on submissions by the generators. In nominal US$ (not adjusted for inflation), the administered nuclear prices held nearly steady around US$34/MWh during 2001–13, rose to US$59/MWh in 2016, then slightly decreased again to US$54/MWh. These prices include fuel costs that rose from ~US$2.8/MWh before 2010 to US$5/MWh in 2018. O&M and Net Capital Additions data do not seem to be available. Subtracting the reported capacity payment[1048] of KRW9.15–10.07/MWh (US$7.9–8.7/MWh) from the US$54/MWh total payment in 2018 implies that regulated operating-cost payments may be around US$45/MWh—high enough to call into question nuclear operations' competitiveness with renewables and certainly with efficiency.

However, US$45/MWh is about 2.5 times the operating cost reported by South Korean officials to the OECD's Nuclear Energy Agency (NEA)[1049] as US$18.2/MWh.[1050,1051] Thus South Korean nuclear operating costs are incompletely reported, just like the South Korean construction costs that several scholars found unanalyzable[1052]—useful to recall when low values are cited.

1047 - KPX, "EPSIS–Settlement > by Fuel Type", Undated, see http://epsis.kpx.or.kr/epsisnew/selectEkmaStmBftChart.do?menuId=050601&locale=eng.

1048 - Joonki Yi, Chin Pyo Park, "Electricity Regulation in South Korea", Bae, Kim & Lee LLC, 26 March 2019, see www.lexology.com/library/detail.aspx?g=4a7f6594-b6b4-4249-a928-a0e02ed683e5.

1049 - IEA/NEA, "Projected Costs of Generating Electricity 2015", September 2015, op. cit.

1050 - NEA says South Korea's 2015 levelized cost of nuclear energy was US$201351.37/MWh at a 10 percent discount rate. That includes fuel and waste costs of US$8.58/MWh, O&M of US$9.65/MWh (apparently all variable, as it does not depend on discount rate), refurbishment (apparently equivalent to Net Capital Additions) of zero, and decommissioning of zero. That value also does not seem to include provisions for the compensation fund (limited accident insurance), probably waste management, or lifetime extension.

1051 - Vara Ha, "Nuclear Power Plant Policy Comparison between the U.S. and Republic of Korea", International Development, Community and Environment (IDCE), Clark University, 17, May 2016, see https://commons.clarku.edu/idce_masters_papers/17.

1052 - See MIT Energy Initiative, "The Future of Nuclear Energy in a Carbon-Constrained World", op. cit., pp 34–35: "Of greatest concern are data from the Chinese and South Korean builds, where a lack of transparency and detail makes it difficult to scrutinize and validate available cost estimates. For example, there is some uncertainty in the cost of the South Korean build in the United Arab Emirates because it may not include all of the owner's cost…." See also p 223.

Similarly, operating-cost data exist for China, now the world's third largest fleet, and Russia, the fifth largest, but are unavailable to independent analysts and are considered unreliable without extensive but published supporting detail.

Climate Implications of Substantial Nuclear Operating Costs

The foregoing evidence suggests that closing many, perhaps most, operating nuclear units will not directly save CO_2, but can indirectly save *more* CO_2 than closing a coal-fired plant, *if the nuclear plant's larger saved operating costs are reinvested* in efficiency or cheap modern renewables that in turn displace more fossil-fueled generation. Therefore, closing *both* coal plants *and* costly-to-run nuclear plants (with reinvestment of avoided operating costs and subsidies) makes sense—the former to save carbon directly, and the latter to save money whose climate-effective reinvestment can then save more carbon.

“ closing both coal plants and costly-to-run nuclear plants makes sense ”

Specifically, using the latest available U.S. data shown above (for 2014–16), half the operating U.S. reactors had average operating costs over US$40/MWh, one-fourth over US$51/MWh. These generating costs can all be avoided by closing the reactors[1053]. So can the billions of dollars' new subsidies to induce those plants' owners to keep them running, such as US$16.5/MWh in Illinois (see **United States Focus** and Annex 4 in WNISR2018 for a state-by-state analysis). Those avoided costs can then be reallocated, voluntarily by the owner or compulsorily by regulators, to more climate-effective investments that cost less and hence save more carbon per dollar. To make up a simple example:

> If a reactor costing US$50/MWh (US$5¢/kWh) to run is closed, the regulator can require the saved operating cost (ignoring any avoided subsidy) to be reinvested in helping customers use electricity more efficiently. If that efficiency investment costs the utility a typical average of US$25/MWh (US$2.5¢/kWh), two kWh will be saved for each nuclear kWh not generated, saving twice as much carbon and thus doubling climate-effectiveness. Shopping carefully for 1¢/kWh efficiency could stretch that advantage to fivefold.

Renewables at those prices could do the same and are interchangeable with efficiency, but efficiency is already delivered to the retail customer, avoiding delivery costs averaging ~US$41/MWh. Even if most of that delivery cost is fixed and sunk, efficiency adds value by freeing existing grid assets to serve new loads without building more facilities.

This argument about "climate opportunity cost," straightforwardly applying bedrock economic principles, has been published but ignored for more than a decade, and lately elaborated in the *Electricity Journal.*[1054] The nuclear industry, like nearly all financial and economic reportage (and now the IEA), instead describes the uncompetitiveness of its product as a market failure—a claim that the market does not properly recognize or value nuclear power's low-carbon generation. Its increasingly adopted remedy—new state-level long-term subsidies for

1053 - Decommissioning costs must be paid later anyhow, and increase with longer operation. Greater discounting for later timing affects accounting values but not real resource costs.

1054 - Amory B. Lovins, "Do coal and nuclear generation deserve above-market prices?", *The Electricity Journal*, July 2017, op. cit., §2.

nuclear power alone, with little or no showing of financial need, no competition, and often a disruptive prompt-closure gun held to the legislators' heads—does not correct a market failure but creates it.[1055] It is a deliberate and direct attack on the very markets that are rejecting nuclear power in favor of its cheaper competitors.

The new around-market subsidies restrict competition, slow innovation, and destroy market mechanisms painstakingly built over decades to guide efficient choices. The new subsidies also "distort pool-wide prices, crowd out competitors, discourage new entrants, destroy competitive price discovery, reduce transparency, reward undue influence, introduce bias, pick winners, and invite corruption."[1056] Two deans of electricity regulation warned such targeted subsidies may "unravel U.S. power markets altogether."[1057] This is a high price to pay for results that a superior market-based way to acquire low- or no-carbon resources could readily yield without burdening customers or taxpayers. It is also intrusive and unnecessary. No political intervention to go around markets is needed or appropriate if existing markets are properly used. As the eminent retired utility and nuclear regulator Peter Bradford counsels,

> Instead of having political leaders and regulators make pin-the-tail-on-the-donkey-type[1058] guesstimates of how much nuclear power we'll need, how long we'll need it, and how much we should pay for it, we should adjust our power markets to procure the needed low-carbon electricity. Beyond that, we can regulate emission results where necessary. We should minimize mandating the continued use of existing power plants. Instead, our power markets can prioritize low-carbon technology just as they have proven themselves capable of doing with reliability and demand response.[1059]

The new nuclear subsidies have convulsed state politics, scrambled federal grid regulation, distracted market actors from doing their jobs, and damaged competition, competitors, customers, and markets to achieve only a slight climate effect. The 13 reactors so far rescued or likely to be rescued for some number of years generate a few percent of U.S. electricity and will likely be matched in output by a few years' renewable growth; indeed, those low-carbon renewables would otherwise have increasingly occupied the same market space if allowed to (Midwest wind power developers complain of blocked grid access meant to shield legacy assets from competition). Any climate benefit is also temporary, because the relentless drop in renewable prices will once more undercut nuclear costs.

Often unnoticed is that climate is just the latest of many rationales successively adduced for customers to pay again for the same assets. First, the nuclear industry was created, its fueling infrastructure built, and the reactor fleet financed by a vast array of often-opaque taxpayer-funded federal subsidies that rivaled or exceeded the plants' construction cost and

1055 - Peter A. Bradford, "Wasting time: Subsidies, operating reactors, and melting ice", *Bulletin of the Atomic Scientists*, Volume 73, 12 December 2016, see https://doi.org/10.1080/00963402.2016.1264207.

1056 - Amory B. Lovins, "Do coal and nuclear generation deserve above-market prices?", *The Electricity Journal*, July 2017, op. cit.

1057 - The United States District Court for the Southern District of New York, "Wood And Bradford's Amicus Brief", Case 1:16-cv-08164-VEC, Doc. 125-1, Filed 24 March 2017, posted in Tim Knauss, "NY nuclear subsidies kick in Saturday, but high-stakes legal challenge looms", *Syracuse.com*, 27 March 2017, see www.syracuse.com/news/index.ssf/2017/03/ny_nuclear_subsidies_kick_in_saturday_but_high-stakes_legal_challenge_looms.html.

1058 - An old American party game in which a series of blindfolded children, spun around to disorient them, try to pin a paper tail onto the back end of a wall-mounted picture of a donkey.

1059 - Peter A. Bradford, "Wasting time: Subsidies, operating reactors, and melting ice", Bulletin of the Atomic Scientists, December 2016, op. cit.

exceeded the value of their output.[1060] Second, decades of regulated electricity tariffs already covered the plants' entire construction, financing, and operating costs, including a just and reasonable return on investment. Third, when owners like Illinois-based Exelon (the largest U.S. nuclear operator) later insisted on creating competitive wholesale markets where they expected to earn more profit than under regulation, customers reimbursed them for the "transition costs" (excess capital costs) of stranded assets totaling ~US$135 billion[1061], mostly—at least US$70 billion—for nuclear plants. Then, when many nuclear plants couldn't compete in those wholesale markets, the owners (while reporting robust profits to Wall Street) demanded and generally got from their host states new multi-billion-dollar-a-year subsidies to keep running their distressed reactors. Then Exelon's successful request to Federal regulators for greater capacity payments—because many plants couldn't clear power-pool auctions, and the state subsidies had upset the delicate balance between state and federal regulation—harvested a fifth stream of payments.

The owners naturally try to get paid as much and as many times as possible for the same assets, and they're doing so with great skill and formidable political muscle. The climate emergency offers them a new opportunity for payment, so long as decisionmakers focus only on carbon, not dollars. But why should electricity markets and climate protection become collateral damage—the practical effect of escalating nuclear subventions? How could the agreed goal of climate protection instead be achieved by technology-neutral market mechanisms that let nuclear power compete fully and fairly with other solutions?

PRACTICAL SOLUTIONS FOR CLIMATE-EFFECTIVENESS

An obvious and attractive process would be for power pools or other authorities to run an annual series of laddered all-resource auctions to elicit bids for demand- or supply-side carbon-saving electrical resources. Connecticut has already established such a low-carbon-resources auction, though only on the supply side—a big omission, since a third of the U.S. does compete demand-side options in normal all-resource auctions, and an unbought efficiency potential four times total U.S. nuclear output costs less than one-third as much as the average U.S. nuclear

1060 - In 2011, Doug Koplow assessed these at ~US¢0.8–4.6/kWh for shareholder-owned and US¢1.7–6.3/kWh for public utilities, excluding ~US¢8.3/kWh of historic subsidies that originally launched the U.S. nuclear enterprise, see Doug Koplow, "Nuclear Power: Still Not Viable Without Subsidies", Earth Track Inc, Union of Concerned Scientists, February 2011, see http://www.ucsusa.org/nuclear-power/cost-nuclear-power/nuclear-power-subsidies-report, accessed 30 August 2019. New U.S. nuclear plants already get slightly higher federal operating subsidies per kWh than new U.S. wind farms, plus far larger capital subsidies (~US¢5–12/kWh); even existing nuclear plants' capital subsidies often exceed the wholesale price they receive. And historically, nuclear power has been far more subsidized per kWh than renewables. See Nancy Pfund, Ben Healey, "What Would Jefferson Do?—The Historical Role of Federal Subsidies in Shaping America's Energy Future", DBL Investors, September 2011, see http://i.bnet.com/blogs/dbl_energy_subsidies_paper.pdf, as cited in Jeff Johnson, "Long History Of U.S. Energy Subsidies", Chemical & Engineering News, Volume 89, Issue 51, 19 December 2011, see https://cen.acs.org/articles/89/i51/Long-History-US-Energy-Subsidies.html, accessed 19 July 2019.

1061 - B.A. Holden, "Deregulation May Cost Electric Utilities US$135 Billion Over 10 Years, Study Says", *The Wall Street Journal*, 7 August 1995, summarizing P.B. Fremont & R.K. Hornstra, "Stranded Costs Will Threaten Credit Quality of U.S. Electrics", Moody's Investors Service Research, August 1995. The US$70 billion estimate is from M.D. Yokell, D. Doyle & R. Koppe, "Stranded Nuclear Assets and What to Do About Them", Presentation to DOE-NARUC Electricity Forum, April 1995, cited by Office of Coal, Nuclear, Electric and Alternate Fuels, "Changing Structure of the Electric Power Industry: An Update", DOE/EIA-0562 (96), Department of Energy, U.S.EIA, December 1996, p.79, which said nuclear stranded costs could decline to US$43–63 billion if restructuring were completed by 1996 or 2000 respectively.

operating cost[1062]. California also acquires resources by competitive bid, and plans to use that process to replace the retiring Diablo Canyon nuclear units with other low-carbon resources at least cost.

“ an unbought efficiency potential four times total U.S. nuclear output costs less than one-third as much as the average U.S. nuclear operating cost ”

Continued nuclear operations might initially win such auctions, perhaps for a year or two, until cheaper new efficiency and renewables could ramp up (a delay of virtually no or even favorable climate consequence, as discussed below), but ultimately the market, not state legislators, would choose the cheapest ways to avoid the most time-integrated carbon.

Another economically sensible way to enable low-carbon resources to compete fairly with gas-fired combined-cycle power plants would be for market-makers and regulators to count the market value of fuel-price volatility[1063] when comparing fossil-fueled with constant-price resources, notably efficiency and renewables, whose price is set 20–30 years ahead by contract (making those assets financially riskless except insurable and diversifiable counterparty risk). Basic financial economics absolutely requires such risk adjustment; ignoring it—today’s common practice—is guaranteed to misallocate risk and capital. Counting fuel-price volatility would probably help nuclear power compete with natural gas even more than carbon pricing could, so it’s puzzling that the nuclear industry isn’t backing this reform.

However, even without this risk adjustment, and even with low-priced U.S. fracked gas, the once-strong business case for new and even most existing combined-cycle gas plants has collapsed: a “clean portfolio” of efficiency, flexible demand, renewables, and storage can provide all the same outcomes more cheaply and without CO_2.[1064] Even some new gas-fired plants in gas-rich Texas are going broke. Contrary to old assumptions that solar power is more capital-intensive up front than gas power, today they have nearly identical cashflow profiles. Both in the U.S. and in countries with costlier natural gas, whether or not dangerous methane escape is properly valued and abated, and with or without nuclear power, long-run gas-fired generation and its climate impact look likelier to trend down than up.

Pricing carbon and counting the market value of price volatility would help nuclear power to compete against natural gas and coal—but not against modern renewables or efficiency, because they emit no carbon and burn no fuel. The nuclear industry tends to blame its competitive woes more on gas than on renewables[1065], which it often seems reluctant to recognize as a legitimate and effective competitor—perhaps because that would call into

1062 - Amory B. Lovins and Rocky Mountain Institute, “Reinventing Fire—Bold Business Solutions for the New Energy Era”, 2011. It found that “efficient end use, using 2010 technologies adopted at a historically reasonable pace, could quadruple 2010 electric end-use efficiency by 2050 at an average levelized technology cost of US$20170.72¢/kWh, i.e.<1¢ including normal transaction costs”; see Amory B. Lovins, “Response to D. Murphy & M. Berkman, ‘Efficiency and nuclear energy: Complements, not competitors, for a low-carbon future”, Electricity Journal, Volume 30, Issue 8, October 2017, see https://doi.org/10.1016/j.tej.2017.09.012.

1063 - Amory B. Lovins, Jon Creyts, “Hot Air About Cheap Natural Gas”, Rocky Mountain Institute, 6 September 2012, see https://rmi.org/hot-air-cheap-natural-gas/.

1064 - Mark Dyson et al., “The Economics of Clean Energy Portfolios”, Rocky Mountain Institute, May 2018, see https://rmi.org/insight/the-economics-of-clean-energy-portfolios/.

1065 - The 2018 MIT nuclear study previously cited considers competitiveness only against coal or gas, not renewables or demand-side resources. Solar and wind competition is later considered only under outdated and constrained assumptions unrelated to modern energy system design. See MIT Energy Initiative, “The Future of Nuclear Energy in a Carbon-Constrained World”, 2018, op. cit.

question many nuclear advocates' claims (reviewed above) that renewable power at scale is infeasible[1066], requiring nuclear "baseload" power for grid stability. But competitors can win whether or not you believe they work. Claims that renewables can't scale will become as discredited by increasingly ubiquitous real-world experience as claims that climate change is a hoax. And if carbon is properly priced, nuclear power will remain as exposed as now to its most formidable competitors—low-carbon renewables and efficiency.

Substitution for Existing Nuclear Plants: 5 Case Studies from the U.S.

In substituting non-nuclear low-carbon resources for nuclear power, one timing issue bears mention. Closing a nuclear plant is often claimed to increase CO_2 emissions by requiring an immediate, and impliedly a long-term, shift to fossil-fueled generation, typically by natural gas. Five U.S. states where reactors were rather hastily closed were analyzed by the Union of Concerned Scientists (UCS)[1067] to test this hypothesis through 2017 (with efficiency data through 2016 and power-sector CO_2 data through 2015):

- **Nebraska**'s time-series was too short to be meaningful, as the Fort Calhoun reactor was only closed in October 2016.
- **Wisconsin** closed the Kewaunee reactor May 2013, cutting nuclear generation by 5 TWh/y. In addition, it cut coal-fired generation by 5 TWh/y. It substituted 5 TWh/y with gas-fired generation and 3 TWh/y with efficiency plus renewables (three-fourths of the nuclear loss), and cut power-sector CO_2 emissions 4 percent.
- **Florida**, another state with relatively unfavorable policies, closed Crystal River-3 in September 2009, lost 3 TWh/y (vs. 2008) net of 0.4 GW of upratings, raised gas-fired generation by 57 TWh/y, cut coal-fired by 16 TWh/y, raised efficiency and renewables by 4 TWh/y, and cut 2008–15 power-sector CO_2 emissions by 11 percent.
- **California**, with strong efficiency and renewable policies and institutions, closed the two San Onofre reactors in January 2012, losing 19 TWh/y, while cutting both coal-fired generation (by 2 TWh/y) and gas-fired (by 0.1 TWh/y), but also raised efficiency and renewables by 47 TWh/y or 2.5 times the nuclear loss, which it erased by the end of 2014; power-sector CO_2 emissions fell 7 percent during 2009–15 (not measured from the exceptionally high-hydro, low-gas year 2011).
- In the two years after **Vermont** Yankee closed in December 2014, that hydro-dominated state cut gas generation, raised other generation, raised efficiency and renewables, and put its tiny power-sector CO_2 emissions back into decline. A separate Rocky Mountain Institute analysis of data for the whole New England power pool (ISO-NE) found that during 2015–16, the nuclear loss was offset 91 percent by renewables and hydro-dominated

1066 - The nuclear industry's positioning itself as a carbon-free replacement for coal and gas power when seeking U.S. state subsidies on climate grounds also sits uneasily with its alliance with coal when seeking US federal subsidies based on the current administration's fondness for both coal and nuclear plants' supposedly resilient attributes. Many major utilities also own both nuclear and coal plants.

1067 - Steve Clemmer, UCS, personal communication, 6 October 2018.

> imports *plus* another 69 percent by reduced sales; the pool's CO2 emissions rose by one-tenth as much as the 2001–15 reduction, but only for a little over one year.[1068]

Such comparisons are complex and sometimes ambiguous due to interfering effects such as price-driven fuel-switching. Nonetheless, this state-level evidence suggests that *if* abrupt nuclear closure raises CO_2 by switching from nuclear to fossil generation, that rise lasts just a few years—or less in states that allow and encourage efficiency and renewables to compete fully with fossil-fueled generation.

Even this temporary CO_2 blip can be avoided altogether by providing enough lead time for orderly replacement of retiring nuclear units. Nuclear owners have tended to threaten abrupt closure that would emit more carbon (even if temporarily), cause political shocks from job losses, and perhaps disrupt grids, all in the hope of pressing politicians to provide new subsidies. In essence, such extortionate tactics hold the climate, for which the owners express such concern, hostage to short-term commercial gain. But responsible and accountable owners can and do take the opposite course. Pacific Gas and Electric Company (PG&E) and its stakeholders all agreed to an 8–9-year closure lead time for Diablo Canyon[1069]—similar to the planned phase-out in Germany (see **Figure 27**)—leaving ample time to ramp up competitive procurement of low-carbon replacements and honorable transitions for workers and communities.

Temporarily burning more gas while efficiency and renewables fill a brief nuclear-retirement gap is also unimportant, because most surplus gas-fired plants are very efficient and CO_2's effects are long-term[1070]: what matters is its *cumulative* long-term release. Gas abatement by efficiency and renewables will last far longer than the retired (generally elderly) nuclear plant's remaining economic life, so the abatement will be at least equal in quantity but longer-lasting, bringing greater climate benefit. Moreover, where efficiency or renewables cost less than continued nuclear operations and are bought instead, that shift will save more carbon per dollar. On both cost *and* speed, therefore, the time-integrated climate benefit will exceed the climate benefit of continued nuclear operation.

NON-NUCLEAR OPTIONS SAVE MORE CARBON *PER YEAR*

If new or old nuclear power is generally not cheaper than efficiency and renewables, and hence cannot save as much carbon per dollar, might it still be desirable or necessary because it's faster to deploy at scale to help deal with the climate emergency? That claim is often made but seldom analyzed. For the past decade, WNISR has been illustrating the fact that renewables have been outpacing nuclear in added kilowatt-hours year after year (e.g. **Nuclear Power vs. Renewable Energy Deployment** and **Figure 40**, **Figure 41** and **Figure 42**). In 2016, a nuclear advocacy group suggested that in some countries *historically* nuclear power would have been rolled out faster than renewables. That image of nuclear power's allegedly rapid deployment speed has been encapsulated by The Breakthrough Institute and promoted by a *Science*

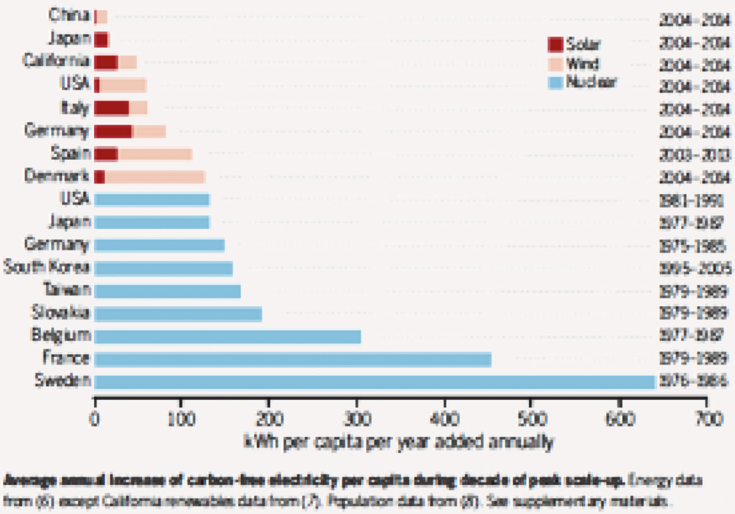
1068 - ISO New England, "Net Energy and Peak Load Report", Editions 2000, 2015 and 2016, see www.iso-ne.com/isoexpress/web/reports/load-and-demand/-/tree/net-ener-peak-load, accessed 7 May 2017.

1069 - Amory B. Lovins, "Closing Diablo Canyon Nuclear Plant Will Save Money and Carbon", *Forbes*, 22 June 2016, op. cit.

1070 - The opposite is true of associated methane releases, but the gas infrastructure is already in place, U.S. gas is in surplus, and little or no upstream development will be required to fuel the brief extra gas burn.

paper[1071], which received withering technical criticism[1072]. Its key meme claims that nuclear growth is generically "much faster" than renewable growth (see **Figure 52**):

Figure 52 | Average Annual Increase of Nuclear, Wind, and Solar—Using Breakthrough Institute Methodology



Source: Cao *et al.*, *Science*, 5 August 2016, Op. Cit.

Rocky Mountain Institute's Amory B. Lovins[1073] has redrawn that seemingly convincing graph—adopting for the sake of argument its highly problematic per-capita metric—to correct its many analytic errors and include its omitted same-country comparisons, where seven of ten countries grew renewables faster than they grew nuclear (see **Figure 53**).[1074] Here we update that corrected graph with three more years' data (2016–18). While the previous chart implies that all nuclear programs outpace all renewable programs, the next chart shows no clear advantage to either—but the rapid nuclear growth was decades ago and long ended, while the rapid renewable growth is here, now, and accelerating (see **Nuclear Power vs. Renewable Energy Deployment**).

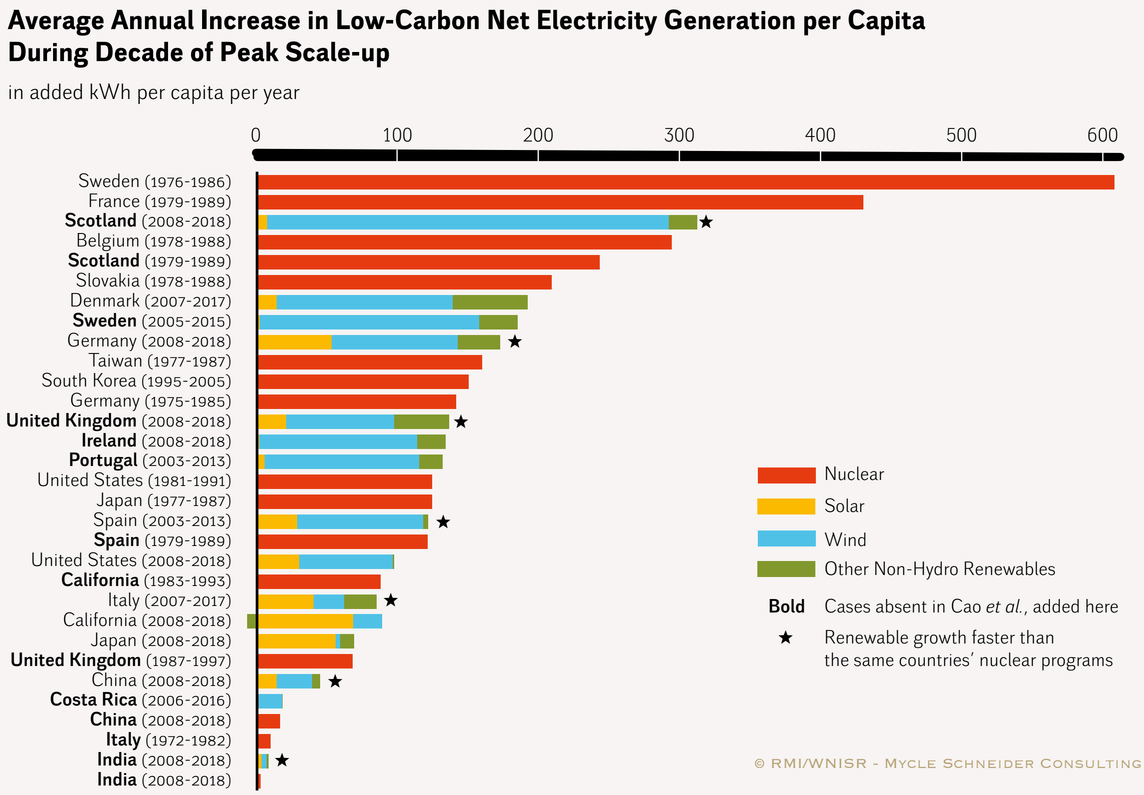
1071 - Junji Cao, Armond Cohen, et al., "China-U.S. cooperation to advance nuclear power", *Science*, Volume 353, 5 August 2016, see https://doi.org/10.116/science.aaf7131.

1072 - Philip Johnstone, Benjamin K. Sovacool, et al., "Nuclear power: serious risks", *Science*, Volume 354, 02 December 2016, see https://doi.org/10.1126/science.aal1777 ; Amory B. Lovins, "Nuclear power: deployment speed", *Science*, Volume 354, 2 December 2016, see https://doi.org/10.1126/science.aal1808 ; Junji Cao, Armond Cohen, et al., "Nuclear power: Deployment speed—Response", *Science*, Volume 354, 2 December 2016, see https://doi.org/10.1126/science.aal2561; Amory B. Lovins, T. Palazzi, et al., "Relative deployment rates of renewable and nuclear power: A cautionary tale of two metrics", *Energy Research & Social Science*, Volume 38, April 2018, see https://doi.org/10.1016/j.erss.2018.01.005; Amory B. Lovins, "Corrigendum to 'Relative deployment rates of renewable and nuclear power: A cautionary tale of two metrics'", *Energy Research & Social Science*, Volume 46 (correcting a minor Supplementary Materials point affecting no content in the main paper), December 2018, see https://doi.org/10.1016/j.erss.2018.08.001.

1073 - Amory B. Lovins is a contributing author to WNISR2019.

1074 - Amory B. Lovins, "Corrigendum to 'Relative deployment rates of renewable and nuclear power: A cautionary tale of two metrics'", *Energy Research & Social Science*, Volume 46, December 2018, see https://doi.org/10.1016/j.erss.2018.08.001.

Figure 53 | Average Annual Increase of Nuclear, Wind, and Solar—According to Rocky Mountain Institute*



Sources: Various (see citation), compiled by Amory B. Lovins, Rocky Mountain Institute, July 2019[1075]

Note

*This graph represents RMI revision of Cao et al.'s Figure S2. See Figure 52.

The same nine nuclear and eight renewable cases are shown; seven nuclear (Scotland, Spain, California, United Kingdom, Italy, China, and India) and seven renewable cases (Scotland, Sweden, Ireland, Portugal, United Kingdom, Costa Rica, and India) are added (bold), using data through 2015. Scotland is part of the UK grid and electricity market, and its nuclear plants were built under UK policy, but Scotland does have autonomy in choosing renewable energy, which grew faster per capita.

This chart was first described, documented, and published in A.B. Lovins, "Corrigendum to 'Relative deployment rates of renewable and nuclear power: a cautionary tale of two metrics'", *Energy Research and Social Science*, 2018, 38:188–192, doi: 10.1016/j.erss.2018.08.001, then updated through 2018 by Jacob W. Glassman using the mid-2019 versions of the same data sources.

Through 2015, modern renewable energy globally was growing faster than nuclear power ever had; through 2018, ten countries moved up in the chart. The world's most aggressive nuclear program (in China) has been outgenerated by China's wind power since 2013, and 2.2:1 by China's non–hydro renewable portfolio in 2018. The corresponding Indian factor is 3.1-fold. (See also **Nuclear Power vs. Renewable Energy Deployment**.) Though the Swedish and French nuclear power programs were uniquely aggressive relative to those nations' populations, those programs were not economically successful—France can scarcely afford to modernize its existing nuclear fleet, let alone replace it—and both nations are now shrinking nuclear and growing renewables to fit today's economics, politics and EU legal obligations.

Deployment speed depends on both installation rate and project lead time. A new assessment[1076] finds that new nuclear plants take 5–17 years longer to build than utility-scale

1075 - All data shown are from BP, "Statistical Review of World Energy 2019", except for Costa Rica and Scotland, taken from online national statistics. BP nuclear outputs are divided by 1.0546 to convert gross to net.

1076 - Mark Z. Jacobson, "Evaluation of Nuclear Power as a Proposed Solution to Global Warming, Air Pollution, and Energy Security", *Cambridge University Press*, 15 June 2019, see https://web.stanford.edu/group/efmh/jacobson/WWSBook/WWSBook./html.

solar or onshore wind power, so existing fossil-fueled plants emit far more CO_2 while awaiting substitution—62–102 gCO_2/kWh more, equivalent to 11–18 percent of average U.S. grid carbon intensity; thus if China had invested its nuclear capital in wind power instead, the quicker deployment could have cut its CO_2 emissions by ~3–6 percentage points. While some may quibble about calculational details, these estimates suggest a sound principle—a significant climate penalty for buying slow rather than fast resources. For resources that are both slow *and* costly, that climate opportunity cost is compounded.

“If nuclear power is neither cheaper nor faster than modern renewables and energy efficiency, it fails both tests of climate-effectiveness, so its substitution would reduce and retard climate protection”

In addition, in illustrative countries with major nuclear power programs, the institutional “formative phases” needed to support scaleup took about 30 years (in France and China—the two most concerted efforts), compared with nine years for comparable renewable milestones (in China and Germany)[1077]. The extra twodecade delay for countries lacking mature nuclear institutional and industrial infrastructures would make their nuclear scaleup far too late.

If nuclear power is neither cheaper nor faster than modern renewables and energy efficiency, it fails both tests of climate-effectiveness, so its substitution would reduce and retard climate protection. How does that square with continued calls for nuclear continuation and expansion, on grounds that over decades have evolved from replacing insecure oil to replacing polluting coal to fighting poverty and protecting the Earth’s climate?

IS NUCLEAR POWER A CLIMATE IMPERATIVE?

Michael Liebreich, an eminent energy commentator who founded and led the data and analytic pioneer Bloomberg New Energy Finance (BNEF), recently encapsulated many popular arguments that despite nuclear power’s acknowledged challenges, its continued use is vital for climate protection.[1078] In paraphrase: After investments nearing US$3 trillion, solar and wind power supply just 7 percent of the world’s electricity. Solar and wind power are unlikely to add as much capacity in the next decade—2–4 times their growth so far—as basic climate goals require. Decarbonizing heating, transport and industry proportionately would need even more electricity, raising that goal to 10–15-fold (or 5–10-fold with more-efficient use). So to “have any hope of…[2C°, let alone 1.5C°], we need to keep as many existing nuclear power stations as possible operating, and to extend their lives for as long as possible,” though new-builds should switch to Small Modular Reactors or other designs yet to be developed.

In fact, nobody claims that just wind and solar, or efficiency, or any single option, can “decarbonize the economy in the near term”. Though solar and wind are ~84 percent of recent non-hydro *electric* capacity additions, modern (excluding big hydro) renewable *energy* not

1077 - Amory B. Lovins, Titiaan Palazzi, et al., “Relative deployment rates of renewable and nuclear power: A cautionary tale of two metrics”, *Energy Research & Social Science, Volume* 38, April 2018, see https://doi.org/10.1016/j.erss.2018.01.005.

1078 - Michael Liebreich, “Liebreich: We Need To Talk About Nuclear Power”, Bloomberg New Energy Finance, 3 July 2019, see https://about.bnef.com/blog/liebreich-need-talk-nuclear-power.

only outgenerates nuclear electricity, but also covers three-fourths more global final *energy* consumption (in all forms, not just electricity) than nuclear power delivers after 65 years' effort.[1079]

The math about needing far more electricity to decarbonize all sectors appears to double-count difficulties. Electric cars and trucks are severalfold more efficient than fueled ones, and severalfold more efficient still if light and low-drag[1080]; with smart charging, electric vehicles wouldn't need materially more electric capacity, but could earn back (some practitioners assert) up to half their sticker price by selling their distributed storage's valuable services back to the grid. Likewise, the far greater efficiency of modern electric heating and cooking can cut primary energy use by several- to manyfold, saving fossil fuels both in direct use and in power generation.

Liebreich overlooks important parallel abatements of greenhouse gases other than CO_2: *e.g.*, OECD's International Energy Agency (IEA)[1081] says upstream hydrocarbon industries can *profitably* abate methane emissions sufficient to stabilize the global methane cycle—equivalent, if sustained to 2100, to instantly abating every Chinese coal-fired power plant's emissions. Such complementary efforts can shrink the climate challenge and buy more time to abate carbon emissions.

The models that simulate ways to reverse climate change were at least as conservative as the climate-science models that predict it, especially understating the practical scope for profitable energy efficiency[1082]. Liebreich assumes only modest efficiency. IPPC's 1.5°C Special Report[1083] features an important 2018 low-energy-demand scenario[1084] that robustly reaches 1.5° with no overshoot, no engineered carbon-removal technologies, and severalfold lower supply investments. Yet it looks technically conservative in both demand and supply. The latest evidence across all sectors[1085] reveals that the energy efficiency resource is severalfold bigger and cheaper than had been thought, and can often yield increasing returns, just like modern renewables. Thus an efficiency-centric approach makes Liebreich's daunting renewable expansions much smaller, easier, and cheaper.

1079 - REN21, "Renewables 2019–Global Status Report", June 2019, see www.ren21.net, shows from IEA data that modern renewables—which exclude hydropower (3.6 percent) and traditional biomass (7.5 percent)—covered 7 percent of the world's total final energy consumption in 2017: modern renewable heat 4.2 percent, non-hydro electricity 2.0 percent, and mobility biofuels 1 percent. For electricity generation alone at the end of 2018, nuclear power provided 10 percent, vs. wind 5.5 percent, photovoltaics 2.4 percent, biopower 2.2 percent, geothermal and others 0.4 percent—a total of 10.5 percent, excluding 15.8 percent from hydropower (of which roughly a fifth is small hydro, <50 MW, which most analysts consider a modern renewable source).

1080 - Amory B. Lovins, "Oil-Free Transportation", AIP Conference Proceedings, Volume 1652:129–139, 2 April 2015, see https://doi.org/10.1063/1.4916175; Transportation Research Board, "Superefficient Vehicles and Easier Electrification", January 2018 annual meeting, session 466, presentation P18-21428, see http://amonline.trb.org/2017trb-1.3983622/t009-1.3999602/466-1.4125818/p18-21428-1.4116638/p18-21428-1.4125823?qr=1; Amory B. Lovins, "Reframing Automotive Fuel Efficiency", in journal review, 2019.

1081 - IEA, "World Energy Outlook 2017", Chapter 10, pp. 399–436, see https://webstore.iea.org/world-energy-outlook-2017.

1082 - Amory B. Lovins, Diana Ürge-Vorsatz, et al., "Recalibrating Climate Prospects", *Environmental Research Letters*, in review as of August 2019. Nearly all Integrated Assessment Models greatly understate efficiency potential, and none properly models and can account for actual renewable growth.

1083 - IPCC, "Special Report: Global Warming of 1.5°C", 2018, op. cit.

1084 - Arnulf Grübler, Charlie Wilson, et al, "A Low Energy Demand Scenario for Meeting the 1.5°C Target and Sustainable Development Goals without Negative Emission Technologies", Nature Energy, 3:517–525 , 4 June 2018, see https://doi.org/10.1038/s41560-018-0172-6. Rocky Mountain Institute plans 2019 publications showing the technical conservatism of some key assumptions, particularly in mobility and industry.

1085 - Amory B. Lovins, "How big is the energy efficiency resource?", *Environmental Research Letters*, 13:090401, 18 September 2018.

Yet his essay does help focus on important questions about cost, timing, and decision making. First, cost: Shouldn't investments seek to deliver the most climate solution with limited money? Life-extending existing reactors, let alone building more, would fail that basic test.

Next, speed: How can new reactors help meet Liebreich's 2030 need when it takes about that long to build one and far longer to build hundreds or thousands? when newcomer countries need two decades more to build the institutions for nuclear than for renewable scaleup? and when only a few outlier countries (even using the deeply flawed per-capita metric) have ever built nuclear faster than they built renewables? Liebreich therefore suggests new kinds of reactors, allegedly quicker to license and build; but how is it a practical and urgent climate solution to divert massive public resources from proven, off-the-shelf energy options to speculative reactor types and fuel chains that do not exist, may never exist, have unknown costs and public acceptance, and (history suggests) will take one or more decades just to develop and test (see **Small Modular Reactors**)? Aren't resources, attention, and time devoted to nuclear new-build therefore diverted from faster and more climate-effective solutions?

The first TW of modern renewables, excluding the 1 TW of hydropower existing in 2013, took about 15 years to install to mid-2018. BNEF expects the second TW will take ~5 years, to 2023, but cost 46 percent or ~US$1 trillion less.[1086] It won't stop there (see **Nuclear Power vs. Renewable Energy Deployment**). If the increasing returns that drive this exponential growth are even partly sustained, as most experts expect, order-of-magnitude scaleups of solar and wind power by 2030 are reasonable[1087], and have already been achieved or surpassed in industries like semiconductors. Practical trajectories for 5–10 TW of PVs alone by 2030 have been expertly compiled.[1088] What about those careful analyses is implausible?[1089]

Finally, decisions and risks: Liebreich's question "are you still sure you want to be shutting down existing nuclear power stations at the same time?" is only about carbon, not also dollars. If IEA's claimed US$40–55/MWh cost for life-extension is correct; if reliability, safety, and public confidence can be sustained; and if owners forego ~US$15–20/MWh of subsidies demanded to cover claimed economic losses; then that nuclear solution will still cost several times today's best unsubsidized renewable prices, so it will abate severalfold less carbon per dollar. If any of those hopes aren't realized, that disadvantage will rise.

Sustaining existing reactors *sounds* easier, faster, and cheaper than replacing their output with new efficiency and renewables. Yet the conditions owners are demanding for continued

1086 - Bloomberg New Energy Finance, "World Reaches 1,000 GW of Wind and Solar, Keeps Going", 2 August 2018, see https://about.bnef.com/blog/world-reaches-1000gw-wind-solar-keeps-going/.

1087 - Felix Creutzig, Peter Agoston, et al., "The underestimated potential of solar energy to mitigate climate change", Nature Energy, 25 August 2017, see https://doi.org/10.1038/nenergy.2017.140; Christian Breyer, Dmitrii Bogdanov, et al., "On the Role of Solar Photovoltaics in Global Energy Transition Scenarios", Conference Paper, 32nd EU PVSEC (Munich), June 2016, see https://www.researchgate.net/publication/304350788_On_the_Role_of_Solar_Photovoltaics_in_Global_Energy_Transition_Scenarios, summarized at http://www.neocarbonenergy.fi/wp-content/uploads/2016/02/13_Breyer.pdf.

1088 - Nancy M. Haegel, Robert Margolis, et al., "Terawatt-scale photovoltaics: Trajectories and challenges", *Science,* Volume 356, 14 April 2017, see https://doi.org/10.1126/science.aal1288.

1089 - Historic learning curves are proving overly conservative; e.g. Rocky Mountain Institute's and its industry partners' three successive halvings of unsubsidized PV system cost (now at ~US$20–25/MWh for streamlined community-scale groundmount installations entering the market) suggest continuing radical system-cost drops not yet in market prices. This and other nested positive feedback loops could greatly speed the energy transition: see M. Abramczyk et al., "Positive Disruption: Limiting Global Temperature Rise to Well Below 2 C°", Rocky Mountain Institute, 2017, see https://rmi.org/insight/positive_disruption_limiting_global_temperature_rise/; and Amory B. Lovins, "Additional sensitive intervention points in the post-carbon transition", in submission as of August 2019.

operation aren't just for billions of dollars a year in new subsidies; they also impose heavy costs and constraints on the fast, widespread, job-rich, and popular renewable solutions. Nuclear power's relationship with modern renewables and efficiency is rhetorically complementary but in practice zero-sum or worse. How can slowing and blocking the cheapest and fastest solutions—confining them to smaller markets and putting them at an artificial price disadvantage—yield better climate outcomes? Why should a particular low-carbon solution, unable to compete after half a century, be awarded walled-garden markets and new subsidies unavailable to other low-carbon solutions? How does this fit IEA's correct call for policy to be technology-neutral?

BNEF's 2019 annual analysis of global electricity[1090] concluded that the global power sector remains on track to meet the basic 2°C Paris Agreement goal (though not yet the safer 1.5°C aspirational goal). But though the report "is fundamentally policy-agnostic,... it does assume that markets operate rationally and fairly to allow lowest-cost providers to win," said BNEF's spokesperson. Nuclear power's advocates have the opposite goal—to replace the market processes that reject their business with political choices their lobbying power can shape. Mandating nuclear choices that the market has rejected also cripples the market-based decision frameworks that underpin the modern energy transformation BNEF so effectively tracks. How can that anti-market U-turn speed our urgent journey beyond fossil fuels?

CONCLUSION ON CLIMATE CHANGE AND NUCLEAR POWER

Stabilizing the climate needs solutions that are "granular, modular, mass-producible, fungible, quickly installable by diverse actors with little institutional preparation, and—most importantly—propelled by the powerful feedback of increasing returns and learning-by-doing."[1091] That describes energy efficiency and modern renewables but not nuclear power. Stabilizing the climate is urgent, but nuclear power is slow. It meets no technical or operational need that these low-carbon competitors cannot meet better, cheaper, and faster. Even sustaining economically distressed reactors saves less carbon per dollar and per year than reinvesting its avoidable operating cost (let alone its avoidable new subsidies) into cheaper efficiency and renewables. Whatever the rationales for continuing and expanding nuclear power, for climate protection it has become counterproductive, and the new subsidies and decision rules its owners demand would dramatically slow this decade's encouraging progress toward cheaper, faster options, more climate-effective solutions.

1090 - See BNEF "New Energy Outlook 2019", 18 June 2019,see https://about.bnef.com/new-energy-outlook.

1091 - Amory B. Lovins, "Additional sensitive intervention points in the post-carbon transition", in submission as of August 2019.