US nuclear power: status, prospects, and climate implications

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In 2020, the world added[1] 5.521 GW (billion watts) of nuclear generating capacity—just above the 5.491 GW[2] of lithium-ion batteries added to power grids. The average reactor is 31 years old—41 in the United States, whose fleet is the world's largest—so it's not surprising that in 2020, maintenance or upgrade costs, safety concerns, and often simple operational uncompetitiveness caused owners to close 5.165 GW. The net nuclear capacity addition was thus the difference, 0.356 GW. In the same year, the world added[3] 278.3 GW of renewables (or 257 GW without hydropower)—782 times as much. Adjusted for relative US 2020 average capacity factors[4], renewables' net additions in 2020 thus raised the world's annual carbon-free electricity supply by ~232 times as much as nuclear power's net additions did. That is, nuclear net growth increased the world's carbon-free power supply in all of 2020 only as much as renewable power growth did every ~38 hours. Renewables also received[5] about 20 times more financial capital, mostly voluntary private investments, while nuclear investments used mainly tax revenues or capital conscripted from customers. These ratios look set to continue or strengthen[6].

In a normal industry, such comparisons, let alone dismal economics (below), might dampen enthusiasm. Yet the industry's immense lobbying and marketing power continues to yield at least tens of billions of dollars in annual public subsidies, still rapidly rising. This reflects broad bipartisan support among US and many overseas political leaders, often contrary to their citizens' preferences and, as we'll see, to their own paramount goal of stabilizing the Earth's climate. To explore this seeming paradox, here is my frank personal impression of nuclear power's status, competitive landscape, prospects, and climate implications in the United States.

1. Status

When nuclear power emerged, from the mid-1950s through the 1960s, US utilities—vertically integrated, three-fourths private, technically and culturally conservative—didn't want it. Yet powerful Federal actors offered heavily subsidized fuel and let them own it, largely relieved them of accident liability, and ultimately tempted and coerced them into a vast nuclear building spree, under implicit threat of displacing them with Federal nuclear utilities[7]. During 1955–2020, US utilities ordered 259 power reactors. The number actually built and run peaked at 112 in 1990, with a straggler begun in 1973 added in 2016. By August 2021, 93 units (95 GW) remained in operation while 40 (19 GW) had been permanently closed. As of mid-2017, only 28 units—some of them slated for closure—had been built, remained competitive in their regional markets, and had not suffered at least one outage lasting one year or more. In the hydrocarbon industries, 28 successful units out of 259 total orders would be called an 89% dry-hole risk.

As construction costs and durations relentlessly rose[8], regulators and customers were assured their initial pain would usher in decades of low-cost generation. This too proved false. Some plants failed early, others' operating costs rose, and decades later, owners are demanding huge new subsidies to keep running. After these scarifying experiences, capital markets are disinclined to invest in nuclear newbuild in the US or elsewhere. Contrary to a widely cultivated myth, the successive accidents (Three Mile Island, Chernobyl, Fukushima Daiichi) widely blamed for this rejection all occurred *after* the business case and investor confidence had collapsed[9].

Lately, however, some unknowable combination of industrywide quality improvement since the late 1980s (chiefly via the Institute of Nuclear Power Operations), closure of troubled units, and laxer safety regulation has kept the winnowed US survivors generating an impressive ~92–93% of their full-time full-power rated output. They've sustained capacity factors >90% since 2014—well above the world average of ~75% or the 2020 French average of ~61%[10]. The remaining US potential output is lost to periodic refueling—its duration halved since the mid-1990s—plus any maintenance needed at other times. This high performance, plus uprating surviving units to offset 8.3 GW retired[11], held the nuclear share of US electricity generation at ~20% for the past two decades, twice the global share[12], though it should decline over the coming decade as retirements far outpace additions.

The US supply chain to sustain the 93 existing reactors persists, more or less, but of the four original US reactor vendors, all have merged (GE with Hitachi), exited, or failed, most recently Westinghouse[13]—bought by Toshiba, bankrupted[14] by its new US projects, then restructured by a Canadian private-equity partnership (which recently considered selling it[15]) to maintain the plants it once built. Export markets have proven elusive despite strong government promotion (even from within the State Department and the National Security Council) under flawed anti-proliferation rules. There is zero US market appetite for large new reactors—and only for as many smaller ones as taxpayers will heavily subsidize. The dwindling domestic nuclear industry must therefore subsist on fueling, repairs, decommissioning, and such waste management as can be devised—most plausibly on Federal lands needing no State consent.

As for fueling, little uranium is mined in the US, globally it's as abundant as tin, cheap enrichment is worrisomely spreading, and reprocessing has demonstrated only costlier and harder waste management, so plutonium reuse and breeder reactors are seldom mentioned. However, some proponents continue to misrepresent "advanced" reactors as a waste solution.

US public acceptance of nuclear power fluctuates, and depends strongly on how and to whom the question is put. Nuclear advocates reported an even split in the 2019 Gallup Poll[16] after long and intensive publicity campaigns. Most in the industry blame its woes on irrational public fears. Many independent observers think this is neither true nor relevant, since nuclear newbuild, like most or all existing nuclear operation, lacks a business case. That makes deployment ever harder unless mandated and funded by governments as in centrally planned economies.

After decades of intense political pressure, industry capture of US nuclear safety and security[17] regulation appears complete, with rules and processes arranged to the operators' liking. The skill and integrity of some US Nuclear Regulatory Commission experts are commendable. But scrapping industry-agreed post-Fukushima[18] safety retrofits, and proposing (later withdrawn) to let operators do their own inspections, inspired little public confidence in the institution[19]. Any remaining confidence may and should fade if the NRC carries out its proposed replacement of decades of licensing philosophy—for “advanced” reactors and indeed *any* new projects—with a drastically different one. The proposed new rule, called Part 53, would replace reliance on demonstrated and publicly scrutable technical realities with appointed Commissioners’ subjective risk judgments based on vendors' claims and proprietary analyses. Part 53 could gut every aspect of protecting radiological public health and safety, with little avenue for public scrutiny or challenge, at the very time when novel designs with troublingly opaque risks are being proposed—with initial designs expected to seek similar exemptions from existing rules even before the new ones are approved. In applying intense pressure for this most dangerous regulatory shift in decades, the industry’s aim is of course to slash capital and operating costs by shrinking or eliminating previous levels of quality assurance, safety margins, protective equipment, exclusion zones, security requirements, exposure limits, and other pesky technicalities inconsistent with vendors’ unsupported (and quite possibly invalid) claims of breakthrough safety.

Even before novel designs seek licenses, reality intrudes from the aging fleet. US power reactors had ten “near misses” in 2015 alone[20], then the next Administration further weakened safety rules. Sloppy practice persists[21]. Institutional honor waxes and wanes with political shifts, but overall, the trend is not encouraging. In recent years, the NRC’s swift license extensions from 40 to 60 years for nearly all reactors[22], 80 for some, with talk even of 100, seems far ahead of convincing safety evidence (though it’s hardly plausible that any can *economically* operate for so long when most or all cannot do so now: the 40 units closed by mid-2021 averaged just 22 years old, and only eight had reached age 40, while the six closed in 2016–20 averaged 46.2 years old but were licensed for 60[23]). The industry seems not to have learned from history that looser regulation tends to cause bad outcomes that further erode public acceptance. Complacency is unwarranted with a technology, said Swedish Nobel physicist Hannes Alfvén, where “no acts of God can be permitted.”

Long-term disposition of US nuclear wastes faces the same geological and social-continuity issues as abroad, complicated by intractable, multi-layered political disputes. The Congressionally mandated Yucca Mountain, Nevada site for high-level waste disposal was scrapped, though not for the right reasons (dubious geology, not just politics). Low-level waste sites continue to spread with little scrutiny. Pending permanent disposal, much spent fuel is still stored in reactor-sited pools requiring active cooling, rather than in less-vulnerable dry casks. Nationwide nuclear-waste transport can be controversial too. Cleanup of long-festering, mainly military, contaminated sites and their concentrated nuclear wastes is late, slow, costly, and inadequate. As more reactors retire, decommissioning is becoming a big business, increasingly under troubling arrangements that transfer accumulated funds to a firm incentivized to work until the money runs out but then seemingly entitled to walk away without liability.

People and culture are also of deepening concern. A symbiotic relationship with the nuclear Navy provides a flow of disciplined reactor operators to civilian plants, probably creating both safety benefits and cross-cultural frictions. Yet recruiting and retaining top talent in the broader effort, both civil and military, is increasingly challenging. So are institutional memory and cultural continuity. Three-fourths of a century into the nuclear enterprise, as I’ve observed it for

58 years, the impressive pioneers' vision and rigor have faded, personal quality and moral probity have eroded, and the culture is pitted by corruption and decay[24]. I fear the enterprise is passing, as Alfvén warned the 1980 IAEA Geneva Conference, "into ever less competent hands."

Self-reflection is also declining with the rise of a new generation of ardent but technically and historically naïve enthusiasts susceptible to social-media memes. Their fervor can generate some political and subsidy support, but it's a weak base on which to rebuild a failing sector. Economist Paul Joskow's lesson needs relearning: "Nuclear power is a business, not a religion."

2. Competitive landscape

The most important determinant of nuclear power's future, though the least discussed by its advocates and even by many of its critics, is its economics. Eminent merchant bank Lazard says US "advanced" nuclear newbuild (a 2.2-GW LWR station) would cost 3–8× more per kWh than unsubsidized solar or windpower[25]. Leading empirical-data synthesist Bloomberg New Energy Finance (BNEF), tracking more than 20,000 projects' actual costs worldwide, says 5–13×[26]. Even the US Energy Information Administration (expert more in historical data than in technology cost forecasting) says 2× and finds that nuclear cost exceeds value[27]. Chinese reactors are cheaper, but so are Chinese wind and solar—respectively 2× and 3× below nuclear in 2025 levelized cost/kWh, says BNEF—so China invested about as much in renewables in 2020 as it had invested *cumulatively* in nuclear power during 2008–20[28], building half the world's 2020 new renewable capacity and 80% of the global increase over 2019's. Moreover, renewables, a diversified US$0.3-trillion-a-year global business, are getting cheaper, while reactors, an increasingly localized and socialized ~$0.015-trillion-a-year specialty, are getting costlier. Renewable learning curves are consistent and steep[29], but claimed nuclear-power learning curves have never been demonstrated[30]. All-renewable supply by 2050 could *save* ~$$10^{13}$ net, but nuclear futures are far costlier[31].

Nuclear costs

Careful analysis confirms[32] the inexorable rise of historical US nuclear capital costs, which dominate its electricity cost. The complex reasons, many understood since the 1970s, have so far proven impervious to proposed solutions. The latest proof is the collapse of the US "nuclear renaissance" based on two flagship twin-reactor projects led by the second- and third-biggest US shareholder-owned utilities[33]. The South Carolina plant was cancelled in 2017 (a year after planned completion but only 40% done) after >$9 billion was spent; four top executives have pled guilty to serious crimes[34]. The Georgia project is struggling toward completion six years late at over twice projected cost[35] (but with $12 billion in Federal loan guarantees and more being sought); it's not yet finished, and potentially serious quality issues are still emerging[36]. In both cases, design and construction innovations failed to control cost and schedule as promised[37]. As in France, the generational gap between the 1970s construction boom and the past decade's efforts at resumption appears to have fatally corroded the finely tuned managerial and supply-chain skills that such complex projects demand.

Nuclear operating costs, long assumed trivial and certainly below those of fossil-fueled generation, have turned out to be neither, because the fuel-cost advantage is offset by unexpectedly high non-fuel costs. Nuclear operating costs remain secret in many countries, even in aggregated forms, but where discoverable, are consistently rather high[38]. In the US, their proprietary reactor-specific values are annually compiled by the industry's respected Electric Utility Cost Group, then published as national summaries by the industry's promotional arm, the Nuclear Energy Institute. The latest (2020) reported US nuclear operating cost[39]—fuel, operation & maintenance, and Net Capital Additions (NCAs[40])—averages US$30.4/MWh, exceeding the typical total capital plus operating costs of new solar power, windpower, or efficient use.

Most elements of nuclear operating cost are reportedly drifting down[41] with cheaper uranium, completion of uprating and safety-retrofit investments, retirement of ill-performing units, and perhaps lighter regulation (regulatory NCAs lately fell sharply, but it's unclear whether that's because fixes got done or fewer were ordered). However, renewable costs are generally declining faster. Geriatric issues might be emerging as a countervailing nuclear cost trend, with "sustaining" NCAs creeping up in the past decade. Uranium has also just attracted financial speculators[42] who are likely to make the price higher and more volatile and to disrupt market stability.

The published average operating cost masks wide variations whose quartile data (still averages but somewhat more meaningful than a single national number) have not been released in usable form since 2014–16—perhaps due to the political delicacy of seeking large new Federal subsidies for a supposedly competitive resource. A similarly awkward straddle is the need to assert robust economics to bolster Federal and public confidence while pleading unsupportable losses to elicit State-level subsidies. In both cases, specific data remain opaque, and apparently of limited interest to politicians now raising nuclear subsidies for other reasons.

Renewables in markets compete with nuclear in legislative back rooms

In 2020, as European renewable generation surpassed fossil-fueled generation, US renewable generation surpassed both coal-fired and nuclear generation, quickly gaining on the leader (natural gas). Lazard[25] reports that unsubsidized US windpower and solar power nominal prices fell 70% and 90% respectively during 2009–20, while new-nuclear costs rose 33%. Therefore in most US regions most of the time, renewable electricity prices set by long-term Power Purchase Agreement private contracts have for years hovered around or below the low end of wholesale prices, while average nuclear operating costs exceed wholesale prices. Thus many existing nuclear plants fail to clear regional electricity auctions and can be run only at a loss. That is, they cannot compete in the unbundled, retail-choice markets that their owners insisted on having. Some operators choose to retire such distressed plants or those facing major repair or upgrade costs—realizing that "A license to operate a nuclear power plant is not a sentence to do so."[43]

Other operators persuade intimidated, compliant, or in some cases corrupt[44] legislators to bail them out with multibillion-dollar State subsidies. So far, five States (Connecticut, Illinois, Ohio, New Jersey, New York) have done so, saving for now 20 reactors from market exit[45] (or 18 excluding two Ohio units' subsidies later rescinded as corruptly arranged; such investigations continue in Illinois; the firms involved would also be the largest beneficiaries of proposed new Federal subsidies). These new State nuclear-specific subsidies take such forms as mandatory utility purchases of output, Zero-Emission Credits, or Nuclear Diversity Certificates. They're mostly fixed at ~US$10–15/MWh, last up to 12 years, and generally bar public scrutiny of claimed financial need. They respond solely to the nuclear industry's parochial interests and political power. In contrast, pricing carbon at ~$20–30/$tCO_2$ would achieve the desired policy result without artificially advantaging nuclear power over renewables or efficient use.

Three more reactors are to retire in 2022–24 in Michigan and California. This is economically rational: independent assessments consistently find that at least many US reactors can't earn enough to cover their costs[46]. Yet almost every retirement is bitterly contested[47]. Some owners openly threaten State governments with job losses and power disruption. The Illinois battle held renewables hostage to nuclear power's bailout; ultimately the owner accepted a nuclear subsidy—informed by an independent study for the Governor—totaling just one-seventh its initial demand[48]. State subsidies have survived court challenges but have been muddied by 2018–21 policy shifts at the Federal Energy Regulatory Commission, which oversees the interstate regional grids operating in most US regions. The most likely outcome is continued State subsidies, but those may be replaced or perhaps augmented by both voted and proposed Federal subsidies for merchant reactors in 2022–26 totaling potentially $46–57 billion[49]—or more if later quietly extended, as has often occurred historically.

Subsidies do help nuclear compete against natural gas. Proposed Federal "clean energy" subsidies would equally advantage renewables but not efficiency (while pricing carbon would equally advantage nuclear, renewables, *and* efficiency without creating a distortion between efficiency and supply). In practice, renewables and efficiency will usually keep beating nuclear *and* gas, even without the temporary renewable subsidies. Yet the nuclear industry cannot acknowledge renewables and efficiency as competitors without impugning its own case for nuclear necessity, so it must pretend its real rival is gas, whose operational role is different—ramping, not steady operation. The more nuclear tries to follow net load (possible within limits, but awkward), the worse its economics. Claiming new market prospects, from process heat to Bitcoin mining[50], makes no more sense than its vanished main use case for "baseload" generation, and no more for small than for big reactors. New use cases cannot remedy uncompetitive electricity costs.

US (like foreign) nuclear power has *already* enjoyed many decades of large and mostly permanent Federal subsidies. Those have lately rivaled nuclear plants' construction cost and exceeded the value of their output[51]. Nuclear power also gets substantial subsidies from some States, plus, for the latest two plants ordered, Federal operating subsidies exceeding windpower's[52]. Claiming we must all pay as much more as necessary to keep uneconomic reactors operating reverses previous trends toward market choice. As Peter Bradford (the dean of US nuclear and utility regulators) urges, policymakers who want carbon-free generation should competitively procure it, just as they buy other resources and attributes, rather than mandating and subsidizing continued use of a specific technology[53]. (Some existing nuclear units might clear such markets in the short run; others or new ones would not.) Professor Mark Cooper suggests how[54].

As Professor Bradford says, guaranteeing nuclear market share with no demonstration of competitiveness (per kWh or per CO_2 ton) compromises climate-effectiveness, and slows the evolution of regional power markets and the clean technologies that win in them. Continuing negotiations about new nuclear subsidies, he concludes, are “essentially a negotiation…about the size of the ransom that the nuclear industry will be able to extract by slowing down the transition to an electric system that transfers control from large central facilities to the premises [and communities] of the customers.”

Grid integration

Nuclear advocates contend that nuclear plants’ normally steady “baseload” operation has unrecognized but large economic, reliability, and resilience value deserving special compensation. No evidence has emerged to support this view[55]. In 2018, FERC (then with three Trump appointees) rejected 5–0 his Energy Secretary’s request for new subsidies to coal and nuclear plants. The February 2021 Texas power crisis gave no reason to revisit the claim[56]. On the contrary, those central thermal plants have proven vulnerable to failure, especially in a changing climate[57].

More broadly, big thermal stations, the mainstay of 20th-Century grids, have lost their operational role and business case in the 21st. Now renewables with near-zero operating cost are dispatched whenever available; other units, timely use, and thermal or electrical storage follow. “Baseload” units’ inflexibility thus becomes a handicap—one of the owner’s reasons for retiring its well-running Diablo Canyon reactors[58]. Cycling reactors, where feasible, to follow varying net loads makes them even less economic to keep operating, so they must run fewer hours until they go broke and close, to be rapidly replaced by zero-carbon resources[59]. How, then, can the reliable supplies traditionally sustained by those units continue with variable renewables?

In a sense, says utility regulatory expert Jim Lazar, “nuclear units have something in common with variable renewable resources: they produce much of their output when it is not needed for the grid.” Nuclear units can’t keep rapidly changing their output on demand as renewables can, so to cope with excess nuclear output at low-demand times, at least 12.2 GW of US hydro pumped storage plants, each >1 GW, were built by the owners of nine nearby US nuclear plants. Their cost was an “inflexibility tax”. Ironically, these renewable resources built to support nuclear ones will be freed by nuclear closures to support an increasingly renewable grid.

Giant fossil-fueled or nuclear plants can unexpectedly lose a billion watts in milliseconds, often for weeks or months, and often without warning, or unexpectedly extended from brief to long outages (as in France in 2020, when the average plant produced zero output a third of the time). The electricity grid was built mainly to manage this intermittence (unpredictable forced outages) by backing up failed generators with working ones. Diversified portfolios of modular renewables don’t suffer such ungracefully massive failures: PV and wind generally falter in far smaller chunks, and their output varies quite predictably—often more so than demand. Thus the same grid can back up their predictable variability, more easily and often more cheaply, with other renewables of other types or in other places (or demand-side resources or storage). But the need for storage is widely overstated.

At least ten kinds of “grid flexibility resources” can reliably balance grids powered largely or wholly by variable renewables[60]. Of these, utility-scale batteries, though often profitable, are the best-known but currently the costliest. They’ll become much cheaper, but probably not as cheap as ample competitors. In typical order of decreasing cost—and besides hydrogen and non-battery bulk storage methods like pumped hydro, compressed air, and gravity storage—these grid-balancers include thermal (heat or coolth) storage, electric-vehicle integration, cogeneration and dispatchable-renewable integration, wider interconnected markets, highly accurate renewable forecasting, strong demand response, and end-use efficiency. The latter two resources have lately turned out to be severalfold larger (yet cheaper) than previously thought[61]. Just modest efficiency gains, ice-storage air conditioning, and smart bidirectional electric-vehicle charging could run the isolated Texas grid reliably and economically in 2050 on 100% renewables with no bulk storage[62]. Simulations denying this simply exclude most of the proven solutions. And rather than comparing technologies singly, locally optimized “clean energy portfolios”—blending efficient use, timely use, renewables, and storage—outcompete both fossil and nuclear energy for *every* need: energy, peak output, ramp rate, and ancillary services[63].

Grid balancing now typically costs a few US$/MWh[64]. The evidence suggests it also tends to cost *less* with wind and solar than with big thermal plants, because big thermal plants’ failures are bigger, longer, and less predictable, making their backup costlier[65]. As Germany’s renewable share of generation quadrupled in 2006–20, its grid operators learned even faster, so reliability broadly improved to five times America’s. In 2020, renewables’ share of German power demand exceeded 50% sometime in almost every week, and in half of the weeks it reached between 80% and nearly 100%. Nuclear and coal phaseouts continued. The lights stayed on. As renewables and efficiency growth offset coal and nuclear closures[66], Germany’s greenhouse gas emissions fell by over half in 2010–20, and the power sector met its climate goal a year early (*before* the pandemic depressed demand) with five percentage points to spare.

Careful choreography has lately met annual national electricity demand with 97% renewables (79% without hydro) in Scotland in 2020, 79% in Denmark (with 0.06% hydro) in 2019, 66% in Portugal in 2018 (42% without hydro), 52% in Germany (with 3.3% hydro) in 2020, and 46% in Spain in 2016 and 2020 (27/33% without hydro). None added bulk storage. All sustained superior reliability, often many times that of the US. They simply learned to run their grids (as my colleague Clay Stranger puts it) the way a conductor leads a symphony orchestra: no instrument plays all the time, but the ensemble continuously makes beautiful music.

This is also how the former East Germany’s ultrareliable grid operator 50Hertz—half wind-and-solar-powered in 2019, 62% renewable in 2020—intends 100% renewables in 2032. Anyone who thinks we need big thermal plants to keep the lights on is not paying attention to modern power engineering, where “grid-forming inverters” and fast-responding power electronics can stabilize grids even better than rotating heavy machines traditionally did. Some European operators also disconnect retired coal or nuclear plants’ generators from their turbines[67] and keep spinning them as grid-connected "synchronous condensers," using their angular momentum to keep on cheaply stabilizing voltage and frequency[68].

Extra wind and solar capacity can also economically substitute for giant batteries or other grid-balancing resources as supply becomes mostly or wholly renewable. But most of the time the surplus electricity, rather than having to be "curtailed" (wasted) as grid-centric analysts assume, can be profitably redeployed to tasks not yet electrified—to run heavy vehicles and decarbonize steel, cement, and other heavy-industrial heat, directly or by making hydrogen or ammonia. That is, our industrial economy is easier and cheaper to decarbonize as a whole than in pieces[69].

Supposed renewable constraints like land-use[70] and critical materials[71] are quite manageable: a well-designed efficiency-and-renewables decarbonization strategy would *decrease* the energy system's land-use. Some places may need grid expansion, but fewer and less than often claimed —especially if efficient and timely use are properly competed or compared with supply, and if local and distributed were fairly competed with remote and centralized. Where grid congestion blocks renewables, another option is a new kind of transmission wire (from a firm I advise) that can carry 2–3× the usual power on the same towers, so existing lines can be quickly and profitably restrung to allow rapid renewable expansion without new rights-of-way or towers.

Efficient use of electricity

Renewables now cost less than new fossil or nuclear plants in 91% of the world (soon all), and less than running existing thermal plants in roughly half the world (soon all)[26]. But there's often an even cheaper choice: wringing more work from each kWh by smarter design and better technologies. "Negawatts" are especially cheap because they're already delivered behind your meter, while electricity generated hundreds of miles away costs an average of US$4/MWh extra to deliver. Efficiency typically costs $0–20 per kWh saved, but properly adjusting for where it's delivered, it has a *negative* cost compared with remote supply. So how much can we save?

A decade ago, using the best 2010 technologies, RMI rigorously showed[72] how to use US electricity fourfold more productively by 2050, so 2.6-fold economic growth during 2010–50, with all-electric automobiles, could use one-fourth *less* electricity than in 2010, yet cost far less. That's part of a tripled-efficiency, quintupled-renewables scenario for the whole US economy, saving $5 *trillion* net present value and cutting CO_2 emissions by 82–86%, with no new inventions or Acts of Congress. With smart State and local policies, it could be led by business for profit. That vision tracks nicely to actual market developments since. Efficiency speeds renewables' takeover: if, hypothetically, that 4× efficiency could have been achieved *in 2020*, then renewables' 20.6% share of 2020 US electricity could have been 82%—cleaning up the power system[73] at far lower cost than needing to quadruple renewable (let alone nuclear) output.

Strikingly, quadrupling US efficiency in using electricity would save kWh at one-tenth the cost of buying them today, so RMI's study should have bought even more efficiency! In contrast, by overlooking the economics of saving *vs.* supplying electricity, a widely cited 2020 study[74] buys much *less* efficiency than RMI's study did, and so assumes the US will need 2–4 times more electricity to produce virtually the same 2050 GDP. That excessive demand creates problems of land-use, transmission, etc., specified in minute detail—all artifacts of buying far too little efficiency. Governments and companies needn't repeat that error and risk building costly supply-side assets that they won't need, can't afford, and may not be able to pay for.

Who chooses and how?

Ideally, everyone could be fully informed, enabled, and motivated to choose the most clean, safe, affordable, and reliable way to deliver any electrical service desired, like hot showers and cold beer—whether with purchased electricity from preferred sources, homemade electricity, or using electricity more productively and timely. In practice, such choices are blocked by dozens of practical barriers[75], each convertible into a business opportunity, but requiring major policy reforms or entrepreneurs' focus and tenacity.

Many entities we entrust with such choices, from utilities to regulatory commissions to governments at all levels, are ill-equipped to compare or compete all those choices either, or don't bother. In fact, most[76] US States' regulatory practices reward utilities for selling you more electricity and penalize them for cutting your usage and bill. This perverse practice creates huge choice, cost, and value gaps between the best buys and what we're actually offered. Caring customers in mindful markets can take many of those choices into our own hands—saving or retiming our use of electricity, producing our own, trading it with each other, or buying the kinds we like. This visionary world is already emerging. People with efficient homes and smart appliances have freedom of choice, giving them more market power than utilities. Add a smart electric car, or rooftop solar and storage, and the utility becomes a mere optional convenience, demoting nuclear power from uncompetitiveness to irrelevance. These trends are well underway.

3. Prospects

In 2010–16, saved energy decarbonized the world three times more than all carbon-free supply growth[77]. In 2010–20, renewable growth decarbonized electricity five times more than nuclear growth did[78]. Nuclear power wasn't consistently faster to deploy than renewables through 2018[79], and in 2020, as we saw, it's over 200-fold behind. Whether in traditional or new forms, it's simply too slow[80] to make much difference to climate. Yet perversely, it *slows down* faster, cheaper options by blocking competition, hogging market space, and diverting money, talent, attention, and time from the most climate-effective solutions. Efforts to expand nuclear power, however well-meant, are thus making climate change *worse*—yet keep intensifying. The less nuclear power can achieve, the more we hear about its vital and wondrous future.

The 2021 US infrastructure bill added $6–12 billion to bail out uneconomic existing reactors for 5–10 years and $6 billion to develop new or smaller kinds claimed to address the problems that the industry most recently strove but failed to solve[81]—affordability, safety, wastes, and proliferation. "Advanced" or "Small Modular Reactors," SMRs[82], seek to revive and improve concepts generally tried and rejected decades ago due to economic[83], technical, safety[84], or proliferation[85] flaws[86]. BNEF estimates early SMRs might generate at ~10× current solar prices, falling by severalfold after tens of GW were built, but not by enough to come near competing. Despite strong Federal support, proposed projects are challenged to find enough customers[87]. Developers and nations are also pursuing >50 diverse designs—a proven failure condition.

SMRs' basic economics are worse than meets the eye, because their goalposts keep receding. Reactors are built big because, for physics reasons, they don't scale down well. Small reactors, say their more thoughtful advocates, will produce electricity initially about twice as costly as today's big ones, which in turn are 3–13× costlier per kWh than modern renewables (let alone efficiency). But those renewables will get another 2× cheaper by the time SMRs could be tested and start to scale toward the mass production that's supposed to cut their costs. High volume cannot possibly cut SMRs' costs by 2 × (3 to 13) × 2-fold, or ~12× to ~54×. Indeed, SMRs couldn't compete even if the steam they produce to turn the turbine were *free*. Why not? In big light-water reactors, ~78–87% of the prohibitive capital cost buys *non*-nuclear components like the turbine, generator, heat sink, switchyard, and controls. Thus even if the nuclear part were *free* and the non-nuclear remainder were still at GW scale so it didn't cost more per unit, the whole SMR complex would still be manyfold out of the money.

SMRs are also too late. Despite streamlined (if not premature) licensing and many billions in Federal funding commitments, the first SMR module delivery isn't expected until 2029—in the same smaller-LWR project just lost over half its subscribed sales as customers considered cost, timing, and risk[88]. The first "advanced" reactors (a sodium-cooled fast reactor and a high-temperature gas reactor), ambitiously skipping over prototypes, are hoped by some advocates to start up in 2027–28. DOE in 2017 rosily assessed that if such initial projects succeeded, a first commercial demonstrator would then take another 6–8 years' construction and 5 years' operation before commercial orders, implying commercial generation at earliest in the late 2030s, more plausibly in the 2040s. But the US Administration plans to decarbonize the grid by 2035, preëmpting SMRs' climate mission[89].

An additional challenge would be siting new SMRs or clusters of them (which cuts cost but means that a problem with one SMR can affect, or block access to, others at the same site, as was predicted and experienced at Fukushima Daiichi). It would take roughly 50 SMR orders to justify building a factory to start capturing economies of production scale, and hundreds or thousands of SMRs to start seeing meaningful, though inadequate, cost reductions. A study assuming high electricity demand and cheap SMRs estimated a US need for just 350 SMRs by 2050[90]. It's hard to imagine how dozens of States and localities could quickly approve those sites, especially given internal NRC dissension on basic SMR safety[91].

Such awkward realities won't stop determined lobbyists and legislators from showering tax funds on SMR developers, seen as the industry's last hope of revival. With little private capital at stake and customers probably bearing cost-overrun risk (as they did in the similarly structured WPPSS nuclear fiasco four decades ago), some SMRs may get built. I expect they'll fail for the same fundamental reasons as their predecessors, then be quickly forgotten as marketers conjure the next shiny object. A lifetime of such disappointments has not yet induced sobriety.

As long as the industry can fund potent lobbying that leverages orders of magnitude more federal funding, the party will carry on. But where does that leave the Earth's imperiled climate?

4. Nuclear power reduces and retards climate protection

The climate emergency is often assumed to require *every* possible source of low-carbon electricity to displace the three-fifths still made from coal and gas. But this assumption is false because it ignores priorities. We relieve famine by buying rice, not steak. To save carbon, we must buy the cheapest, fastest, most climate-effective displacements for fossil-fueled generation. Every dollar (or CHF) we spend on a costly or slow solution saves less carbon, later, than if we spent the same money on a cheap and quick solution. Properly counting carbon *and* money *and* time, because all three matter, makes the arithmetic obvious. Arithmetic is not an opinion[92]. Buying a nuclear kWh that's 3–13× costlier than a renewable kWh gives us 1 nuclear kWh *instead of* 3–13 renewable kWh, and at least a decade later. Choosing renewables instead would thus save 3–13× more carbon, a decade sooner. Efficiency, being even cheaper, saves even more carbon per dollar—usually cheaper than just *operating* an existing reactor, let alone building a new one.

Thus the basic assumption that nuclear power, of any kind and size, is an effective substitute for fossil-fueled generation is simply wrong. Only if today's three carbon-free power choices—nuclear, renewables, and efficiency—were all equivalent in cost and speed could they be equally climate-effective and thus selectable based on other attributes like reliability, resilience, stability, and safety. Since they're actually manyfold different in cost and speed, hence in climate-effectiveness, that difference would seem decisive in a climate emergency.

Coal plants were built by counting cost but not carbon. Nuclear plants are justified by counting carbon but not cost. Effective climate solutions must count carbon *and* cost *and* speed. If you haven't heard this logic before, perhaps it's because the nuclear industry is desperately keen not to discuss economics, still less comparative economics, and least of all climate-effectiveness. They want you to think that operating without emitting CO_2 is good enough, and that relative cost and speed don't matter because we need every option. If you don't hear a clear response to my logic, perhaps that's because they fear you might understand why cost and speed matter.

Climate will be stabilized by judicious choices, not mushy mantras or nostalgic nostrums. As US nuclear critic Dave Kraft puts it, "We're in a climate crisis, not a Chinese buffet." Our goal must be not to choose one dish from each category, but to select the menu items that will save the most carbon with the limited time and money we have, satisfying our hunger and fitting our wallet. It's really that simple. "All of the above" remains a popular bipartisan substitute for thoughtful analysis in US energy policy, which seems about to reclassify nuclear power as "clean" to qualify it for new mandates and subsidies. But Peter Bradford completed the political mantra "We're not picking and backing winners" by adding: "They don't need it. We're picking and backing losers."

Like a proud, stubborn, and illusion-ridden elder mortally stricken with cancer, nuclear power is slowly dying of an uncurable attack of painful market forces, yet is unwilling to accept reality and enter hospice. From powering postwar growth to displacing oil to displacing coal to saving the climate to serving the poor, nuclear power has run through and now run out of reasons to live. Despite outward cheer and booming voice, its pallor and withering can be seen through the makeup. How much more money, talent, attention, political capital, and precious time will its intensive care continue to rob from the life of its vibrant successors? Will its terminal phase be orderly or chaotic, graceful or bitter, emerging by default or by design? That is our choice.

Author

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[1] International Atomic Energy Agency (IAEA) PRIS, NPP Status Changes, 2020.

[2] Bloomberg New Energy Finance (BNEF), 2H-2021 Energy Storage Market Outlook, 28 July 2021. Of those additions, 1.464 GW were in the US: A. Colthorpe, "In 2020 the US went beyond a gigawatt of advanced energy storage installations for the first time ever," *Energy Storage News*, 4 Mar 2021.

[3] International Energy Agency (IEA), "Renewable Energy Market Update 2021," May 2021. The authoritative nongovernmental REN21 *Renewables 2021 Global Status Report*, 14 Jun 2021, concurs: its non-hydro 2020 additions total 256 GW.

[4] US Energy Information Administration (USEIA), https://www.eia.gov/electricity/monthly/epm_table_grapher.php?t=epmt_6_07_b: 92.5% nuclear, 74.3% geothermal, 63.2% non-wood biomass, 58.4% wood, 41.5% hydro, 35.4% windpower, 24.9% photovoltaic, etc. IEA (ref. 3) says PVs added 134 GW in 2020, wind 113.6, hydro 20.6, and others 10.1, each calculated as the weighted average of all projects, with each counted from its in-service date. Applying these to global 2020 net capacity additions (278.3 GW) implies 2020 net additions of ~82.7 average GW with an implied average capacity factor of 0.30. For comparison, IRENA's *Renewable Energy Statistics 2021* reports 2019 global output of 6,963 TWh from 2.542 TW of renewables, a 0.31 average capacity factor unadjusted for installation timing—reasonable agreement.

[5] In 2019: p 8, Frankfurt School/UN Environment Programme/BNEF, "Global Trends in Renewable Energy Investment 2020," reports $282.2b for modern renewables (plus $15b for big hydro, p 33) vs ~$15b for new nuclear; ~$297.2b / ~$15b = 19.8. *World Nuclear Industry Status Report 2021*, p 291, estimates slightly higher 2020 nuclear commitments (~$18.3b).

[6] *World Nuclear Industry Status Report 2021*, p. 64, projects at 1 July 2021 that world nuclear capacity will fluctuate slightly to 2023 and then plummet, declining every year to 2050 and losing 95 net GW in this decade, 77 in the 2030, and 70 in the 2040s. Holding current capacity constant would require extra, currently unplanned, addition of 15 GW/y (nearly three times the 2011–20 average). IEA and most other projections show that 2020-like renewable growth is the new normal.

[7] I. Bupp & J.-C. Derian, *Light Water: How the Nuclear Dream Dissolved*, Basic Books (NY), 1978.

[8] J. Koomey & N. Hultman, "A reactor-level analysis of busbar costs for US nuclear plants, 1970–2005," *Energy Policy* **35**(11):5630–5642 (2007). An international analysis of 180 reactors found 97% had mean 117% or $1.2b cost overruns and 64% time overruns, bearing the highest financial risk among electricity infrastructure options: B. Sovacool, A. Gilbert, & D. Nugent, "Risk, innovation, electricity infrastructure and construction cost overruns: Testing six hypotheses," *Energy* **74**:906–917 (2014).

[9] As shown both by the official statistics of orders/cancellations and by contemporary press. For example, three months before the TMI accident, *Business Week*'s 25 Dec 1978 cover-story Special Report "Nuclear Dilemma: The atom's fizzle in an energy-short world" (pp 54–68) began with "One by one, the lights are going out for the U.S. nuclear power industry. Reactor orders have plummeted from a high of 41 in 1973 to zero this year." The same issue's parallel overseas story (pp 44, 49) began: "As in the U.S., nuclear power in Europe and Japan is facing the most serious crisis in its 30-year history." Of course, TMI reinforced and deepened the *prior* collapse of business and public confidence, but did not cause it.

[10] Respectively from IAEA PRIS (ref. 1) and RTE data in *World Nuclear Industry Status Report 2021*, 28 Sep 2021. The latter source excludes output lost due to load-following or inadequate heatsink. Yet the average reactor had *zero* output for 115.5 days, or about a third of the time (p. 87). On 169 days in 2020, at least 20 units were down for at least part of the day; on 335 days, at least 10; every day, at least 6 at once.

[11] NEI, "Nuclear by the Numbers" 2020, p 18, 2013 through August 2020.

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[12] In the US, 2020 net generation was 19.5% nuclear, 20.6% renewables; globally, 10% nuclear, ~29% renewables. In both, the nuclear share was stagnant or falling, the renewable share rapidly rising.

[13] T. Hals, "How two cutting edge U.S. nuclear projects bankrupted Westinghouse," Reuters, 1 May 2017. Westinghouse had previously bought the nuclear businesses of Combustion Engineering and Stone & Webster.

[14] D. Cardwell & J. Soble, "Westinghouse Files for Bankruptcy, in Blow to Nuclear Power," *N.Y. Times*, 29 Mar 2017.

[15] "Brookfield 'at a crossroads' on whether to sell Westinghouse,", *World Nuclear News*, 8 Feb 2021. For now, a sale is off.

[16] American Nuclear Society, "Public opinion on nuclear energy: Turning a corner?," *Nuclear Newswire*, 12 Jul 2019.

[17] Union of Concerned Scientists (UCS), "Nuclear Plant Security," 2014/2016; G. Jaczko, *Confessions of a Rogue Nuclear Regulator*, Simon & Schuster (NY), 2019.

[18] UCS, "Preventing an American Fukushima," 2016.

[19] D. Lochbaum, "The Nuclear Regulatory Commission and Safety Culture: Do As I Say, Not As I Do," UCS, 2017.

[20] UCS, "Near Misses at US Nuclear Plants in 2015," 2016.

[21] UCS, https://allthingsnuclear.org/category/nuclear-power-safety-2/.

[22] No such request was denied, though a few owners didn't ask. Refurbishment cannot fix deficient old designs: nuclear engineer and operator Arnie Gundersen points out that Fukushima Daiichi Unit 1 got its license extended for another 40 years just one month before it melted down—the first unit there to explode, because its old Isolation Condenser design failed.

[23] *World Nuclear Industry Status Report 2021*, pp. 59–62, which also gives broadly consistent global data.

[24] *World Nuclear Industry Status Report 2021* includes a disquieting chapter on criminality and the global nuclear industry, citing multiple serious incidents in all reactor-exporting countries and seven of eight top operators. I have also observed deterioration in the scruples exhibited by leading nuclear industry promotion groups.

[25] Lazard, "Levelized Costs of Energy, Levelized Cost of Storage, and Levelized Cost of Hydrogen," 29 Oct 2020, v14.0.

[26] BNEF, subscriber database, 1H2021 LCOE update.

[27] USEIA, "Levelized Costs of New Generation Resources in the *Annual Energy Outlook 2021*," Feb 2021, Tables 1b, 4b, B1b, B4b.

[28] *World Nuclear Industry Status Report 2020*. In 2020, China connected 0 nuclear GW, 48 solar GW, and 72 wind GW, raising approximate annual output by respectively 0, 60, and 120 TWh/y; added nuclear output has never exceeded added wind output since at least 2010, and added less than new solar output since 2016 (except, slightly, in 2019). China has 7 of the world's top 10 wind turbine makers and 9 of the 10 top solar component makers: M. Barnard, "A Decade Of Wind, Solar, & Nuclear In China Shows Clear Scalability Winners," *CleanTechnica*, 5 Sep 2021.

[29] The photovoltaic slope since 1976 was 23%, i.e. doubled cumulative production reduces real cost 23%, but during 2007–20 it steepened to 40%: M. Victoria *et al.*, "Solar photovoltaics is ready to power a sustainable future," *Joule* **5**:1041–1056 (19 May 2021). The same paper shows that nearly all climate models assume PV prices in 2050 above the 2019 actual, and understate long-term PV sales by severalfold by assuming their prices outside the model rather than generating it inside so the observed learning curve's increasing returns to volume can actually operate continuously as it does in actual markets.

[30] Except in the first few units of the French program in the 1970s: A. Grübler, "The French Pressurised Water Reactor Programme," at pp 146–162 in A. Grübler & W. Wilson, eds., *Energy Technology Innovation: Learning from Historical Successes and Failures*, Cambridge University Press (Cambridge, UK), 2013. Contrary claims by J. Lovering *et al.* ("Historical construction costs of global nuclear power reactors," *Energy Policy* **91**:371–382 (2016)), claiming a learning curve for South Korean reactors based on unanalyzably opaque and unvalidated claims by the builder, were demolished by Koomey, Hultman, & Grübler in *Energy Policy* **102**:640–643 (2010) and by Gilbert *et al.* Lovering *et al*'s reply merited and received no response.

[31] R. Way, M. Ives, P. Mealy, & D. Farmer, "Empirically grounded technology forecasts and the energy transition," Institute for New Economic Thinking at the Oxford Martin School, U. of Oxford (UK), No. 2021-01, 7 Sep 2021. See also M. Victoria *et al.*, "Solar photovoltaics is ready to power a sustainable future," *Joule* **5**(5):1041–1056 (19 May 2021).

[32] Ref. 8.

[33] The Tennessee Valley Authority, a self-regulating Federal entity, also revived in 2007 and completed in 2016 the Watts Bar 2 reactor begun in 1973 and suspended in 1985—the only US new unit opened in 2000–21.

[34] T. Clements, "US attorney details illegal acts in construction projects, sealing the fate of the 'nuclear renaissance'," *Bulletin of the Atomic Scientists*, 31 Aug 2021; J. Sondegroth, "Legal: Westinghouse Cooperates With DOJ in V.C. Summer Probe," *Nuclear Intelligence Weekly*, 3 Sep 2021.

[35] R. Gold, "Vogtle Nuclear Plant in Georgia Faces More Construction Delays," *Wall Street Journal*, 8 Jun 2021. Some overrun estimates are higher, including 4.6× in nominal dollars at mid-2021 (*WNISR 2021*).

[36] J. Plautz, "NRC special inspection at Vogtle could lead to more delays for troubled nuclear project," *Utility Dive*, 28 June 2021.

[37] R. Smith, "Prefab Nuclear Plants Prove Just as Expensive," *Wall St. J.*, 27 July 2015.

[38] "Climate change and nuclear power," pp 228–256 in *World Nuclear Industry Status Report 2019*, esp. Fig. 51.

[39] Nuclear Energy Institute (NEI), "Nuclear by the Numbers," Aug 2020.

[40] NCAs are major repairs and betterments that don't pay back within a year, so they're capitalized not expensed. NEI lists them as the "Capital" component of operating costs, misleading some readers to suppose that they somehow reflect initial construction costs. They do not. "Generating costs" include no initial construction or financing costs, but only operating costs that need not be paid if the plant doesn't run. However, they do not include *all* operating costs: they omit insurance, other market and

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operational risk management, property taxes, spent fuel storage costs, or returns on investment—items "that would be key factors in decisions about whether to continue operating a particular station. Also not included…are costs that could be relevant for other considerations such as depreciation or interest costs." Ref. 41, p 12. No public accounting of the *full* private (or public) costs of nuclear operation appears to be available in the US or probably anywhere else.

[41] NEI, "Nuclear Costs in Context," Oct 2020.

[42] H. Sanderson & N. Hume, "Uranium prices soar as investors scoop up nuclear power fuel," *Financial Times*, 9 Sep 2021; J. Sondgeroth, "Nuclear Fuel Market: Uranium Hits 7-Year High in Sput-Led Price Rally," *Nuclear Intelligence Weekly*, 10 Sep 2021.

[43] Judge Stephen F. Williams paraphrasing Lilco counsel (Don Irwin or Taylor Reveley), *Shoreham-Wading River Central School District v. USNRC,* 931 F.2d 102, 289 U.S.App.D.C. 257, No. 90–1241, 30 Apr 1991, courtesy of Peter Bradford, who quoted the remark in ref. 53.

[44] C. Jeffery & M. Ramana, "Big money, nuclear subsidies, and systemic corruption," *Bulletin of the Atomic Scientists*, 12 Feb 2021.

[45] Including the Byron, Dresden, and LaSalle twin-unit plants rescued by $0.7 billion in new Illinois subsidies for 2022–27, approved in September 2021. NEI ("Nuclear by the Numbers", 2020, p 20) includes two units and 1.8 GW "saved" in Pennsylvania, which rejected new subsidies but joined a regional carbon cap-and-trade program.

[46] There are exceptions: e.g. Monitoring Analytics, LLC, *2021 Quarterly State of the Market Report for PJM: January Through June*, discussed in S. Carpenter, "A Report Undercuts Nuclear Firm's Claims That Its Plants Need Bailouts. But Is It For Real?," *Forbes*, 1 Feb 2021. Also useful is Carpenter's 30 Sep 2020 backgrounder "When Zero-Carbon Nuclear Asks for Money, States Find It Hard To Say No," 30 Sep 2020.

[47] A notable exception was pre-agreed by the parties, including the utility owner, which foresaw lower costs and greater grid flexibility to expand renewables: A. Lovins, "Closing Diablo Canyon Nuclear Plant Will Save Money and Carbon," *Forbes*, 22 Jun 2016. Shutdown and replacement by least-cost carbon-free resources was unanimously approved by the California PUC, affirmed by the Legislature and Governor, and summarily upheld by the State's Court of Appeal.

[48] However, a noted commentator considers the outcome good for renewables: D. Roberts, "Illinois' brilliant new climate, jobs, and justice bill," *Volts*, 22 Sep 2021.

[49] The higher estimate is from Nuclear Information and Resource Service, "Cost of Proposed Nuclear Energy Subsidies: Build Back Better Act and Bipartisan Infrastructure Bill," 16 Sep 2021, www.nirs.org. The currently proposed Build Back Better Act subsidy would be price-adjusted, with hard-to-estimate effect, but could go even to profitable-to-run reactors.

[50] P. Chafee, "Technology: Non-Power Applications in Focus," *Nuclear Intelligence Weekly*, 10 Sep 2021.

[51] D. Koplow, "Nuclear power: still not viable without subsidies," UCS, 2011.

[52] In 2005, the next 6 GW of US reactors were offered an eight-year Production Tax Credit matching windpower's but of longer duration and hence higher present value per kWh. This encouraged 4.5 GW of orders, half later canceled and the rest hoping for 2022 completion.

[53] P. Bradford, "Wasting time: Subsidies, operating reactors, and melting ice," *Bulletin of the Atomic Scientists* **73**(1):13–16 (2017). The Connecticut program is so structured: USEIA, "Five states have implemented programs to assist nuclear power plants," 7 Oct 2019.

[54] He suggests existing reactors compete for capped, limited-duration subsidies in a reverse auction open to rising fractions of other carbon-free resources; nuclear must-run status be abolished; unsubsidized resources be supported at least equally by transmission and other assets; and rate design fairly compensate distributed resources. Nuclear operators rejecting such reasonable rules should be offered no subsidy, since their intent is not to fix existing market distortions but to create more. Peter Bradford points out that New York's Ginna nuclear plant failed to clear an auction (but the Governor saved it and two more anyway, at an estimated cost around $1 billion for the first two years). Auctions also sank Maine's and Vermont's participation in the Seabrook nuclear plant and a northwestern Maine powerline from Québec. But some recently closed reactors seem to have been replaced by renewables that probably wouldn't have been bought if the reactors had stayed open, occupying market space that other resources therefore could not bid to fill.

[55] A. Lovins, "Do coal and nuclear power deserve above-market prices?," *Electricity Journal* **30**(6):22–30 (July 2017). As the largest US regional grid, PJM-ISO, wrote in 2016, "The PJM markets show no signs of inadequately compensating legacy units and forcing a premature retirement of economically viable generators.…The simple fact that a generating facility cannot earn sufficient market revenue to cover its going-forward costs does not reasonably lead to the conclusion that wholesale markets are flawed. More likely, it demonstrates that the generating facility is uneconomic."

[56] In this disaster fatal to hundreds of Texans—triggered by a 35-GW peak load to heat poorly insulated buildings electrically—renewables underperformed for 10 h (by a maximum of 1.4 GW for one hour 18 hours into the crisis, while >30 GW of gas plants were down) but overperformed through the rest of the 4.3-day outage. A 1.35-GW nuclear unit was offline for 63 hours. Another 2.42 GW twin reactor was within minutes of tripping offline due to grid underfrequency. Abruptly stopped light-water reactors can take 1–2 weeks to restart, due to Xe/Sm neutron poisoning, as happened with nine perfectly running units in the 2003 Northeast US/Canada blackout—a unique "anti-peaker" attribute making those reactors unavailable when most needed.

[57] E.g. nuclear plant outages rose 7× in the past decade: A. Ahmad, "Increase in frequency of nuclear power outages due to changing climate," *Nature Energy* **6**:755-762 (7 Jul 2021). See also *World Nuclear Industry Status Report 2021*, pp 308–337.

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[58] A. Lovins, ref. 47.

[59] Nuclear advocates claim inevitable replacement by gas or even coal power. Five State-level cases instead show actual replacement by cheaper efficiency and renewables, typically within a year or two (ref. 38, pp 249–250) and often in larger cumulative quantity. Newer examples include New York (Riverkeeper, "Energy analysis confirms: No new fossil fuels needed to replace Indian Point," 2 Sep 2021) and California (J. St. John, "California may build 11.5GW of almost all carbon-free resources to replace its last nuclear plant," 26 May 2021).

[60] A. Lovins, "The coming transformation of the electricity sector: A conversation with Amory Lovins," *Electricity Journal* **33**(7):106827 (2020).

[61] Demand response: eight forms, thoroughly installed on the 2050 ERCOT grid, could eliminate the "duck curve" (or in Texan, "dead armadillo curve"), cut nonrenewable capacity by a fourth and daily load range by half, make renewables one-third more valuable, and pay back in about five months. Efficiency: "integrative design" across all sectors can enlarge the efficiency resource by severalfold, often with increasing returns.

[62] A. Lovins, "The storage necessity myth: how to choreograph high-renewables electricity systems," 8 Jul 2014.

[63] RMI, "The economics of clean energy portfolios," 2018, and subsequent updates such as https://rmi.org/insight/clean-energy-portfolios-pipelines-and-plants/.

[64] R. Wiser *et al.*, "Wind Energy Technology Data Update: 2020 Edition," LBNL, Aug 2021, p 78.

[65] See notes 73–75 in ref. 55 above.

[66] German generation in 2010–20 fell by 37% for lignite, 64% for hard coal, and 54% for nuclear power. Similarly in Japan, despite the government's efforts to suppress windpower and slow solar growth, and despite utilities' preference to run costly legacy fossil-fuel plants rather than admit competitors onto their regional grids, efficiency and renewables more than displaced the post-Fukushima loss of nuclear output, supporting both economic growth and carbon savings that should accelerate with 2021 policy shifts.

[67] GE, https://www.ge.com/steam-power/products/synchronous-condenser.

[68] ENTSOE, https://www.entsoe.eu/Technopedia/techsheets/synchronous-condenser.

[69] A. Lovins, "Profitably decarbonizing heavy transport and industrial heat," RMI, 20 Jul 2021, and companion paper "Decarbonizing our toughest sectors—profitably," *MIT Sloan Management Review*, 4 Aug 2021. If nuclear electricity can't compete with renewable electricity, it can't make cheaper green hydrogen either. Nuclear process heat doesn't look worth the trouble *vs.* modern competitors, and industry generally isn't interested.

[70] A. Lovins, "Renewable energy's 'Footprint' Myth," *Electricity Journal* **24**(6):40–47 (2011); SolarPower Europe, *Agrisolar: Best Practices* Guidelines; https://agri-pv.org/en/; Fraunhofer ISE, "Agrivoltaics: Opportunities for Agriculture and the Energy Transition," 2020; M. Simon, "Growing Crops Under Solar Panels? Now There's a Bright Idea," Wired, 14 Oct 2021; S. Joshi *et al.*, "High resolution global spatiotemporal assessment of rooftop solar photovoltaics potential for renewable electricity generation," *Nature Commns.* **12**:5738 (2021).

[71] A. Lovins, "Clean energy and rare earths: Why not to worry," *Bulletin of the Atomic Scientists*, 23 May 2017.

[72] A. Lovins and RMI, *Reinventing Fire: Bold Business Solutions for the New Energy Era*, Chelsea Green (White River Junction VT), 2011.

[73] The remainder could be any least-cost mix of further efficiency (much understated in *Reinventing Fire*), renewables, and integration with cogeneration (transitioning from fuels to renewables) for industrial process heat. New nuclear capacity is not plausibly competitive for completing the grid's journey off carbon, and has no operational need.

[74] See https://netzeroamerica.princeton.edu/?explorer=year&state=national&table=2020&limit=200.

[75] A compact list is on pp 11–20 of A. & L.H. Lovins, "Climate: Making Sense *and* Making Money," RMI, 2007.

[76] That is, over half the United States still link electricity revenues to sales. However, revenues and sales have been decoupled for at least one electric or gas utility in 32 of the United States—a reform supported by both industries' trade groups.

[77] IEA, "Energy Efficiency Market Report 2017".

[78] IEA, "Global Energy Review: CO2 Emissions in 2020," 2 March 2021.

[79] A. Lovins *et al.*, "Corrigendum to 'Relative deployment rates of renewable and nuclear power: A cautionary tale of two metrics' [Energy Res. Soc. Sci. 38 (2018) 188–192]," *Energy Research & Social Science* **46**:381–383 (Dec 2018).

[80] A. MacFarlane, "Nuclear Energy Will Not Be the Solution to Climate Change," *Foreign Affairs*, 8 July 2021.

[81] M. Ramana & Z. Mian, "One size doesn't fit all: Social priorities and technical conflicts for small modular reactors," *Energy Research & Social Science* **2**:115–124 (2014).

[82] E. Shao, "Utilities Eye Mini Nuclear Reactors as Climate Concerns Grow," *Wall Street Journal*, 2 Aug 2021; M. Bernard, "Small Modular Nuclear Reactors Are Mostly Bad Policy," *CleanTechnica*, 3 May 2021.

[83] M. Ramana, "Small Modular and Advanced Nuclear Reactors: A Reality Check," *IEEE Access* **9**:42090 (2021). Smaller units, of course, cost less per kWh but also produce even fewer kWh at higher unit cost, so they save money only in the sense in which a smaller helping of foie gras helps you lose weight. The sales pitch for SMRs struggles to avoid criticizing big old light-water reactors, though that may not matter when they have no genuine market.

[84] E. Lyman, "'Advanced' Isn't Always Better," UCS, 18 Mar 2021.

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[85] A. Glaser, L. Hopkins, & M. Ramana, "Resource requirements and proliferation risks associated with small modular reactors," *Nuclear Technology* **184**:121–129 (2013). The medium-enriched uranium needed for most designs also lacks a supply chain or a timely path to one—M. Bandyk, "Nuclear reactors of the future have a fuel problem," *UtilityDive*, 30 Aug 2021—while making enrichment to bomb-usable levels much easier, and encouraging the dangerous spread of uranium enrichment capabilities.

[86] Small-to-medium-sized light-water reactors using highly enriched fuel were successfully applied in the US and other nuclear Navies because the unique strategic value of their long fueling cycles, avoidance of at-sea refueling (except aviation fuel for aircraft carriers), and lighter weight justified their high cost. Those Naval values don't translate to stationary civilian reactors that must compete with declining-cost on-grid and distributed electricity resources.

[87] M. Ramana, "Eyes Wide Shut: Problems with the Utah Associated Municipal Power Systems Proposal to Construct NuScale Small Modular Nuclear Reactors," 2 Sep 2021. By Sep 2021, before anything was built, the UAMPS proposal for a cluster of Federal-sited first-of-a-kind 60-MW (now 77-MW) pressurized-water reactors to supply six states' small municipal utilities has seen doubled cost, halved module count, and (depending on which plan one starts with) 4–15 years' delay: A. Cho, "Several U.S. utilities back out of deal to build novel nuclear power plant," *Science*, 4 Nov 2020; T. Gardner & N. Groom, "Some U.S. cities turn against first planned small-scale nuclear plant," Reuters, 2 Sep 2020. By autumn 2021, customer commitments more than halved to about one-ninth the output of the originally proposed project, as concern rose about opaque but apparently rising costs; unreassuringly, industry experts' cost estimates for a similar configuration (Scenario 3) exhibited a ~5–10× range. (Other estimates compiled in 2019 also show wide ranges.) Meanwhile, renewables' market prices to the same customers and even from UAMPS itself are far lower and falling. The majority shareholder and proposed builder, Fluor, has lost 73% of its value (peaking at 90%) in three years. The developer expects 462 MW of subscriptions by the end of 2021 but has 103 MW, subject to at least two off-ramps; it estimates cost at $5.3b, less $1.4b of DOE grant and potential further loans or guarantees, but has just $0.2b in equity offers, apparently all from potential vendors. Similar concerns with conventional reactors sank the WPPSS nuclear project in 1983, causing the largest-ever US municipal bond default and harming similar customers—even one of the same customers.

[88] See ref. 87.

[89] This does not necessarily depend on legislation, because the market forces at work are so potent: after President Obama's Clean Plan was scuttled by his successor, its actual adoption accelerated and its goals were met early.

[90] Slides 183–184 of the 2020 Princeton *Net Zero America* deck. The study assumed a need for ~1 TW of thermal generation in 2050 for grid stability; the reasoning isn't yet clear but probably reflects assumptions of costly renewables and storage, plus model constraints that exclude most of the ten kinds of grid flexibility resources described in refs. 60 and 62.

[91] See E. Lyman remarks at release of Ramana analysis, ref. 87.

[92] This Italian proverb, often attributed to Garibaldi, is apparently due to Mariotti.