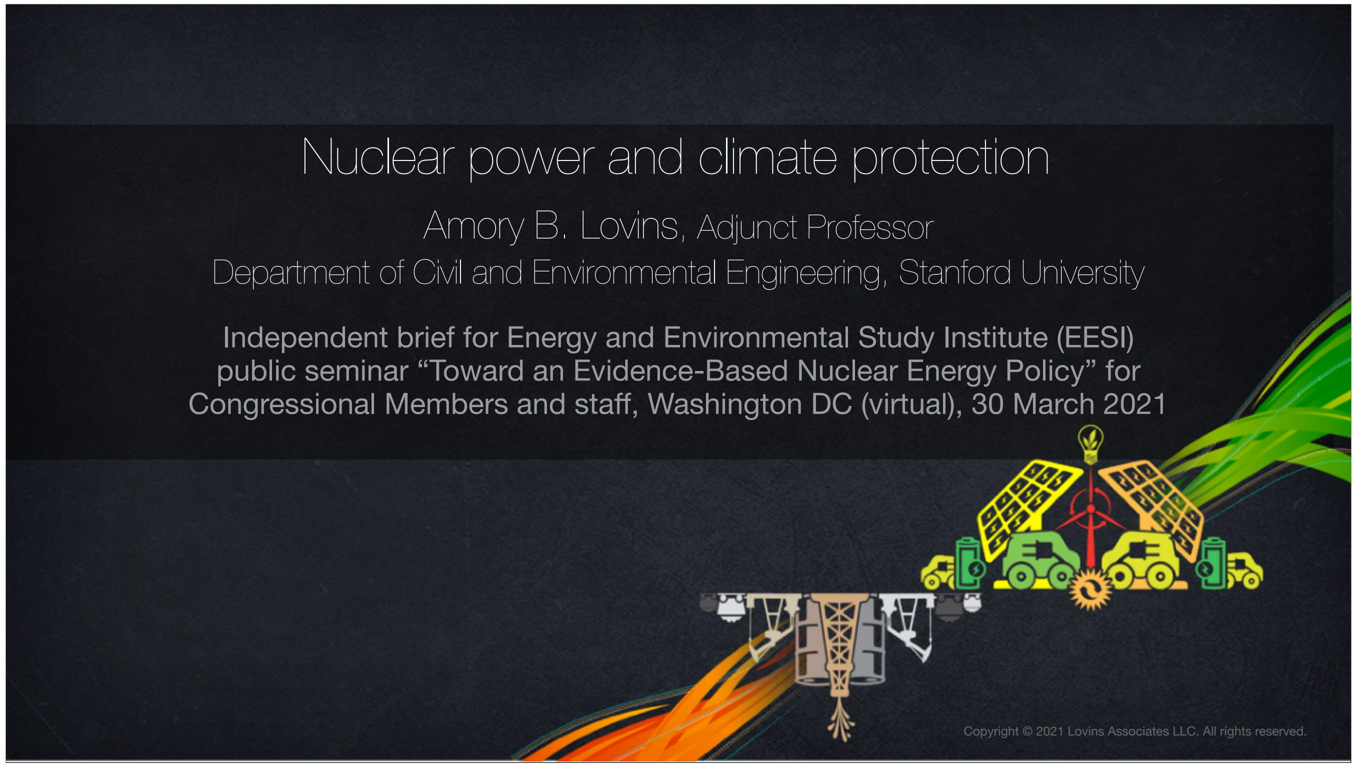

Nuclear power and climate protection

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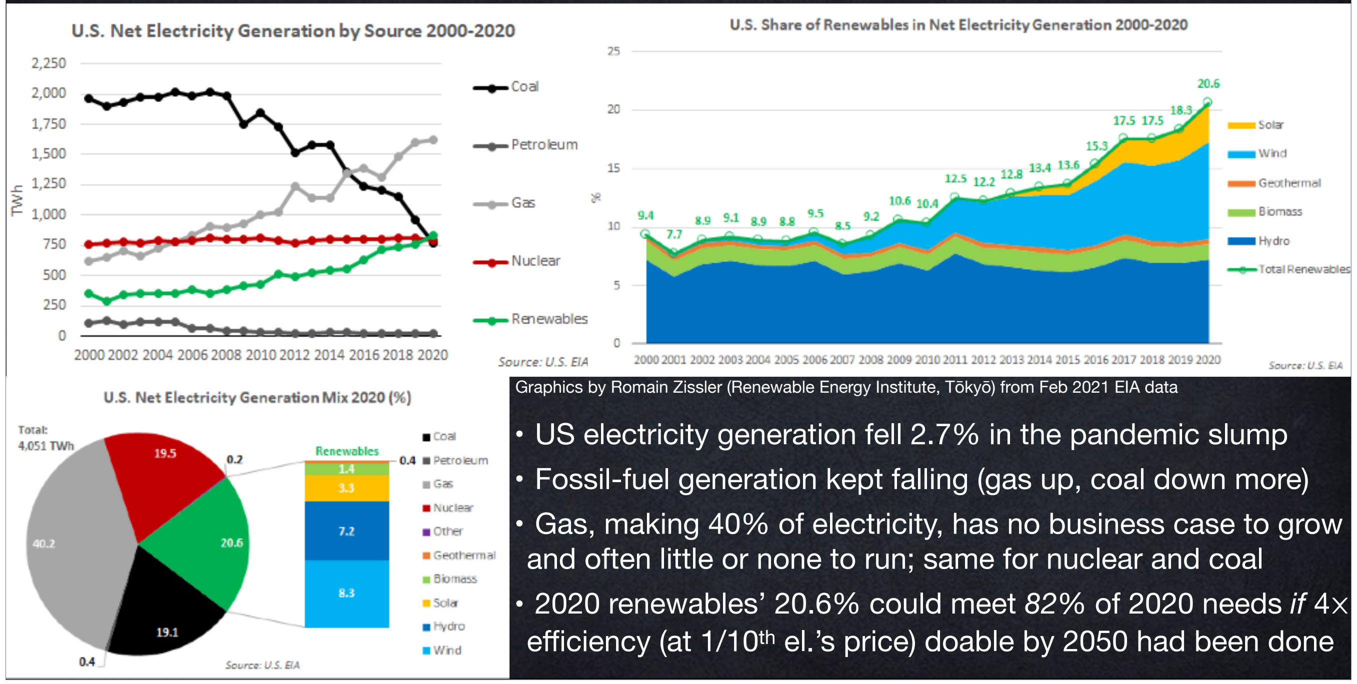
Independent brief for Energy and Environmental Study Institute (EESI)
public seminar “Toward an Evidence-Based Nuclear Energy Policy” for
Congressional Members and staff, Washington DC (virtual), 30 March 2021

[target ~20m, rehearsal 21] [* = click for build, animation, or transition] [bracketed small type won’t be spoken]

Good day. I thank EESI for sponsoring this event and each of you for kindly joining. Today I’m honored to offer my personal views on nuclear power’s status, prospects, and role in climate protection. A widespread and bipartisan view holds that continued and expanded use of nuclear power can help reduce climate change. I’ll show that’s incorrect because of nuclear power’s most important but least discussed attribute—its economics.

My analysis doesn’t count any past, present, or future emissions from nuclear activities, nor will I address relative risks. If nuclear power has neither a business case nor a climate benefit, it falls at the first hurdle, and any other issues are relevant only to managing risks already created. *

In 2020, US renewable generation overtook both coal and nuclear output



U.S. Net Electricity Generation by Source 2000-2020

Source: U.S. EIA

U.S. Share of Renewables in Net Electricity Generation 2000-2020

Source: U.S. EIA

U.S. Net Electricity Generation Mix 2020 (%)

Source: U.S. EIA

Graphics by Romain Zissler (Renewable Energy Institute, Tōkyō) from Feb 2021 EIA data

- US electricity generation fell 2.7% in the pandemic slump
- Fossil-fuel generation kept falling (gas up, coal down more)
- Gas, making 40% of electricity, has no business case to grow and often little or none to run; same for nuclear and coal
- 2020 renewables' 20.6% could meet *82%* of 2020 needs *if* 4× efficiency (at 1/10th el.'s price) doable by 2050 had been done

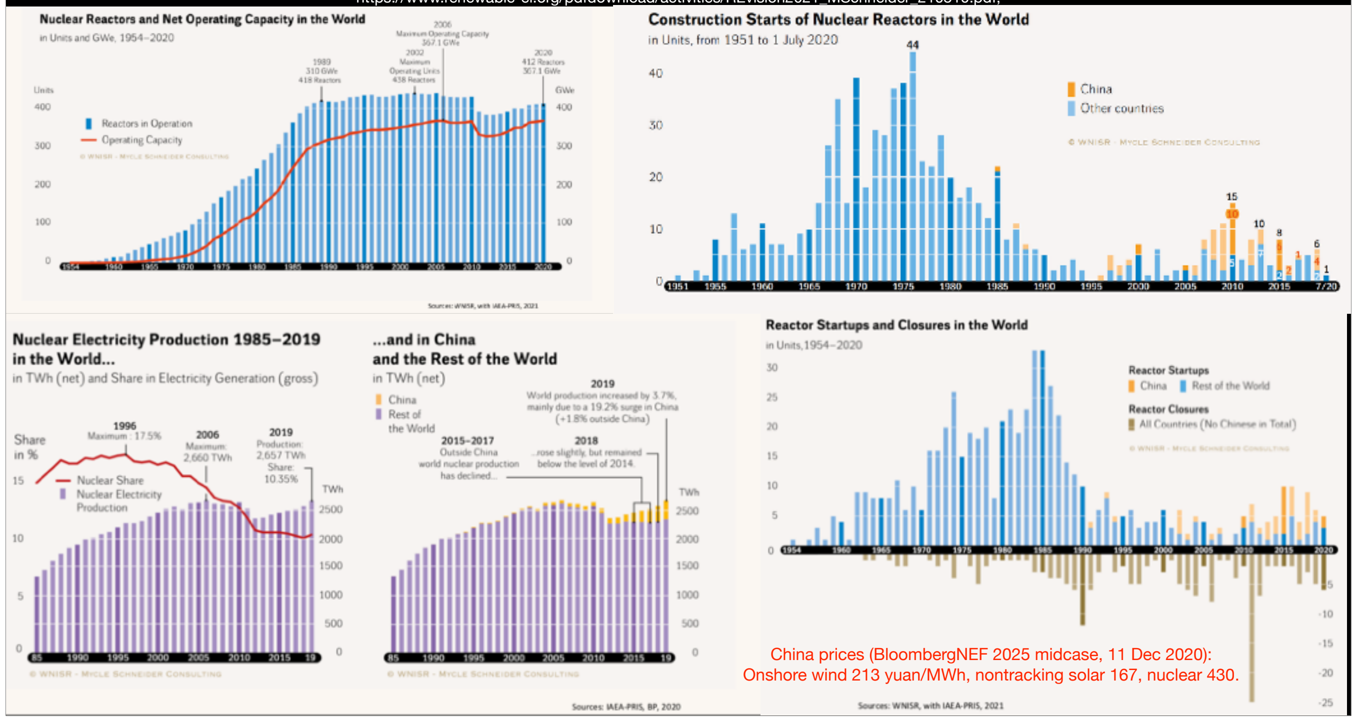
In 2020, US renewables, mostly wind and solar, outproduced coal power. Renewables also surpassed nuclear power's current and historic-peak output—in the upper-left graph, green crossing red and black. The other two graphs detail the shares.

Efficient use of electricity could do the same or better if fully competed or compared with supply. It's far easier to decarbonize the electricity system if we also use electricity in a way that saves money. RMI's 2011 business synthesis *Reinventing Fire* showed how the US could use electricity 4× more productively by 2050, with 2010 technologies costing a tenth today's price of electricity. Such productive use could quadruple the share of a given amount of renewables. Yet most states^ still reward utilities for selling you more electricity and penalize them for cutting your bill. *

[^A map of decoupling status as of February 2020 is at https://www.nrdc.org/resources/gas-and-electric-decoupling.]

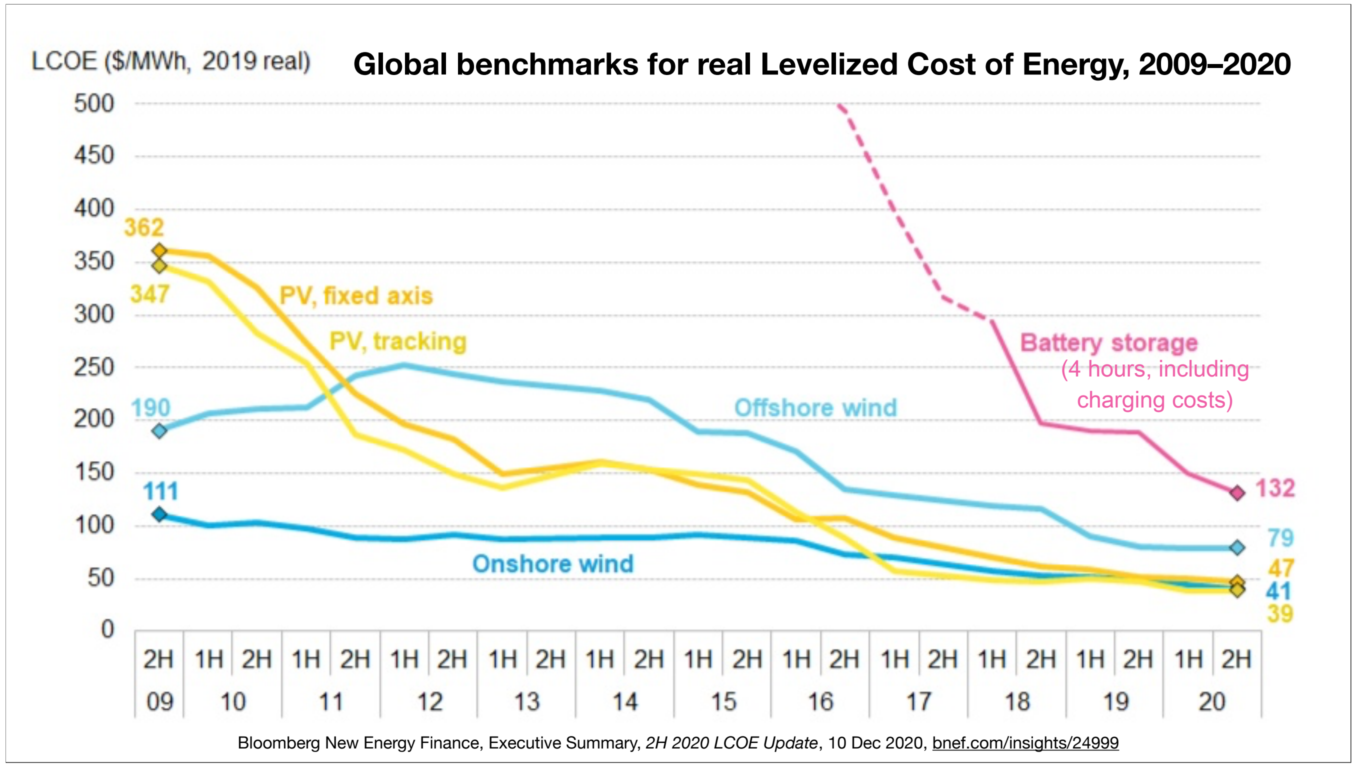
WNISR 2020 summaries of world nuclear power status

https://www.renewable-ei.org/pdfdownload/activities/REvision2021_MSchneider_210310.pdf,



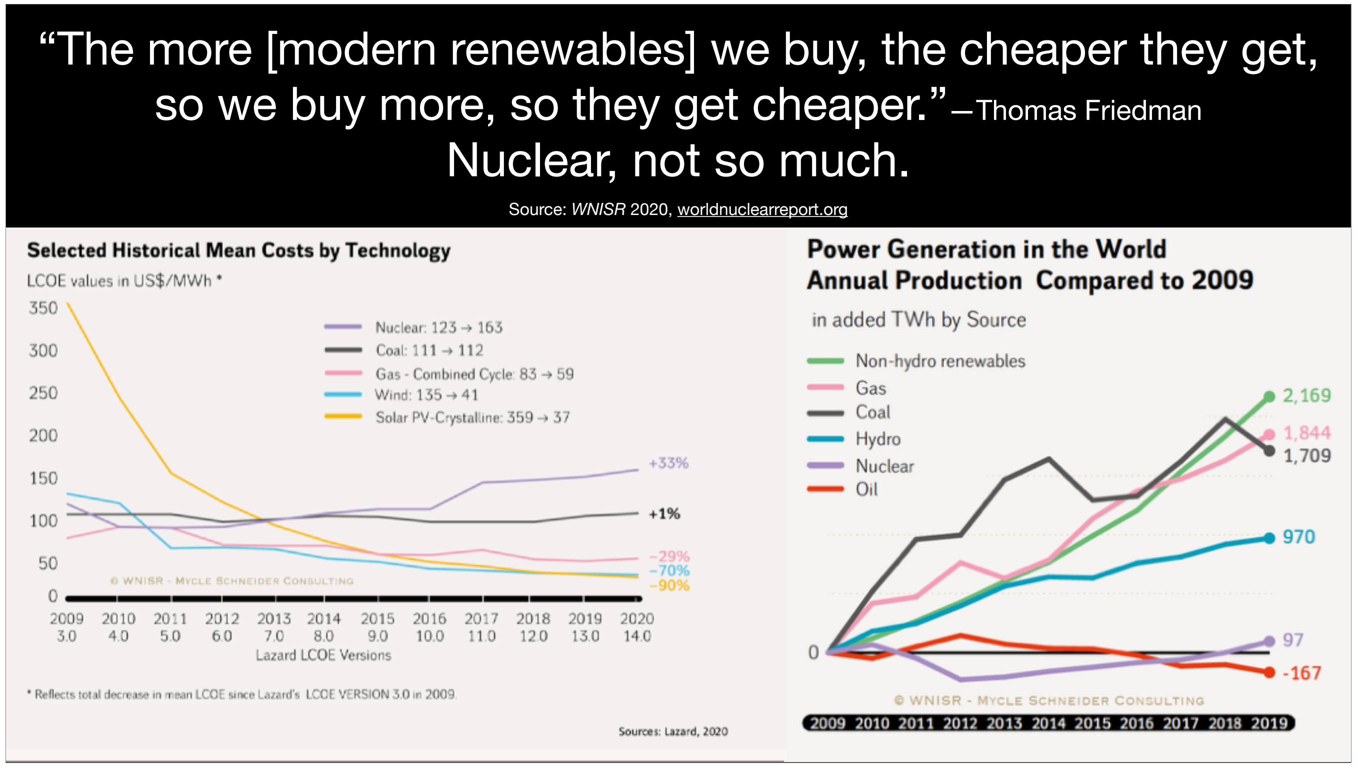
China prices (BloombergNEF 2025 midcase, 11 Dec 2020):
Onshore wind 213 yuan/MWh, nontracking solar 167, nuclear 430.

The US story of dwindling nuclear relevance echoes the world's. * The global reactor fleet just regained its 2002 peak capacity. Its output probably remains below the 2006 peak. * The nuclear share of global electricity peaked in 1996 at 18%, then shrank to 10%. * Most new reactors are in China (shown in yellow), but they're missing their targets and losing official favor because modern renewables are bigger, faster, and far cheaper, * as shown in red, so China doubled its renewable additions last year, adding more wind capacity than the world added the year before. As China's nuclear ardor fades, so do other countries' additions. Total additions are being overtaken by retirements (the brown bars below the axis), so the fleet struggles to sustain itself. Last year, China added 2 nuclear GW and 120 solar and wind GW. In both 2019 and 2020, world nuclear capacity gained at best 1 GW net of retirements, depending on how you count the timing, while renewable capacity grew by around 200 GW. Wind and solar power *have lately added more capacity about every two days than nuclear power adds in a year.* (Their average capacity factors differ only by severalfold.) *



Bloomberg New Energy Finance, Executive Summary, *2H 2020 LCOE Update*, 10 Dec 2020, bnef.com/insights/24999

The International Energy Agency says 90% of the world's net capacity additions last year [2020] were renewable, due mainly to their plummeting unsubsidized costs, graphed here by Bloomberg New Energy Finance based on ~13,000 actual projects worldwide. *



"The more [modern renewables] we buy, the cheaper they get, so we buy more, so they get cheaper."—Thomas Friedman
Nuclear, not so much.

Source: *WNISR* 2020, worldnuclearreport.org

Selected Historical Mean Costs by Technology

LCOE values in US$/MWh *

* Reflects total decrease in mean LCOE since Lazard's LCOE VERSION 3.0 in 2009.

Sources: Lazard, 2020

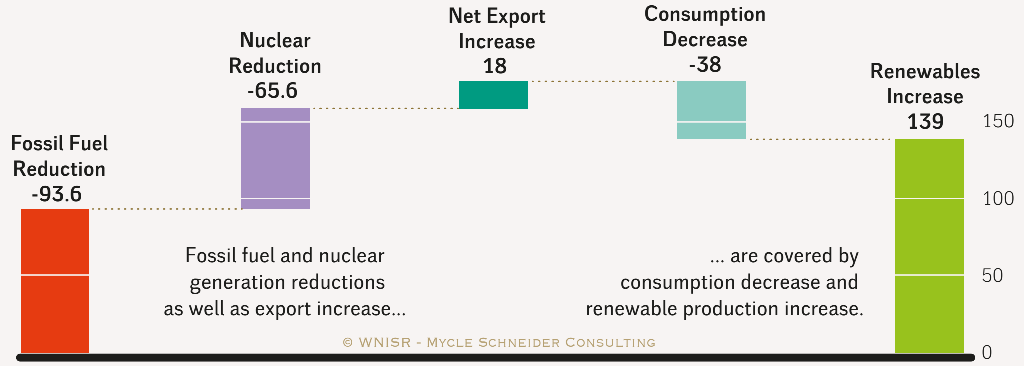
Power Generation in the World
Annual Production Compared to 2009

in added TWh by Source

* Lazard finds the same for the US, with windpower (aqua) and solar (gold) widening their lead over gas (pink), while new-nuclear costs (purple) kept rising.
* So on the right, world nuclear output (purple) stagnated and coal power (black) headed down, while nonhydro renewables (green) outgrew even gas generation and added over 2 trillion kWh/y in a decade. IEA says those renewables plus hydropower (blue) produced 29% of world electricity last year [2020] and will rise to 47–72% by 2040 while nuclear sticks around 10%. This pattern repeats nearly worldwide, particularly in China and India. Let me highlight two other examples often misrepresented. *

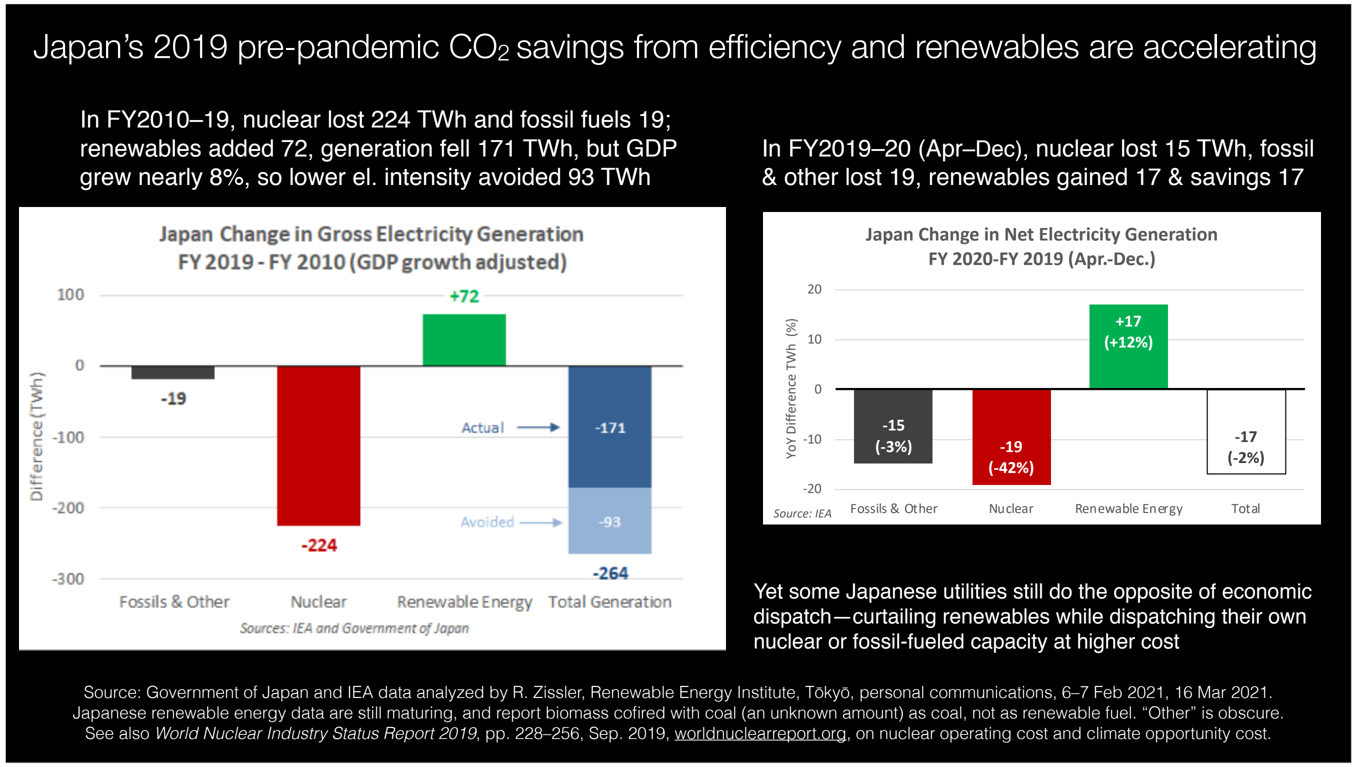
Germany’s nuclear phaseout came with huge coal and CO_2 reductions; Germany in 2021 will start closing coal plants opened as recently as 2015

Main Evolution of the German Power System Between 2010 and 2019
in TWh



with 2010–19 GDP +17% and national greenhouse gas emissions –53%
2010–20 update: –130.9 –76.3 +1.1 –60.7 +149.5

Germany’s nuclear phaseout (purple), agreed two decades ago and set to conclude next year [2022], accompanied major fossil-fuel *reductions* (red) and increased power exports (teal). These three shifts were offset by electrical savings (aqua) plus renewables (green), * while the economy grew and total greenhouse gas emissions fell 53%. * In 2020, windpower alone outgenerated coal plus lignite. Germany’s power sector met its 2020 climate goal a year early (*before* the pandemic) with five percentage points to spare. *



Japan's 2019 pre-pandemic CO_2 savings from efficiency and renewables are accelerating

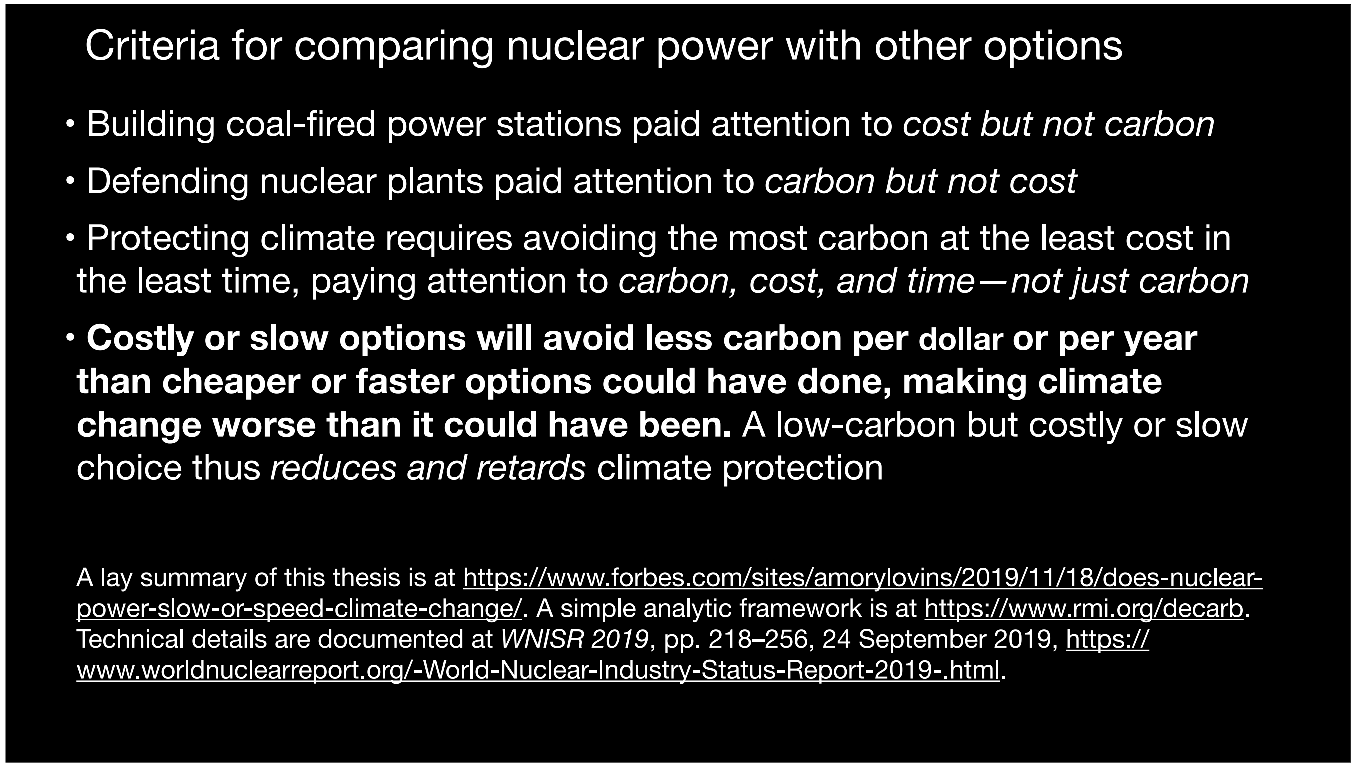
In FY2010–19, nuclear lost 224 TWh and fossil fuels 19; renewables added 72, generation fell 171 TWh, but GDP grew nearly 8%, so lower el. intensity avoided 93 TWh

In FY2019–20 (Apr–Dec), nuclear lost 15 TWh, fossil & other lost 19, renewables gained 17 & savings 17

Yet some Japanese utilities still do the opposite of economic dispatch—curtailing renewables while dispatching their own nuclear or fossil-fueled capacity at higher cost

Source: Government of Japan and IEA data analyzed by R. Zissler, Renewable Energy Institute, Tōkyō, personal communications, 6–7 Feb 2021, 16 Mar 2021. Japanese renewable energy data are still maturing, and report biomass cofired with coal (an unknown amount) as coal, not as renewable fuel. "Other" is obscure. See also *World Nuclear Industry Status Report 2019*, pp. 228–256, Sep. 2019, worldnuclearreport.org, on nuclear operating cost and climate opportunity cost.

Japan's utilities replaced lost nuclear output (red) largely with fossil fuels (black) while national policies suppressed renewables (especially windpower) and shielded legacy assets from competition. More than a third of Japan's nuclear capacity has closed, and most of the rest remains in limbo as utilities' credibility and financial strength ebb. Yet in nine years after the Fukushima disaster, renewables (green) plus savings (blue) displaced 150% of Japan's lost nuclear output if adjusted for GDP growth, 108% if not adjusted. Thus Japan's old nuclear market vanished before more reactors could restart—if restart had a business case. * In the first three-fourths of the current Fiscal Year, nuclear *and* fossil fuels fell even faster as renewables grew 23% of Japan's generation—the official target for ten years later [22–24% in FY2030]. *

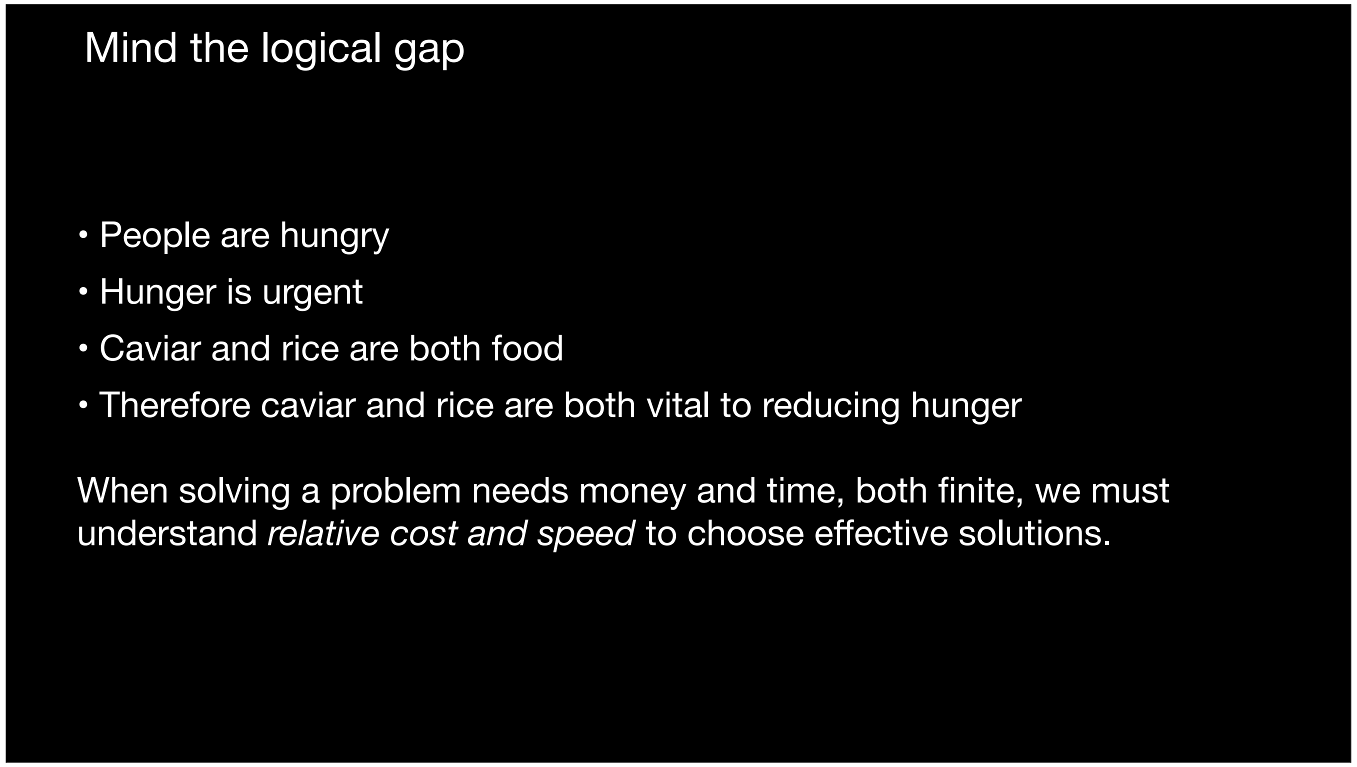


Criteria for comparing nuclear power with other options

- Building coal-fired power stations paid attention to *cost but not carbon*
- Defending nuclear plants paid attention to *carbon but not cost*
- Protecting climate requires avoiding the most carbon at the least cost in the least time, paying attention to *carbon, cost, and time—not just carbon*
- **Costly or slow options will avoid less carbon per dollar or per year than cheaper or faster options could have done, making climate change worse than it could have been.** A low-carbon but costly or slow choice thus *reduces and retards* climate protection

A lay summary of this thesis is at https://www.forbes.com/sites/amorylovins/2019/11/18/does-nuclear-power-slow-or-speed-climate-change/. A simple analytic framework is at https://www.rmi.org/decarb. Technical details are documented at *WNISR 2019*, pp. 218–256, 24 September 2019, https://www.worldnuclearreport.org/-World-Nuclear-Industry-Status-Report-2019-.html.

So given these trends, how should we compare different ways to power America's economy from now on? * We built coal-fired power plants by counting cost but not carbon. * Nuclear power is promoted by counting carbon but not cost. * But to protect the climate, we must save the most carbon at the least cost and in the least time, counting *all three* variables—carbon *and* cost *and* time. * Costly or slow options save less carbon per dollar or per year than cheaper or faster options. Thus even a low- or no-carbon option that is too costly or too slow will *reduce and retard* achievable climate protection.
*** I've posted a simple way to compare climate-effectiveness in a *Forbes* article submitted for the record, documented by detailed analysis that I'll now sketch. *



Mind the logical gap

- People are hungry
- Hunger is urgent
- Caviar and rice are both food
- Therefore caviar and rice are both vital to reducing hunger

When solving a problem needs money and time, both finite, we must understand *relative cost and speed* to choose effective solutions.

Many analysts ignore common-sense comparisons of cost and speed, leading to results akin to arguing that since * people are hungry, * hunger is urgent, and * caviar and rice are both food, therefore * both caviar and rice are vital to reducing hunger. Since in reality money and time are both limited, ** our priorities in feeding people, or in providing energy services, must be informed by *relative cost and speed*. Lower cost saves more carbon per dollar. Faster deployment saves more carbon per year. We need both these outcomes. *

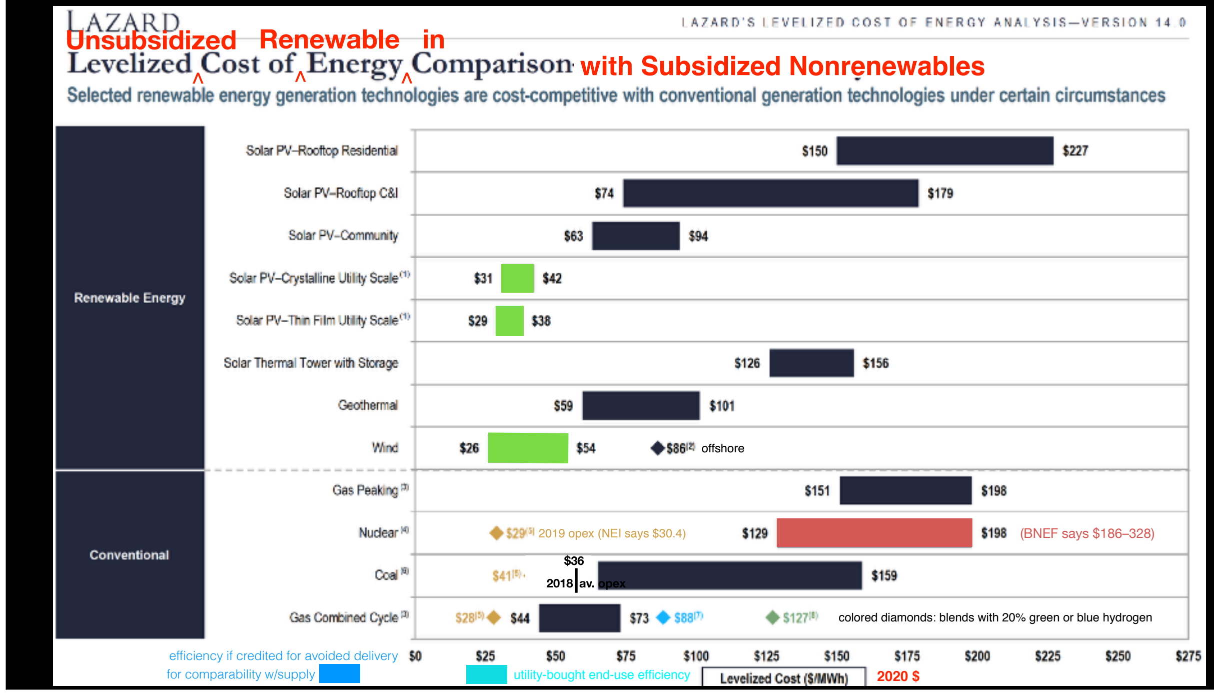
Climate opportunity cost

- You can buy only one thing with the same money at the same time.
- Nuclear and fossil-fueled generation compete with renewables and efficiency to meet the same finite demand for electrical services, so each kWh met by one resource is lost to its competitors.
- Since new, and often even existing, nuclear plants can no longer win in the marketplace, their owners often seek and get from politicians major new subsidies or preferences—misdescribed as “not forcing nuclear out of the market,” “not taking nuclear off the table,” or “keeping the nuclear option open.” Success displaces renewables and efficiency.
- Every kWh of nuclear output forced into walled-garden markets in which renewables (and efficiency) are forbidden to compete slows the growth, hence the cost reductions, of those zero-carbon competitors.

* The economic principle of “opportunity cost” means you can’t spend the same money on two different things at the same time. Each purchase foregoes others. * Buying nuclear power displaces buying efficiency and renewables, and vice versa, so nuclear owners strive to beat coal and natural gas while their allies often disparage or suppress renewables. * Yet despite subsidies that rival construction cost, most US nuclear plants (including all 16 in PJM) are uneconomic just to run. Many are closing, so their powerful owners seek and often get multi-billion-dollar bailouts from malleable (or in some states apparently corrupt) state legislators. Congress is often asked to federalize these new subsidies and add new ones. But * replacing market choices with political logrolling distorts prices, crowds out competitors, slows innovation, reduces transparency, rewards undue influence, introduces bias, picks winners, invites corruption, and even threatens to destroy the competitive regional electricity markets where renewables and efficiency win. These violations of the conservative economic principles I favor seem high prices to bear for small or negative benefits. Yet many political leaders of both parties think climate’s urgency demands *every* option, including preserving nuclear power at any cost. So what *is* that cost? *

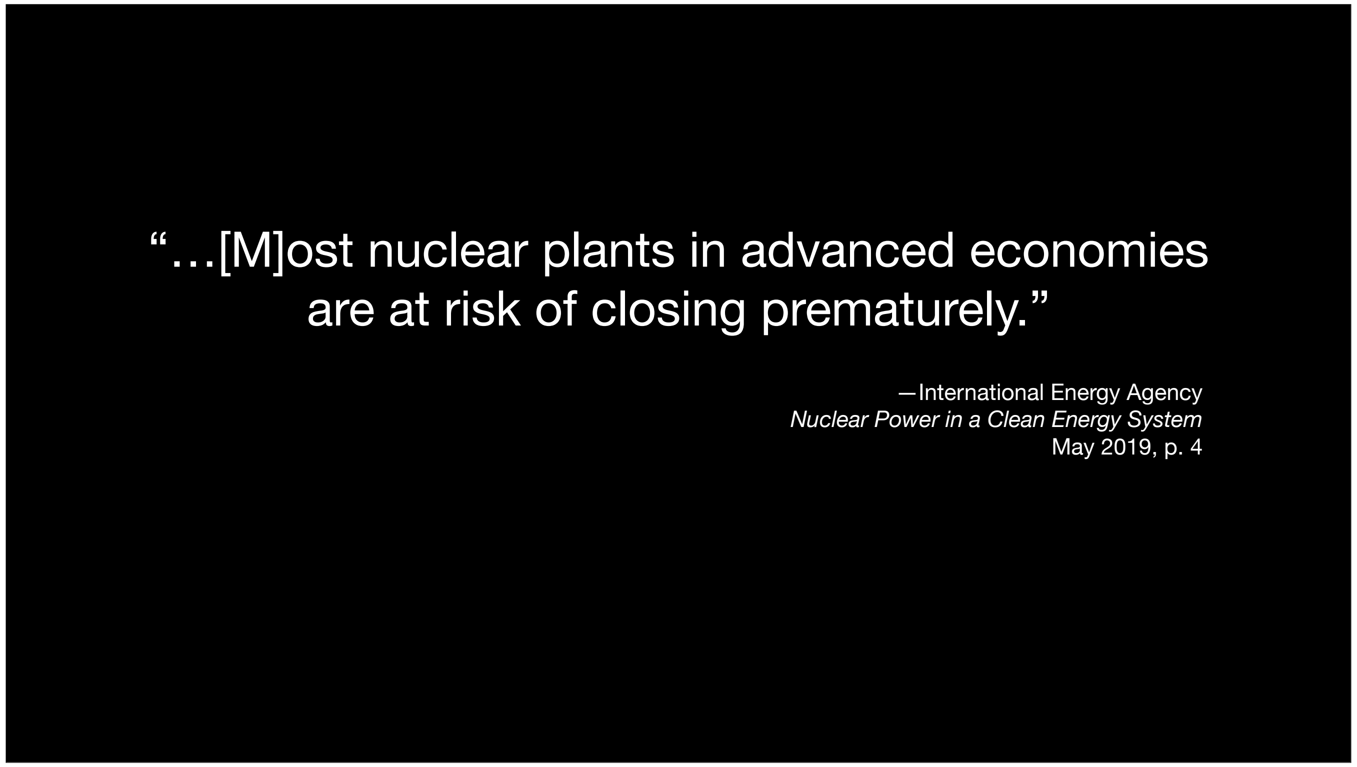
[^See https://www.ucsusa.org/resources/nuclear-power-still-not-viable-without-subsidies.]

Lazard's October 2020 view of new US electricity resources' costs



Last October [2020], the eminent 173-year-old [as of ≤16 Mar 2021] financial house Lazard published its latest annual snapshot of electricity sources' US market prices. I've edited the slide's title in red because Lazard removed renewables' temporary tax credits but tacitly retained nonrenewables' larger permanent subsidies—especially to nuclear power^. /
I've colored Lazard's solar and windpower costs in green, and * added in aqua US utilities' typical costs of customers' electric efficiency, * credited in blue for avoiding remote sources' delivery costs and losses, because end-use efficiency is already delivered. * So new nuclear plants in red are grossly uncompetitive with efficiency and renewables; that's why the private capital market won't finance more reactors, and why they're not bid into open auctions. The coal row's vertical black line, showing coal plants' 2018 *operating* cost, can't beat the green renewables either, so coal power is dwindling, followed by new gas power. /
The other leading data sources show similar renewable costs, though * Bloomberg's nuclear costs are much higher than Lazard's. Nuclear costs are also rising, renewable costs falling. And historical experience doesn't warm investor sentiment: of the 259 power reactors ordered in the US, just 96 remain, and by mid-2017 only 28 units or 11% of original orders got built, remained competitive in their regional markets, and hadn't suffered at least one outage lasting a year or more. In the oil business that's called an 89% dry-hole risk. *

[^See https://www.ucsusa.org/resources/nuclear-power-still-not-viable-without-subsidies.]

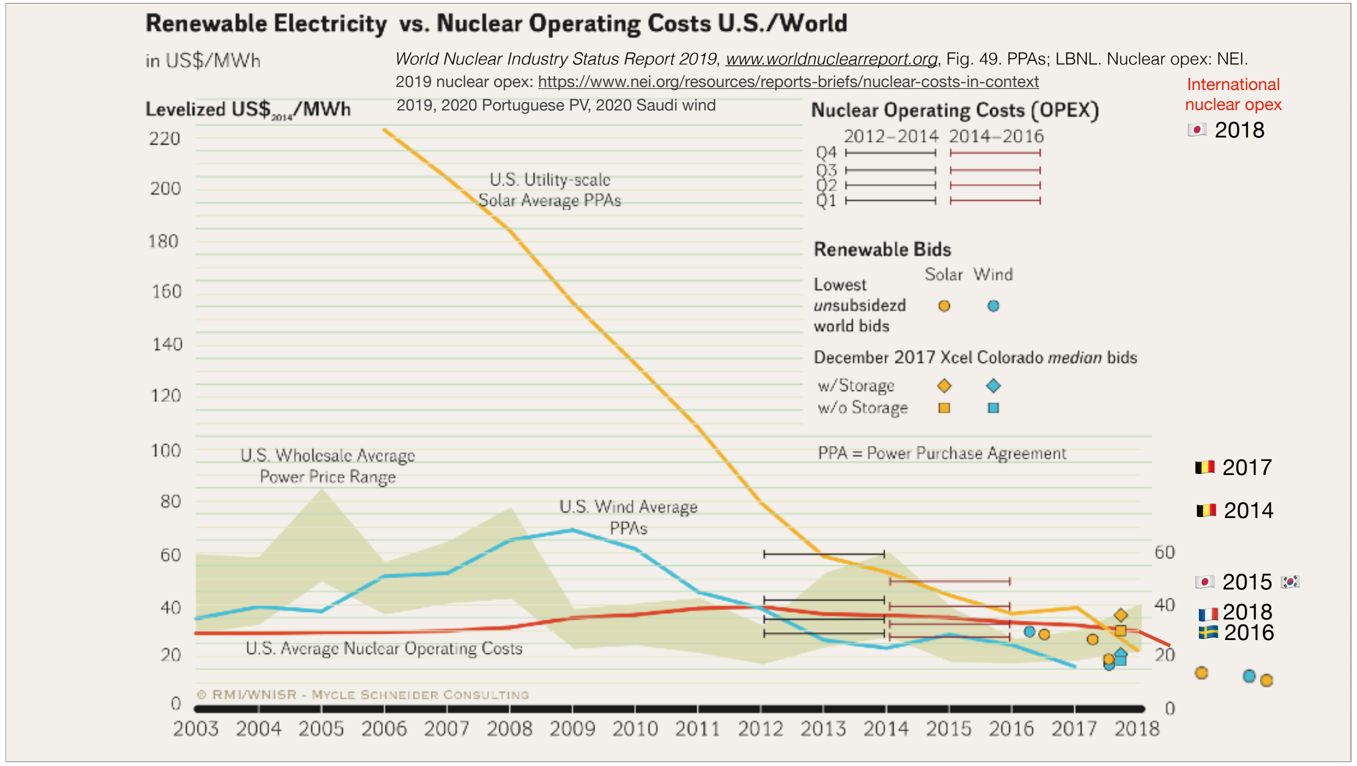


> "…[M]ost nuclear plants in advanced economies are at risk of closing prematurely."
>
> —International Energy Agency
> *Nuclear Power in a Clean Energy System*
> May 2019, p. 4

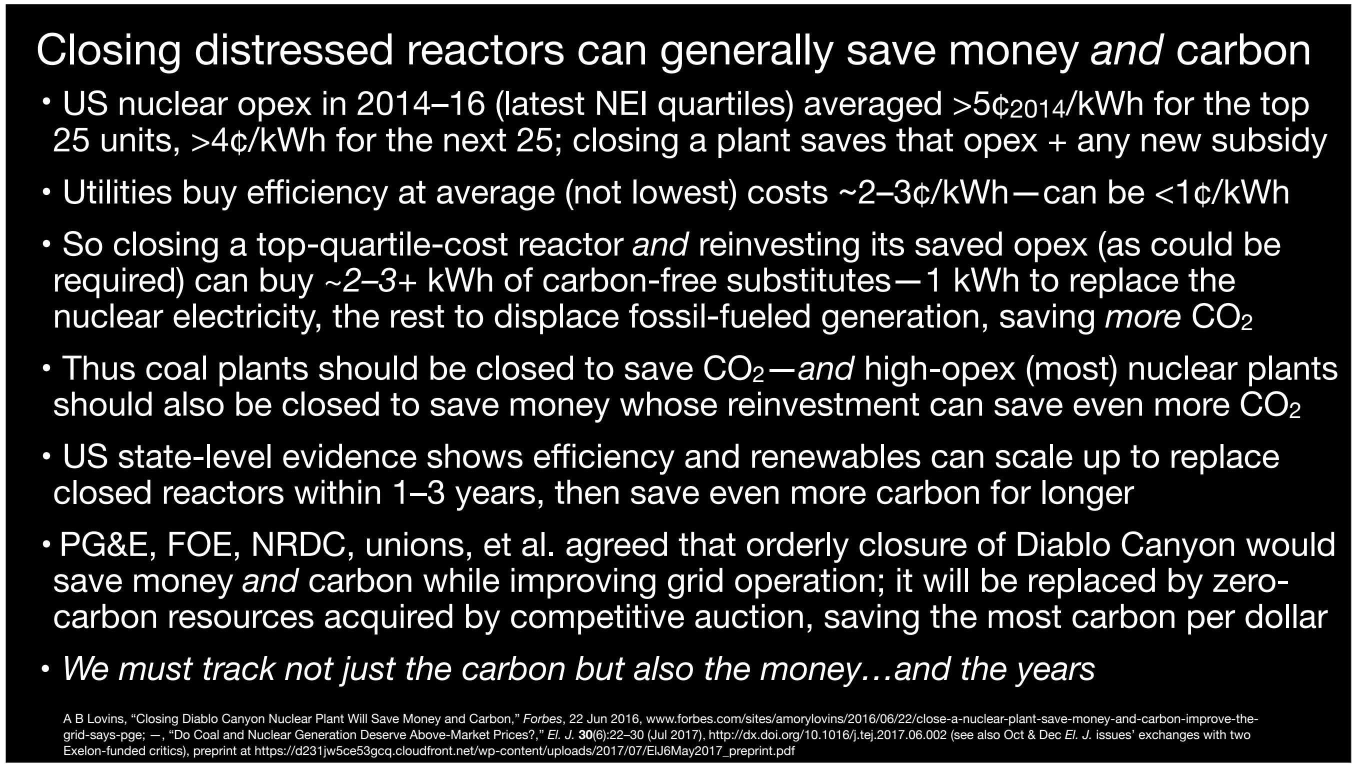
A bigger question today is whether the world's 400-odd *existing* reactors should stay open. Many cost more to run than their output can earn—or than it would cost to provide the same services by building and operating new renewables or efficiency improvements.

[A May 2019 IEA report claimed that sustaining the existing nuclear fleet is vital for climate protection, is cost-effective, and merits government support. Those claims seem dubious and inconsistent. IEA assumed expensive renewables—as costly to finance as nuclear, for which capital markets charge a risk premium. At actual renewable prices, IEA's life-extended reactors (even if their owners would run them without new subsidies) would abate less carbon per dollar than modern competitors.

The logic is puzzling too. If existing reactors could compete with actual renewable prices, they wouldn't be at risk of closure and wouldn't need further subsidies; but if they cannot compete now, they'd compete even less after life-extension investments, so why would they deserve further subsidies? IEA's claim that allowing uneconomic reactors to exit the market and lower-cost renewables to replace them would need a third of a trillion dollars' more investment is neither obvious nor transparent.] So let's examine operating reactors' competitiveness by going step by step through an eyechart about *actual* nuclear operating costs—the costs that need not be paid if the plant does not operate. *



The light-green zone shows the range of US wholesale electricity prices for 2003–18 in constant 2014 dollars. The aqua line for windpower, and the gold line for utility-scale photovoltaics, show the *average* prices set in long-term private-market Power Purchase Agreements or PPAs. You can see that average new wind and solar power sell at or below the lowest wholesale prices from nonrenewables, and trend downward, so windpower in 2018 averaged under $20/MWh and was as low as $11/MWh or 1.1¢/kWh. Wind and solar power's temporary national subsidies, now phasing out, don't change the basic outcome: the lower-right corner of the graph shows as round dots the comparable *un*subsidized prices of wind and solar in Chile, Mexico, Morocco, Portugal, and Saudi Arabia. The squares are bids for Colorado solar and wind; the diamonds add electricity storage with only modest cost. / Now let's compare the red line—US nuclear plants' average *operating* cost excluding all original construction cost. You can see that average nuclear operations cost more than new modern renewables, with or without their temporary subsidies. During the latest reported periods, the gray and brown horizontal bars show that those average nuclear operating costs by quartile fell as the least competitive reactors were closed—*but renewable prices fell even faster*. Nuclear operating costs will be hard to cut much further in reactors averaging over 40 years old, but renewable prices promise strong further declines for decades to come. / International nuclear operating costs * tend to be even higher. Troubled fleets like France's and Japan's must spread their operating costs over less output, and often must buy costly post-Fukushima upgrades from which NRC has largely exempted US operators. *

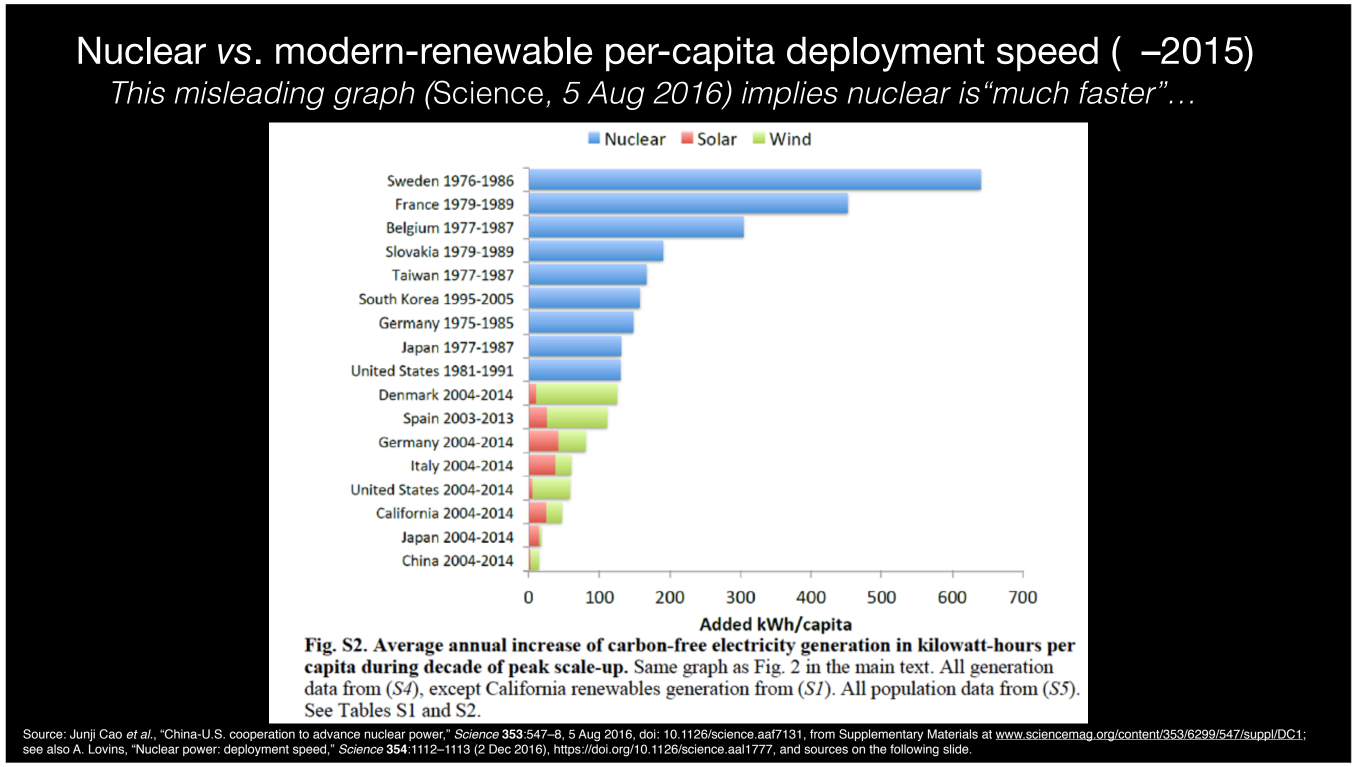


Closing distressed reactors can generally save money *and* carbon

- US nuclear opex in 2014–16 (latest NEI quartiles) averaged >5¢$_{2014}$/kWh for the top 25 units, >4¢/kWh for the next 25; closing a plant saves that opex + any new subsidy
- Utilities buy efficiency at average (not lowest) costs ~2–3¢/kWh—can be <1¢/kWh
- So closing a top-quartile-cost reactor *and* reinvesting its saved opex (as could be required) can buy *~2–3+* kWh of carbon-free substitutes—1 kWh to replace the nuclear electricity, the rest to displace fossil-fueled generation, saving *more* CO_2
- Thus coal plants should be closed to save CO_2—*and* high-opex (most) nuclear plants should also be closed to save money whose reinvestment can save even more CO_2
- US state-level evidence shows efficiency and renewables can scale up to replace closed reactors within 1–3 years, then save even more carbon for longer
- PG&E, FOE, NRDC, unions, et al. agreed that orderly closure of Diablo Canyon would save money *and* carbon while improving grid operation; it will be replaced by zero-carbon resources acquired by competitive auction, saving the most carbon per dollar
- *We must track not just the carbon but also the money…and the years*

A B Lovins, "Closing Diablo Canyon Nuclear Plant Will Save Money and Carbon," *Forbes*, 22 Jun 2016, www.forbes.com/sites/amorylovins/2016/06/22/close-a-nuclear-plant-save-money-and-carbon-improve-the-grid-says-pge; —, "Do Coal and Nuclear Generation Deserve Above-Market Prices?," *El. J.* **30**(6):22–30 (Jul 2017), http://dx.doi.org/10.1016/j.tej.2017.06.002 (see also Oct & Dec *El. J.* issues' exchanges with two Exelon-funded critics), preprint at https://d231jw5ce53gcq.cloudfront.net/wp-content/uploads/2017/07/ElJ6May2017_preprint.pdf

These operating-cost data reveal an important climate opportunity. * The latest reported operating cost (opex) by quartile for 2014–16 exceeds 4¢/kWh for the costlier-to-run half of US reactors, or 5¢ for the costliest quartile, making them money-losers. Yet * electric efficiency costs utilities only *2–3¢/kWh* on average—less if they shop carefully. Therefore * closing a top-quartile-cost nuclear plant *and buying efficiency instead would save several times as much carbon as continuing to run the nuclear plant*. Owners could volunteer, regulators require, or markets elicit that substitution, and renewables should compete too. * Thus, while we close coal plants to save carbon *directly*, we should *also* close distressed *nuclear* plants and reinvest their large saved operating cost in cheaper options to save carbon *in*directly. * Replacing a closed nuclear plant with efficiency or renewables empirically takes only 1–3 years. If owners don't give such advance notice—a common tactic to extort subsidies by making closure more disruptive—more natural gas might temporarily be burned for typically a year or two, but then will be more than offset by cheaper carbon-free replacements. * California's biggest utility will therefore replace its well-running Diablo Canyon reactors with least-cost carbon-free resources to save money and carbon and help the grid work better. * To get these outcomes, we must track *not just carbon but also money and time.* Investing judiciously, not indiscriminately, saves the most carbon per dollar. /
What about per *year*? *



Nuclear *vs*. modern-renewable per-capita deployment speed (–2015)

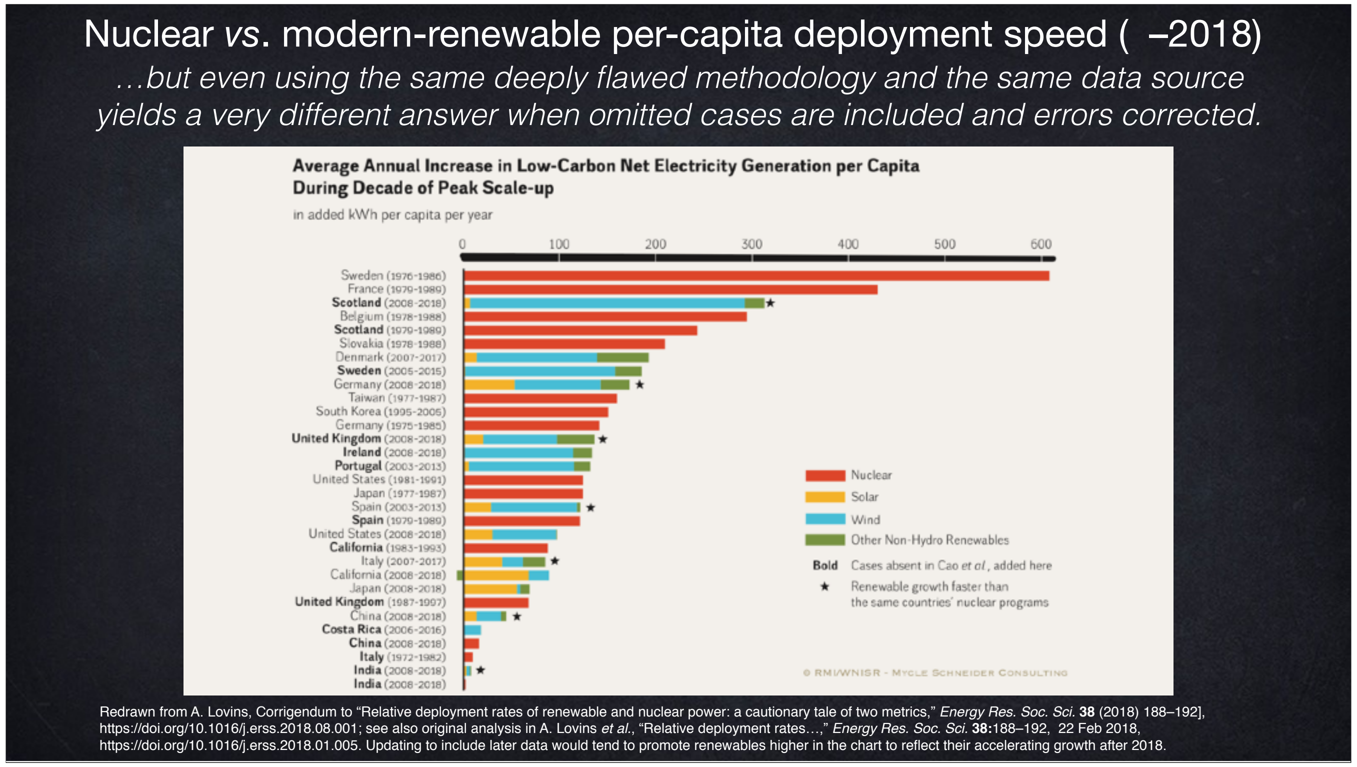
*This misleading graph (*Science*, 5 Aug 2016) implies nuclear is“much faster”…*

Fig. S2. Average annual increase of carbon-free electricity generation in kilowatt-hours per capita during decade of peak scale-up. Same graph as Fig. 2 in the main text. All generation data from (*S4*), except California renewables generation from (*S1*). All population data from (*S5*). See Tables S1 and S2.

Source: Junji Cao *et al.*, “China-U.S. cooperation to advance nuclear power,” *Science* **353**:547–8, 5 Aug 2016, doi: 10.1126/science.aaf7131, from Supplementary Materials at www.sciencemag.org/content/353/6299/547/suppl/DC1; see also A. Lovins, “Nuclear power: deployment speed,” *Science* **354**:1112–1113 (2 Dec 2016), https://doi.org/10.1126/science.aal1777, and sources on the following slide.

Claims that nuclear generation grows “much faster” than renewables, making nuclear important for climate, use cherry-picked old data and a strange methodology based on not absolute but *per-capita* growth. This makes the climate benefit depend on the population of the country where it occurs, so Sweden or Slovakia look far more important than China. Ironically, all nine old nuclear programs shown in blue are now troubled, and the fastest, in Sweden, is now adding windpower even faster.

This widely reprinted graph comes from a 2016 paper in the journal *Science*. But once I’d corrected that paper’s seven analytic flaws and distortions in two peer-reviewed journals…



Nuclear *vs*. modern-renewable per-capita deployment speed (–2018)

…but even using the same deeply flawed methodology and the same data source yields a very different answer when omitted cases are included and errors corrected.

Average Annual Increase in Low-Carbon Net Electricity Generation per Capita During Decade of Peak Scale-up

in added kWh per capita per year

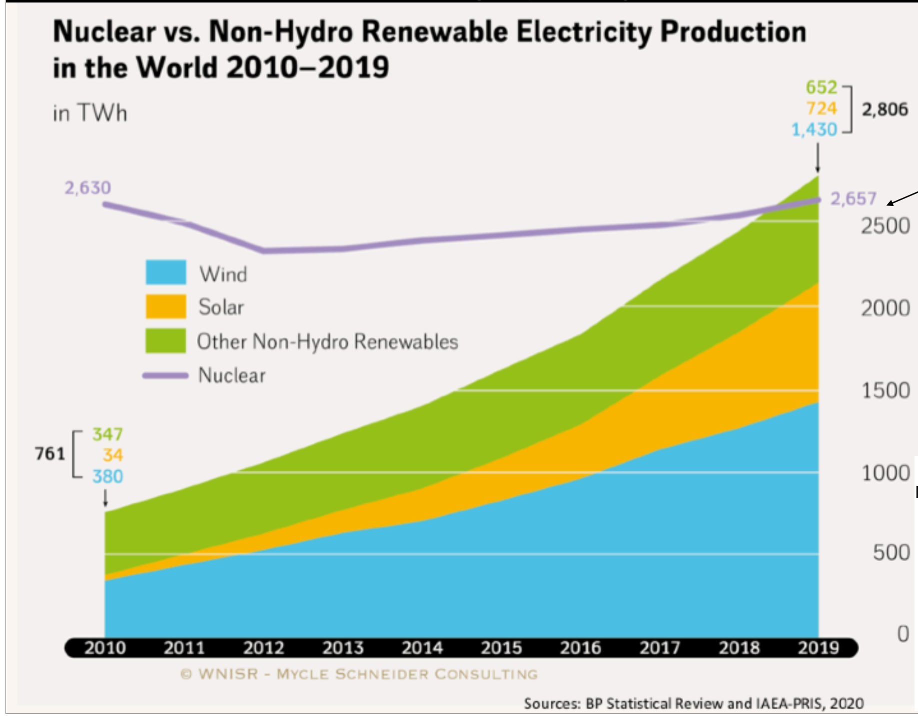
Redrawn from A. Lovins, Corrigendum to "Relative deployment rates of renewable and nuclear power: a cautionary tale of two metrics," *Energy Res. Soc. Sci.* **38** (2018) 188–192], https://doi.org/10.1016/j.erss.2018.08.001; see also original analysis in A. Lovins *et al.*, "Relative deployment rates…," *Energy Res. Soc. Sci.* **38:**188–192, 22 Feb 2018, https://doi.org/10.1016/j.erss.2018.01.005. Updating to include later data would tend to promote renewables higher in the chart to reflect their accelerating growth after 2018.

…that finding reversed. Even using the same flawed methodology, and the same data source updated four years, nuclear output (red) and nonhydro renewable output (other colors) can actually grow at similar speeds. If, unlike the *Science* authors, we compare nuclear in ten countries with renewable growth *in the same ten countries*, renewables grew faster in seven of those ten. But the rapid nuclear growth occurred decades ago under conditions that no longer exist, while comparable or faster renewable growth is here, now, and accelerating. /

Nuclear power's slowness incurs a big carbon penalty—even bigger because it also needs three times more lead time for institutional preparations, so renewables can start saving carbon many years sooner. Being later, slower, *and* costlier than its competitors makes nuclear power triply unhelpful for climate. /

[The previous graph's *Science* paper was discredited by three devastating scientific-journal critiques, but was the sole basis cited by two World Nuclear Association press releases during IAEA's 2019 annual conference: [24 Sept 2019] "Combatting climate change faster with new nuclear build" and [25 Sep 2019] "Nuclear energy is the fast track to decarbonization."]/ *

Nuclear output is roughly stagnant while renewable output soars



Nuclear vs. Non-Hydro Renewable Electricity Production in the World 2010–2019

© WNISR - Mycle Schneider Consulting

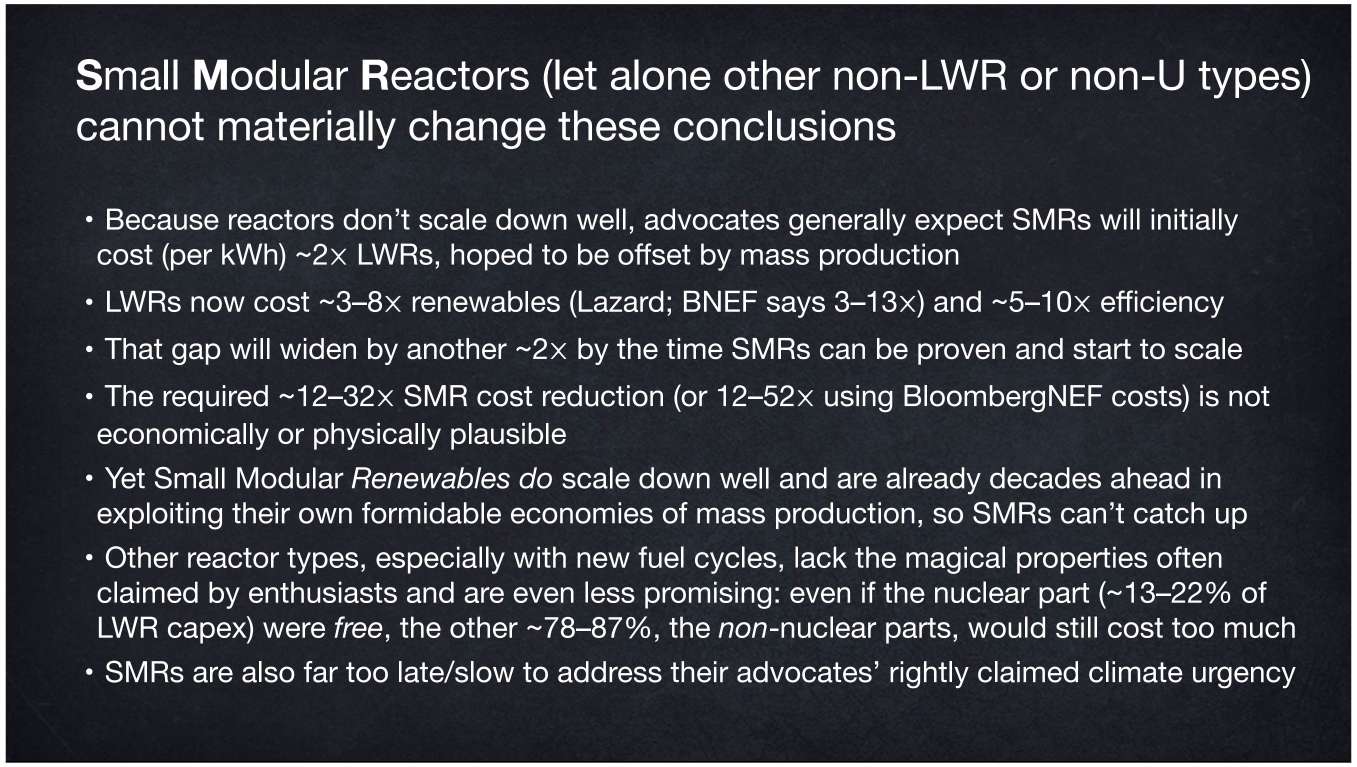
Sources: BP Statistical Review and IAEA-PRIS, 2020

https://www.renewable-ei.org/pdfdownload/activities/REvision2021_MSchneider_210310.pdf

BNEF's latest (26 Mar 2021) estimate of 2020 output shows wind and solar totaling 2,589 TWh, showing their further acceleration in 2020.

Methodological note from M. Schneider and A. Lovins: Nuclear generation, from IAEA-PRIS, is net of in-plant use. (BP calculates 2019 gross nuclear generation, 2796 TWh, by adding an unsourced ~5.5% to net generation.) Renewable outputs are net, but are immaterially (<<1%) different from gross generation for wind and solar, so nearly all data sources report only net generation. For thermal generation from geothermal, biomass, and wastes, all shown in the green wedge, the difference is bigger, but generally comparable to BP's nuclear estimate of in-plant use, making the net/gross distinction unimportant overall for this comparison.

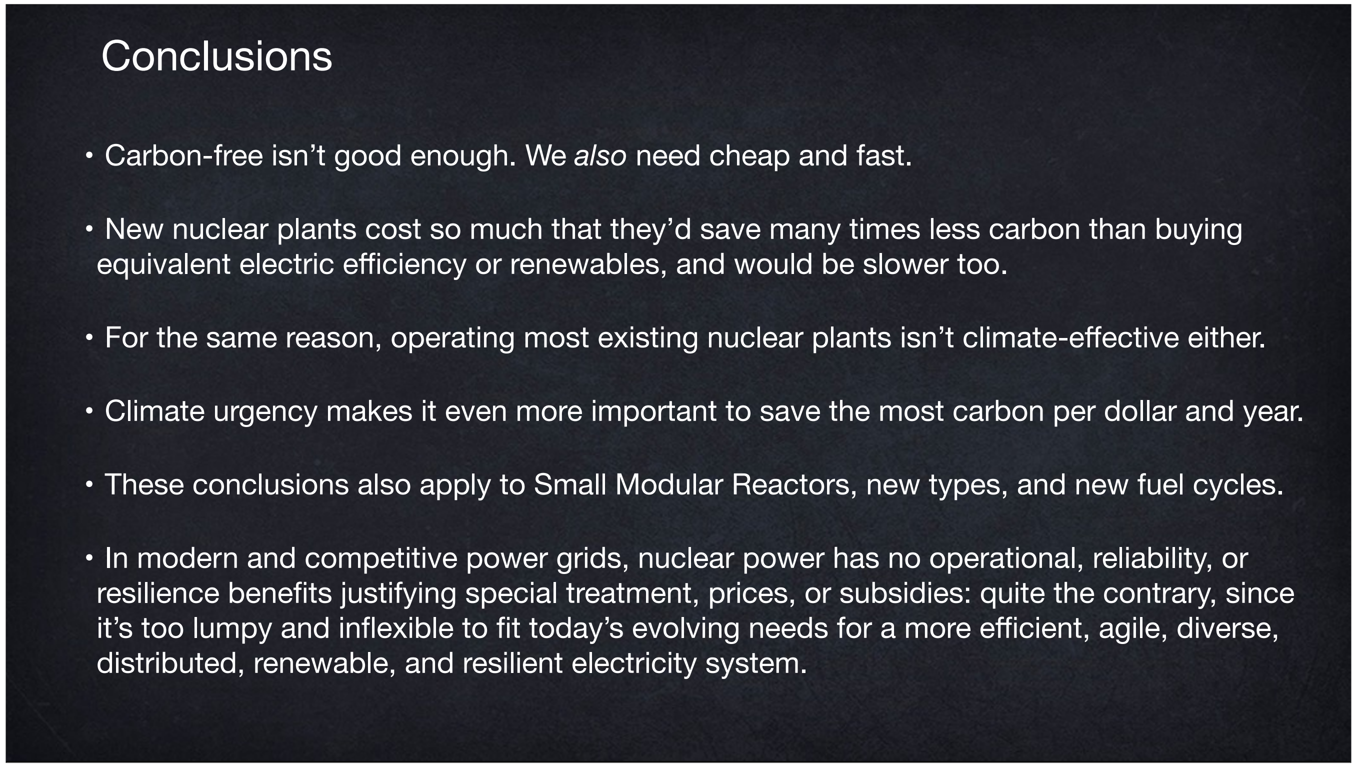
More simply, just comparing different technologies' *total* growth in *global* electricity production reveals that modern renewables nearly quadrupled their output in a decade, pulled ahead of stagnant nuclear output (in purple) two years ago, and are growing faster than nuclear power ever did. In the past decade, says IEA, they were 6× more effective than coal-to-gas fuel-switching and 5× more effective than nuclear growth in reducing power-sector carbon emissions.*



Small **M**odular **R**eactors (let alone other non-LWR or non-U types) cannot materially change these conclusions

- Because reactors don’t scale down well, advocates generally expect SMRs will initially cost (per kWh) ~2× LWRs, hoped to be offset by mass production
- LWRs now cost ~3–8× renewables (Lazard; BNEF says 3–13×) and ~5–10× efficiency
- That gap will widen by another ~2× by the time SMRs can be proven and start to scale
- The required ~12–32× SMR cost reduction (or 12–52× using BloombergNEF costs) is not economically or physically plausible
- Yet Small Modular *Renewables do* scale down well and are already decades ahead in exploiting their own formidable economies of mass production, so SMRs can’t catch up
- Other reactor types, especially with new fuel cycles, lack the magical properties often claimed by enthusiasts and are even less promising: even if the nuclear part (~13–22% of LWR capex) were *free*, the other ~78–87%, the *non*-nuclear parts, would still cost too much
- SMRs are also far too late/slow to address their advocates’ rightly claimed climate urgency

Enthusiasts claim that substituting various kinds of Small Modular Reactors will achieve competitive costs. But that takes magical thinking, and today’s reactors are the wrong competitor. * Early SMRs would produce electricity at about twice the cost of today’s light-water reactors, which * Lazard found are ~3–8× costlier than modern renewables (or ~5–10× costlier than onsite efficiency). But by the time SMRs (if successful) could begin mass-production, their carbon-free rivals are * set to get another 2× cheaper, based on observed learning curves (which nuclear power has never demonstrated). * Just do the math: 2 × (3 to 8) × 2 means mass production must make SMRs ~12–32× cheaper—or 12–52× using Bloomberg’s cost figures. Neither range is plausible. * SMRs can’t catch up, because Small Modular *Renewables*, which *do* scale down well, have decades’ head start in exploiting their own formidable economies of scaling and learning. * Novel reactor designs or fuel cycles offer no escape, because even if the minor nuclear part of the prohibitive capital cost of today’s reactors were *free*, the *non*-nuclear remainder would still be ~2–6× too costly. * Nor could SMRs be developed and scaled *fast* enough to meet the urgent decarbonization need that their advocates rightly claim. SMRs would only divert investment, attention, and time from off-the-shelf, popular, benign competing technologies that have already proven rapidly scaleable and that win a half-trillion dollars of private investment each year. Substituting costly, slow SMRs would thus make climate change worse. *



Conclusions

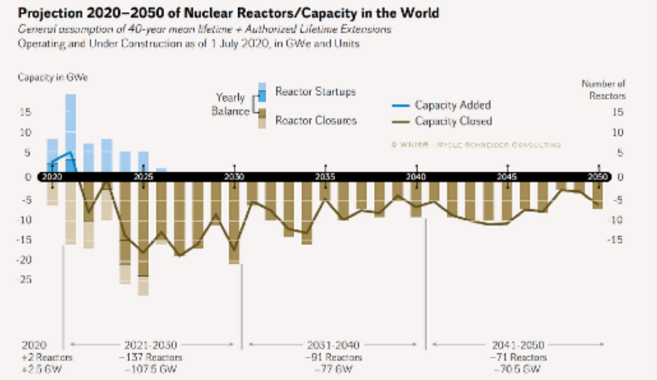
- Carbon-free isn't good enough. We *also* need cheap and fast.
- New nuclear plants cost so much that they'd save many times less carbon than buying equivalent electric efficiency or renewables, and would be slower too.
- For the same reason, operating most existing nuclear plants isn't climate-effective either.
- Climate urgency makes it even more important to save the most carbon per dollar and year.
- These conclusions also apply to Small Modular Reactors, new types, and new fuel cycles.
- In modern and competitive power grids, nuclear power has no operational, reliability, or resilience benefits justifying special treatment, prices, or subsidies: quite the contrary, since it's too lumpy and inflexible to fit today's evolving needs for a more efficient, agile, diverse, distributed, renewable, and resilient electricity system.

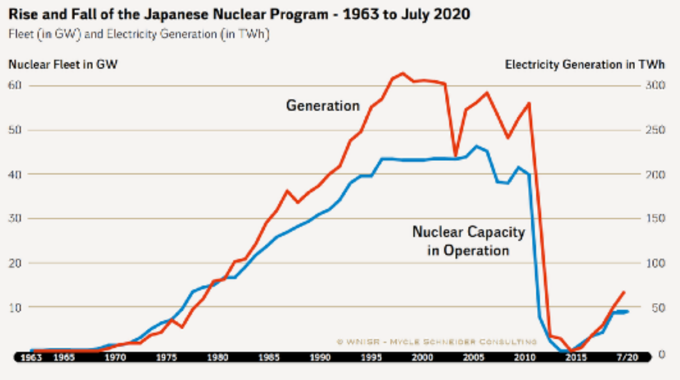
If you haven't heard this economic thesis before, now you have. Published in peer-reviewed journals since the '80s, it's been sometimes attacked but never rebutted—perhaps because the industry doesn't want to draw it to your attention. I do respect-fully suggest you consider it, and invite you to start counting carbon *and* money *and* time. So to summarize: * Carbon-free is necessary but not sufficient; we *also* need cheap and fast. * Actual market prices and deployment speeds mean that new nuclear plants would save manyfold less carbon per dollar and per year than cheaper, faster efficiency or modern renewables. * Operating money-losing existing nuclear plants wastes money that could buy cheaper options saving even more carbon. * The more urgent you think climate change is, the less sense it makes to keep running those uneconomic reactors. * No proposed changes in size, technology, or fuel cycle would change these conclusions: they're intrinsic to *all* nuclear technologies. / A climate non-solution isn't worth paying for, let alone extra. * Nuclear power also offers no benefits for grid reliability or resilience justifying special treatment. I've provided for the record some extra evidence on why traditional "baseload" generation by big thermal plants is no longer necessary, desirable, or economic, and why we don't need a storage miracle. The ultrareliable former East German grid (50Hertz) is already more than half powered by wind and solar, over 60% by renewables, without adding bulk storage, and plans to be 100% renewable by 2032. Some European countries with modest or no hydropower are already half to three-fourths or more renewably powered, without adding bulk storage, and with reliability far better than America's. We can explore these issues further in discussion. Thank you for your kind attention. *

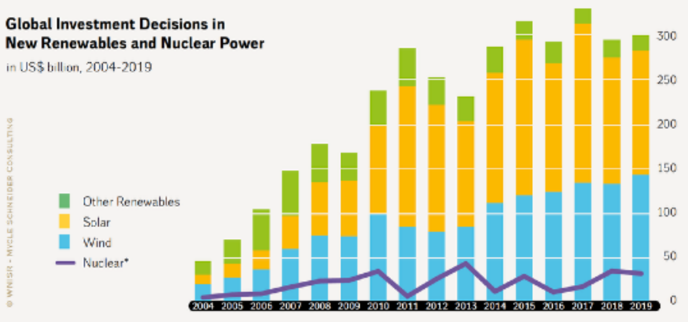
[redacted]

Appendix: 34 supplementary slides with Presenter’s Notes

WNISR 2020 summaries of world nuclear power prospects, investment, and Japan (worldnuclearreport.org)

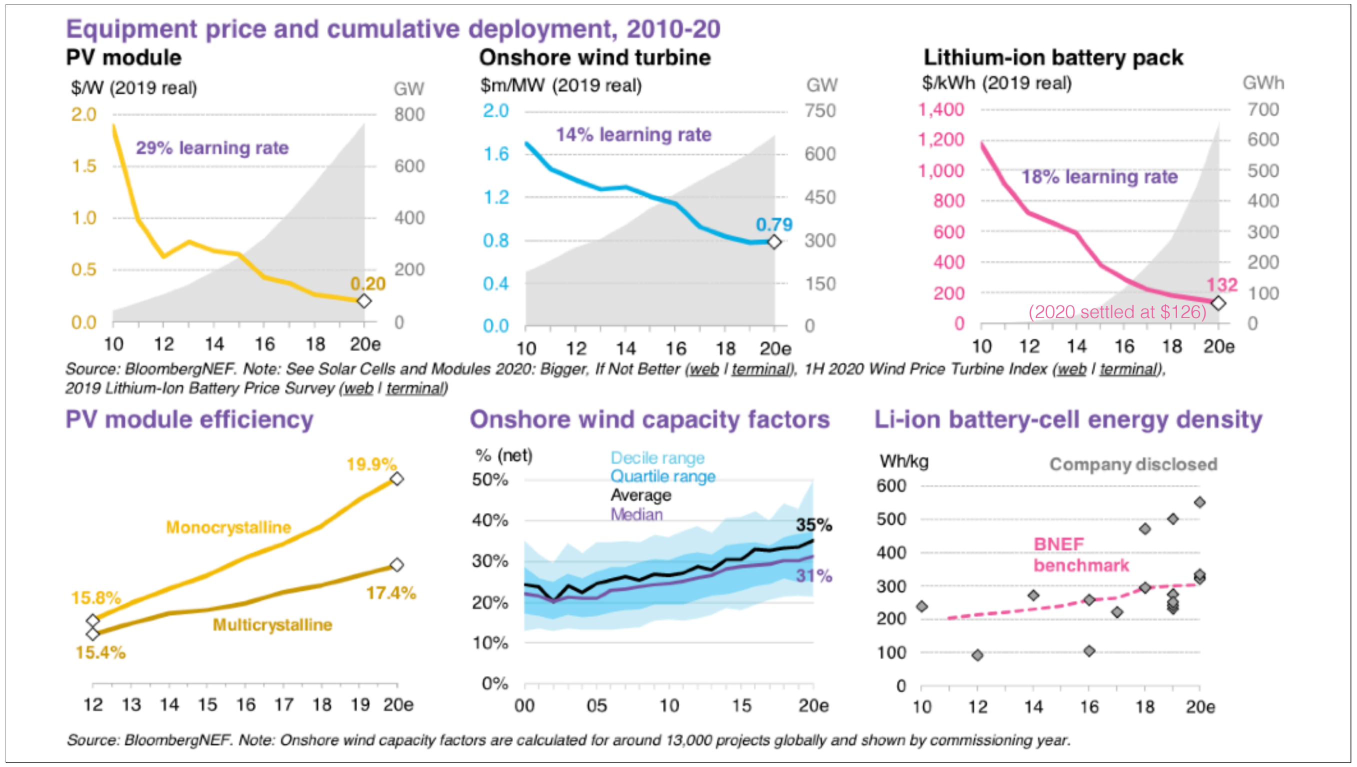






In the decade since the Fukushima accident, electricity savings and renewables offset Japan's drop in nuclear share from 25% to 6% (above) while slightly *decreasing* fossil-fueled generation. The renewable share rose from 11% to 23% despite the national government's ingeniously opaque efforts to suppress it (esp. windpower) to shield utilities' legacy assets from competition. That battle continues to evolve.

If all new reactors now under construction are built (aqua) and old or infirm ones close as planned (brown) after an average lifetime of 40 years plus whatever extensions their national regulators have granted, the fleet will inexorably retire by about 2060. More could be ordered, but with no business case, private financing is scant and enthusiasm waning. • Global capital commitments to modern renewables dwarf the magenta line for nuclear projects—by 19× in 2019. * If something major goes wrong, like Fukushima, the enterprise can dwindle much faster. Some 21 reactors in Japan were or are being abandoned. Despite the central government's strenuous efforts to restart a further two dozen idled reactors and complete costly safety retrofits, most remain closed and it's unclear if they'll ever have a business case to reopen—* especially if the emerging national policy of gradually opening them to competition brings, as expected, the flood of cheap renewables that competitive markets have elicited elsewhere. Though poor in fuels, Japan is exceptionally *rich* in renewables, efficiency, and capability to exploit both if allowed to. Unfortunately the utilities own the grids and are adept at blocking competitors from reliable access, despite important efforts to introduce real competition that I suspect will increasingly bear fruit. *



Equipment price and cumulative deployment, 2010-20

PV module

Onshore wind turbine

Lithium-ion battery pack

Source: BloombergNEF. Note: See Solar Cells and Modules 2020: Bigger, If Not Better (web I terminal), 1H 2020 Wind Price Turbine Index (web I terminal), 2019 Lithium-Ion Battery Price Survey (web I terminal)

PV module efficiency

Onshore wind capacity factors

Li-ion battery-cell energy density

Source: BloombergNEF. Note: Onshore wind capacity factors are calculated for around 13,000 projects globally and shown by commissioning year.

The learning curve—the decline in real cost for each doubling of cumulative production—is actually faster for PVs than for batteries. Each learning curve depends on carefully analyzed technical and operating trends that add up to the lower row of improvements. Notice the upper row shows hardware prices, not project or energy prices…. *

IEA finds cost of capital for renewable projects with
10–20-y offtake agreements has fallen markedly

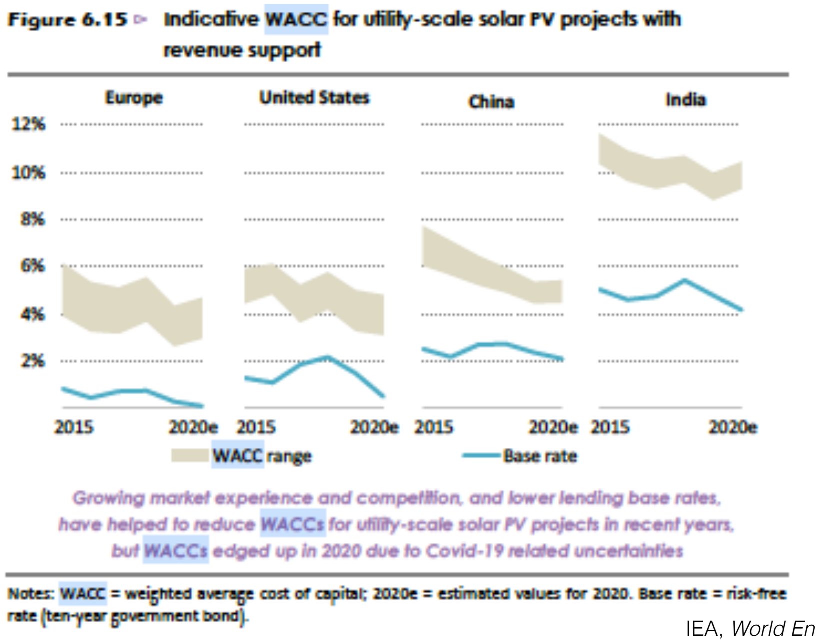


Figure 6.15 ▷ Indicative WACC for utility-scale solar PV projects with revenue support

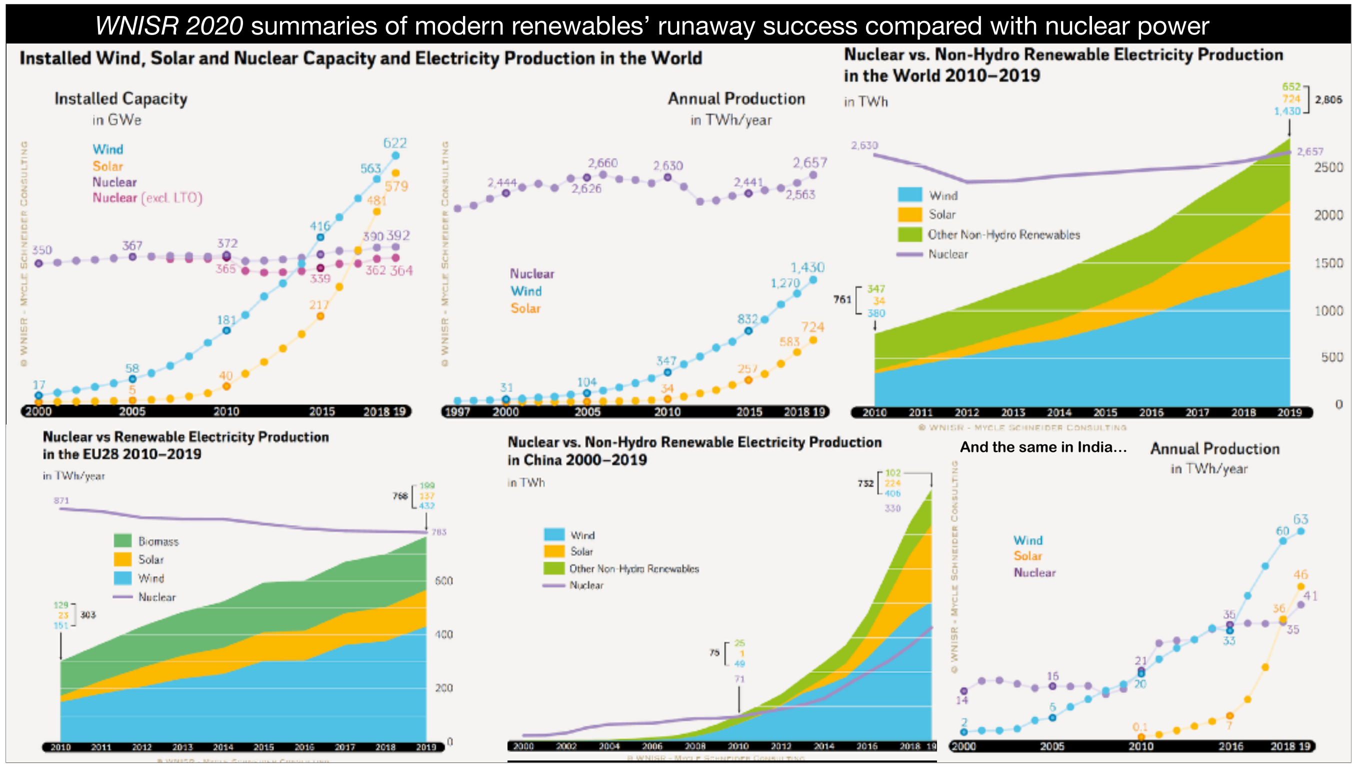
Growing market experience and competition, and lower lending base rates, have helped to reduce WACCs for utility-scale solar PV projects in recent years, but WACCs edged up in 2020 due to Covid-19 related uncertainties

Notes: WACC = weighted average cost of capital; 2020e = estimated values for 2020. Base rate = risk-free rate (ten-year government bond).

IEA, *World Energy Outlook 2020*, p. 235

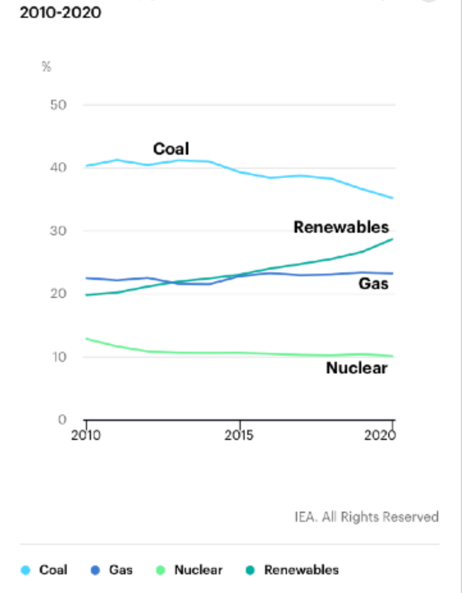
…which also depend strongly on the cost of capital, since these renewables have almost no operating costs. Capital has become markedly cheaper, especially for renewable projects under long-term contracts (as most big ones are) because of their solid annuity-like financial structure and low financial risk—often more counterparty and sovereign than technology or execution risk. *

WNISR 2020 summaries of modern renewables’ runaway success compared with nuclear power



Solar and windpower growth in both capacity and output has far outpaced nuclear, which struggles to sustain its output. * In 2019, electricity from solar, wind, biomass, and other nonhydro electricity generators like geothermal (but excluding both small and big hydro) together overtook nuclear power, rising 3.7-fold in the past decade. This is happening not just in * Europe but also in * China and * India. In two years, both nations increased their renewable generation by more than their entire 2018 nuclear output. China alone targets 1,300 GW of solar and wind by 2030. In the United States, renewables surpassed nuclear’s 20% share in 2020, four years early. Bloomberg forecasts wind and PV in 2050 will generate 56% of global electricity, and all renewables 69%, *vs.* 6% for nuclear. *

Renewables in 2010–20 grew to nearly 3× nuclear power’s share of global electricity (29% *vs.* 10%), saving 5× as much additional CO_2/y



Global electricity generation mix, 2010-2020

IEA. All Rights Reserved

2010–20 global electricity (L)

Renewables gained 9 percentage points’ share and gas 1, while coal lost 5 and nuclear 3

2010–20 global power-sector CO_2 emissions

Renewable growth offset 48% of emissions’ rise from demand growth

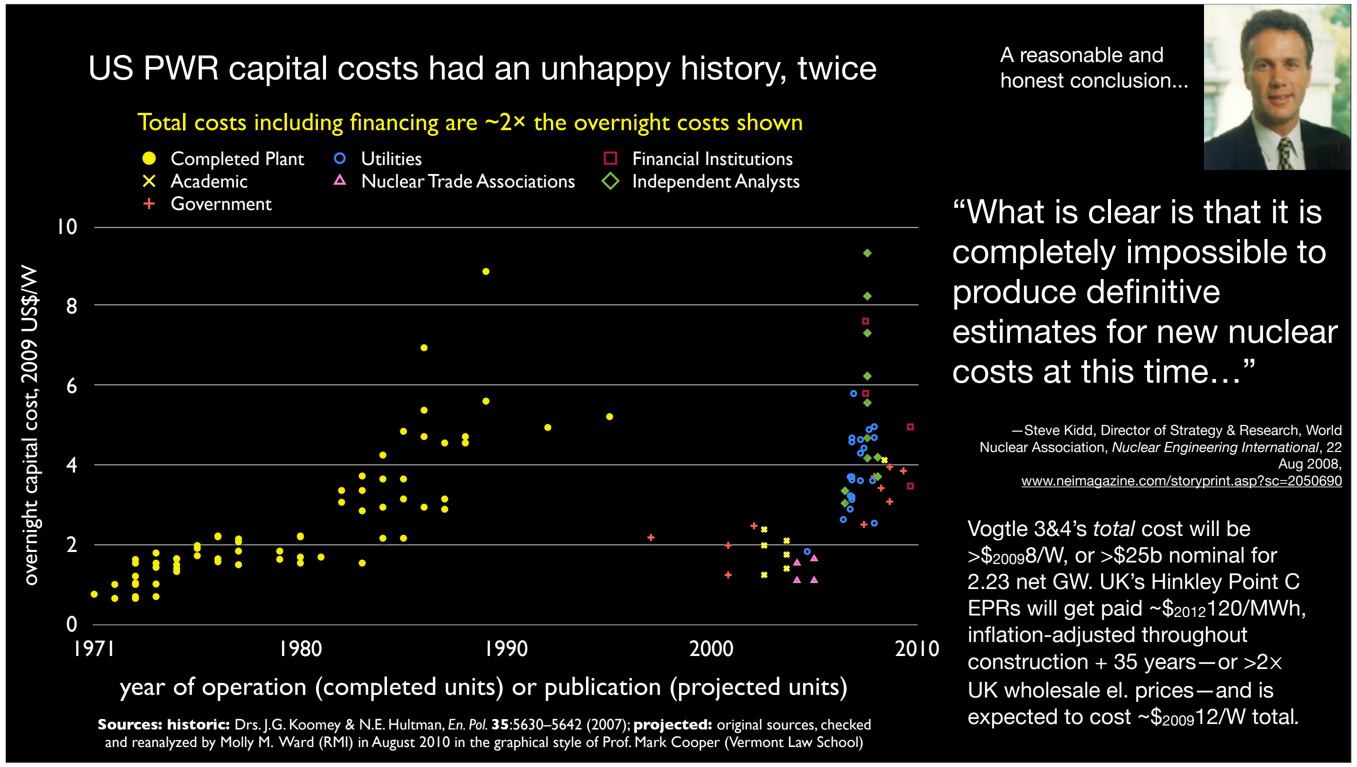
Renewable growth cut emissions 6× as much as coal-to-gas growth and 5× as much as nuclear growth

International Energy Agency, “Global Energy Review: CO2 Emissions in 2020,” 2 March 2021 www.iea.org/articles/global-energy-review-co2-emissions-in-2020

Change in power sector emissions by effect, 2010-2020

IEA. All Rights Reserved

The International Energy Agency confirms renewables rose last year to nearly three times the nuclear share of global electricity generation, and * over the past 11 years, renewables were 6× more effective than coal-to-gas fuel-switching (not counting any methane slip) and 5× more effective than nuclear growth in reducing power-sector carbon emissions. *



US PWR capital costs had an unhappy history, twice

Total costs including financing are ~2× the overnight costs shown

Sources: historic: Drs. J.G. Koomey & N.E. Hultman, *En. Pol.* **35**:5630–5642 (2007); **projected:** original sources, checked and reanalyzed by Molly M. Ward (RMI) in August 2010 in the graphical style of Prof. Mark Cooper (Vermont Law School)

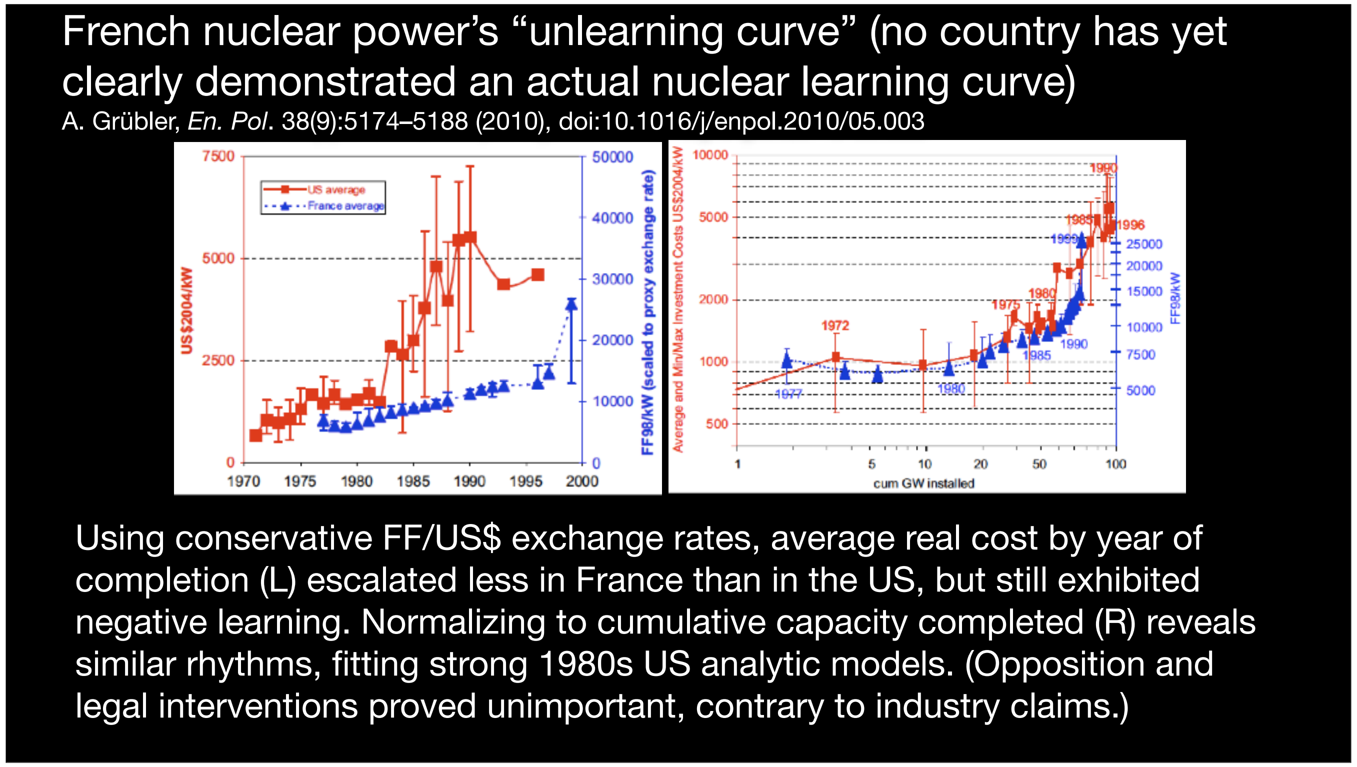
A reasonable and honest conclusion…

> “What is clear is that it is completely impossible to produce definitive estimates for new nuclear costs at this time…”

—Steve Kidd, Director of Strategy & Research, World Nuclear Association, *Nuclear Engineering International*, 22 Aug 2008, www.neimagazine.com/storyprint.asp?sc=2050690

Vogtle 3&4’s *total* cost will be >$\$_{2009}$8/W, or >$25b nominal for 2.23 net GW. UK’s Hinkley Point C EPRs will get paid ~$\$_{2012}$120/MWh, inflation-adjusted throughout construction + 35 years—or >2× UK wholesale el. prices—and is expected to cost ~$\$_{2009}$12/W total.

In contrast to falling renewable costs, nuclear cost escalation and delay are the norm, now and from the industry’s start (claimed Korean and Chinese exceptions are often dubious and unverifiable). For the US, the yellow points show the historic fleet’s real “overnight” capital costs (if hypothetically the reactor could be built by tomorrow morning, incurring zero financing cost during construction—but actual financing and real escalation historically about double the overnight cost). The first few decades exhibited Cheops’ Law: multiply the initial cost estimate by π (or if high-tech, π^2). On the right side of the graph, the varicolored dots show cost estimates underlying the proposed Nuclear Renaissance touted over a decade ago. They range over ~4× depending on who made them: academic, government, and nuclear-industry advocates claimed very low costs—to be paid by someone else—while financial institutions and independent analysts found very high costs. As sales pitches evolved into contractual negotiations with billions of actual dollars at risk, the bid costs converged to or above the upper estimates. / This continues today in the US and UK reactor pairs now trying to struggle across the finish line despite prodigious cost overruns and financial risks. How risky? The UK owner (Électricité de France) said last year [2020] that its juicy guaranteed real payment for output comprises 21% for operating costs, just 12% for overnight construction cost, 28% for financing if it were a normally risky project, and *39% for this first-of-a-kind project’s extra risk*—over 3× as much cost for unique financial risk as for actual construction! Yet ÉdF will still lose billions because it underbid the actual risk, which keeps rising. * As forthright ex-WNA executive Steve Kidd said, obody really knows what new reactors will cost. That’s why promoters want someone else to take the risk. *



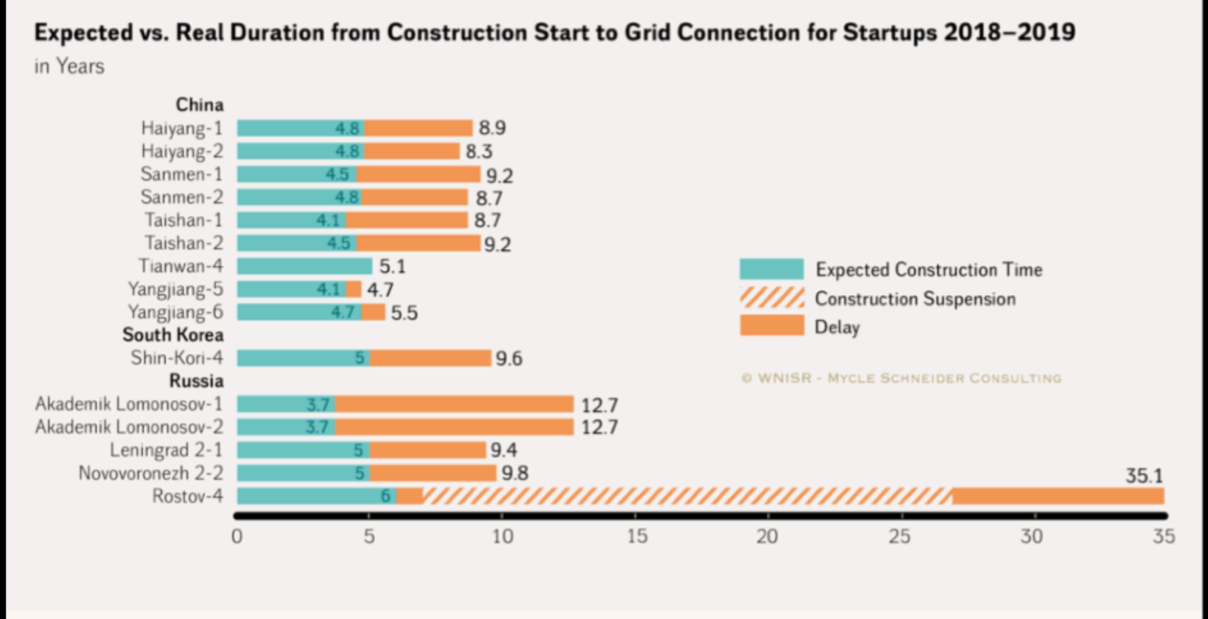
French nuclear power’s “unlearning curve” (no country has yet clearly demonstrated an actual nuclear learning curve)

A. Grübler, *En. Pol*. 38(9):5174–5188 (2010), doi:10.1016/j/enpol.2010/05.003

Using conservative FF/US$ exchange rates, average real cost by year of completion (L) escalated less in France than in the US, but still exhibited negative learning. Normalizing to cumulative capacity completed (R) reveals similar rhythms, fitting strong 1980s US analytic models. (Opposition and legal interventions proved unimportant, contrary to industry claims.)

Rising costs and slowing construction aren’t just a US issue; they’re nearly worldwide. Claimed nuclear learning curves (real costs falling as you build more) have long been claimed and assumed, but never reliably observed except in the first few units of France’s program in the late 1970s. France has unique institutional conditions: no enabling statute governing the world’s most ambitious nuclear program, everything run by a uniquely cohesive technocratic group controlling every key energy policy lever in the central government, full access to the public purse with no market discipline, illegality of opposition, and until recently, little or no transparency, independent regulation, or fair competition. France’s elite nuclear corps was also bold, technically capable, and disciplined enough to stick to four variants of a single broad reactor design. However, its latest reactor projects in France and Finland are around π× original cost and construction time, largely (I suspect) because building on an aggressive steady rhythm overbuilt the French market, then the predicted export market collapsed, so orders paused for 14 years (1991–2005) and a whole generation of construction managers retired, leaving successors too unseasoned to manage these complex projects, supply chains too deteriorated to deliver them, and some institutional cultures too accustomed to opacity to deal honestly and transparently with awkward issues and new needs for accountability. *

Nuclear construction delays continue to be widespread



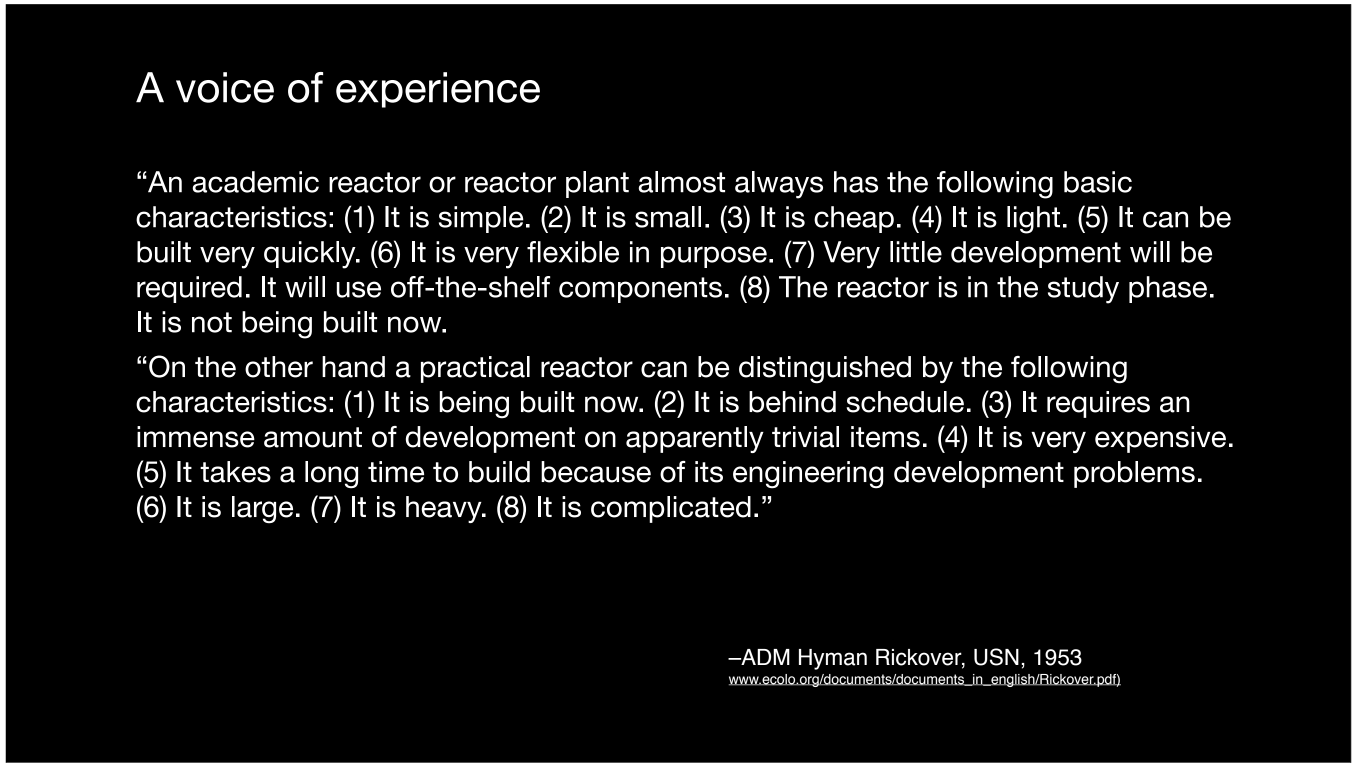
Expected vs. Real Duration from Construction Start to Grid Connection for Startups 2018–2019

in Years

Sources: WNISR, with IAEA-PRIS, 2020

https://www.renewable-ei.org/pdfdownload/activities/REvision2021_MSchneider_210310.pdf

The prevalence of unexpected construction delays continues even in the countries most extolled for cheap and efficient reactor-building, notably China and South Korea. Of 15 nuclear units started in 2018–19, it appears only one (Tiánwān-1) was finished on time, and twofold overruns were common. It appears that the Korean-built Barakah 1 in the United Arab Emirates, begun in July 2012 and projected to enter commercial service in early 2021, would be graphed above at ~8.1 y (*vs.* ~5 expected). Barakah 2 began construction 16 April 2013 and got its operating license 9 March 2021 but was not yet connected to the grid. *



A voice of experience

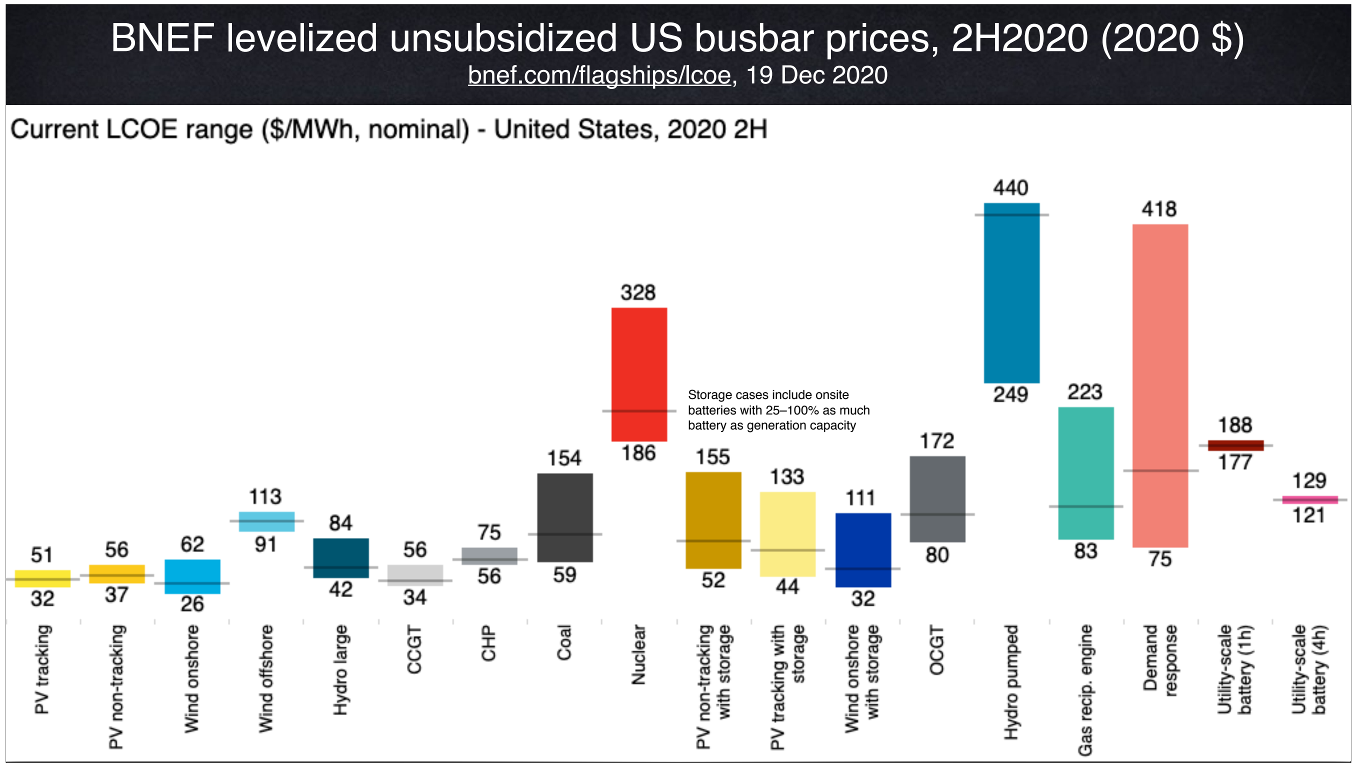
“An academic reactor or reactor plant almost always has the following basic characteristics: (1) It is simple. (2) It is small. (3) It is cheap. (4) It is light. (5) It can be built very quickly. (6) It is very flexible in purpose. (7) Very little development will be required. It will use off-the-shelf components. (8) The reactor is in the study phase. It is not being built now.

“On the other hand a practical reactor can be distinguished by the following characteristics: (1) It is being built now. (2) It is behind schedule. (3) It requires an immense amount of development on apparently trivial items. (4) It is very expensive. (5) It takes a long time to build because of its engineering development problems. (6) It is large. (7) It is heavy. (8) It is complicated.”

–ADM Hyman Rickover, USN, 1953
www.ecolo.org/documents/documents_in_english/Rickover.pdf)

Doing nuclear power well and safely is very, very hard. Admiral Hyman Rickover, the famously rigorous and demanding genius who created the US nuclear Navy and its demanding technical culture, wrote these trenchant comments about the difference between theoretical reactors and actual ones. His insights are being re-proven in the current wave of efforts to create new (or rediscovered old) kinds of reactors.

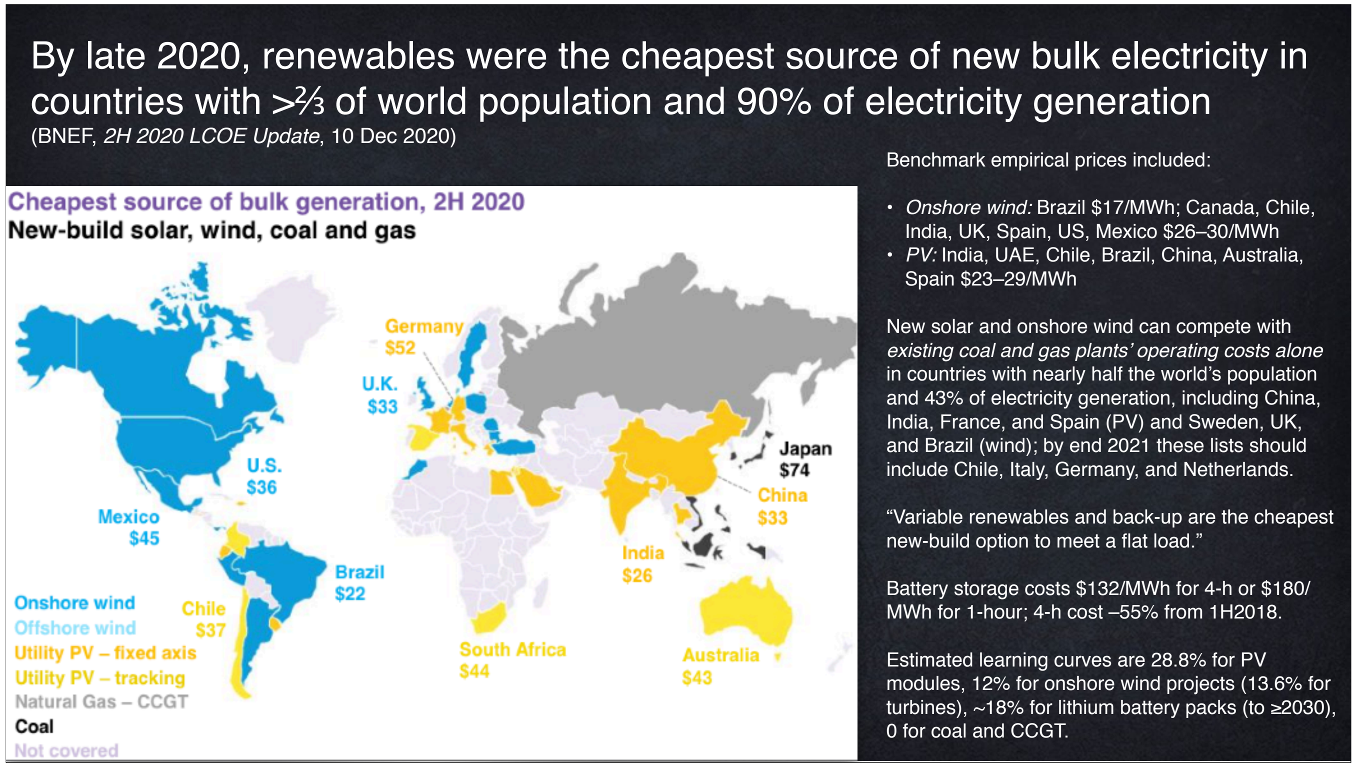
(Do you know how Rickover ensured top-quality hull welds on the first US nuclear submarines? Simple: he told the welders and the CEOs that they’d all be aboard for the maiden dive. That worked. Unfortunately it doesn’t deter reactor promoters, because so much of the investment comes from taxpayers.) *



BNEF levelized unsubsidized US busbar prices, 2H2020 (2020 $)

bnef.com/flagships/lcoe, 19 Dec 2020

Here’s the latest Bloomberg comparison of the empirical levelized long-term prices at which a developer of a US project financed in 2020 must sell electricity in order to recover all costs (capex, opex, tax, financing) and meet the market target for returns to equity investors. Externalities aren’t included, such as carbon or methane emissions and fuel-price volatility. Federal tax credits are removed for renewables while the more subtle, opaque, and important subsidies to nonrenewables probably remain embedded in these numbers, but renewables are generally winning and pulling ahead. Bloomberg doesn’t yet include demand-side competitors but hopes to. *



By late 2020, renewables were the cheapest source of new bulk electricity in countries with >⅔ of world population and 90% of electricity generation

(BNEF, *2H 2020 LCOE Update*, 10 Dec 2020)

Cheapest source of bulk generation, 2H 2020

New-build solar, wind, coal and gas

Benchmark empirical prices included:

- *Onshore wind:* Brazil $17/MWh; Canada, Chile, India, UK, Spain, US, Mexico $26–30/MWh
- *PV:* India, UAE, Chile, Brazil, China, Australia, Spain $23–29/MWh

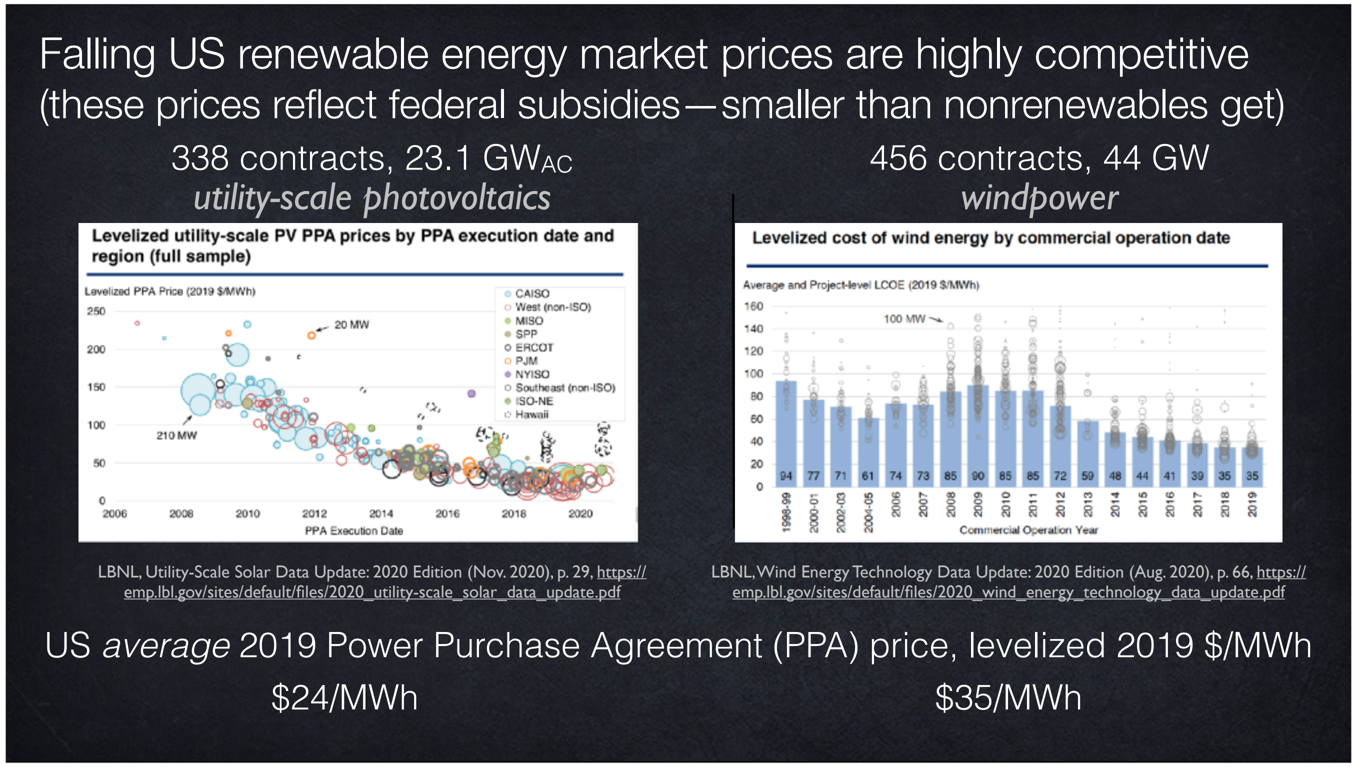
New solar and onshore wind can compete with *existing coal and gas plants' operating costs alone* in countries with nearly half the world's population and 43% of electricity generation, including China, India, France, and Spain (PV) and Sweden, UK, and Brazil (wind); by end 2021 these lists should include Chile, Italy, Germany, and Netherlands.

"Variable renewables and back-up are the cheapest new-build option to meet a flat load."

Battery storage costs $132/MWh for 4-h or $180/MWh for 1-hour; 4-h cost –55% from 1H2018.

Estimated learning curves are 28.8% for PV modules, 12% for onshore wind projects (13.6% for turbines), ~18% for lithium battery packs (to ≥2030), 0 for coal and CCGT.

From this rich bottom-up dataset, Bloomberg concluded that in countries with over two-thirds of the world's people and 90% of its power generation, renewables in 2020 became the cheapest source of new bulk electricity. In countries with nearly half the world's people and 43% of electricity generation, notably including China and India, new solar or wind beats just the operating costs of existing coal and gas plants. Moreover, the cheapest way to meet a flat load is now variable renewables plus backup (storage, renewable, or fueled)—not traditional thermal power plants. These findings are strengthening year by year, because renewables (and batteries) are getting rapidly cheaper while coal and gas plants exhibit no learning curves. *



Falling US renewable energy market prices are highly competitive (these prices reflect federal subsidies—smaller than nonrenewables get)

338 contracts, 23.1 GWAC
utility-scale photovoltaics

456 contracts, 44 GW
windpower

Levelized utility-scale PV PPA prices by PPA execution date and region (full sample)

Levelized cost of wind energy by commercial operation date

LBNL, Utility-Scale Solar Data Update: 2020 Edition (Nov. 2020), p. 29, https://emp.lbl.gov/sites/default/files/2020_utility-scale_solar_data_update.pdf

LBNL, Wind Energy Technology Data Update: 2020 Edition (Aug. 2020), p. 66, https://emp.lbl.gov/sites/default/files/2020_wind_energy_technology_data_update.pdf

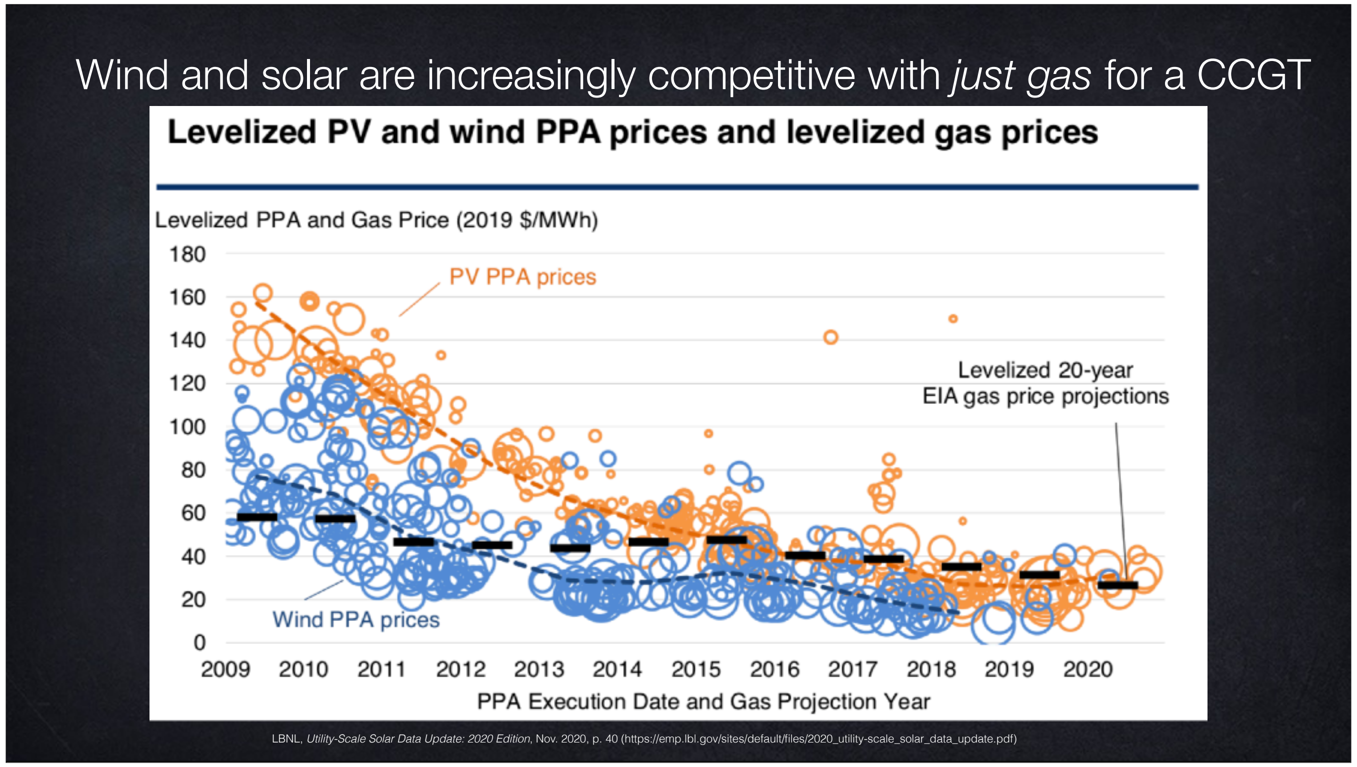
US *average* 2019 Power Purchase Agreement (PPA) price, levelized 2019 $/MWh

$24/MWh

$35/MWh

US natural gas is no longer the real competitor to beat; other modern renewables now are. Here are Berkeley Lab's authoritative actual *project-by-project* solar and windpower US contract prices. Each PV or windpower project is a circle whose diameter is proportional to its capacity. You can see much variation between projects and regions (which for simplicity I've shown only for PVs), but the general trends are favorable.

LBNL also analyzes distributed PVs—projects up to 5 MWAC. Their 2019 installed prices in the commercial sector averaged 2× those of utility-scale projects, residential 3×, both excluding batteries—but by being near or mounted on customers' buildings, distributed PVs can avoid most or all of the grid cost, which typically exceeds the cost of the electricity itself. *



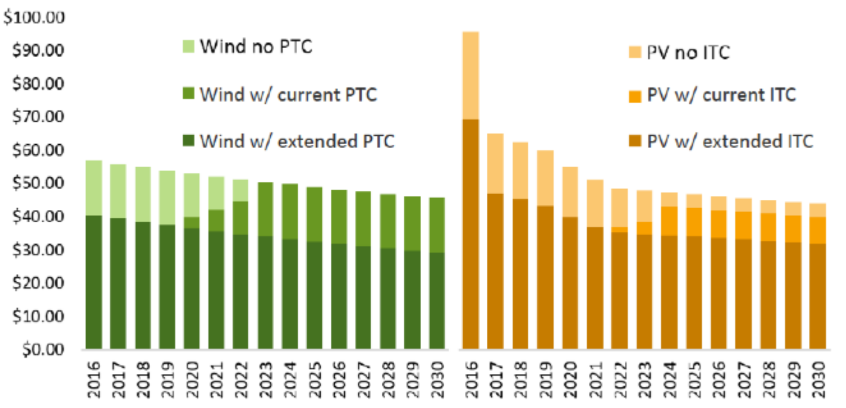
Wind and solar are increasingly competitive with *just gas* for a CCGT

Levelized PV and wind PPA prices and levelized gas prices

LBNL, *Utility-Scale Solar Data Update: 2020 Edition*, Nov. 2020, p. 40 (https://emp.lbl.gov/sites/default/files/2020_utility-scale_solar_data_update.pdf)

This graph compares the market prices of actual US projects (diameter indicates capacity) for PVs in gold *and* wind in blue with the heavy dashed line—the *gas cost alone* for existing combined-cycle plants. Solar and wind generally beat existing gas plants, which will therefore run fewer hours until they go broke, as some already have, even in Texas. Digitization, renewables, and new business models will move the power system's asset utilization the other way—from 50% to 80–90%—and drive marginal power cost to near zero. Bloomberg too reckons new *un*subsidized PV and wind already beat most US coal opex and will beat gas opex by 2035. So renewable growth no longer depends significantly on the uncertain gas price, and both new and existing gas power are in deep trouble against today's *un*subsidized renewables (let alone actually subsidized ones), all *without* costing gas's CO_2 and methane emissions or the market value of its price volatility. *

Temporary renewable tax credits (less than permanent nonrenewable subsidies) are set to phase down/out—and a substantial part of their value doesn't reach the developer anyway



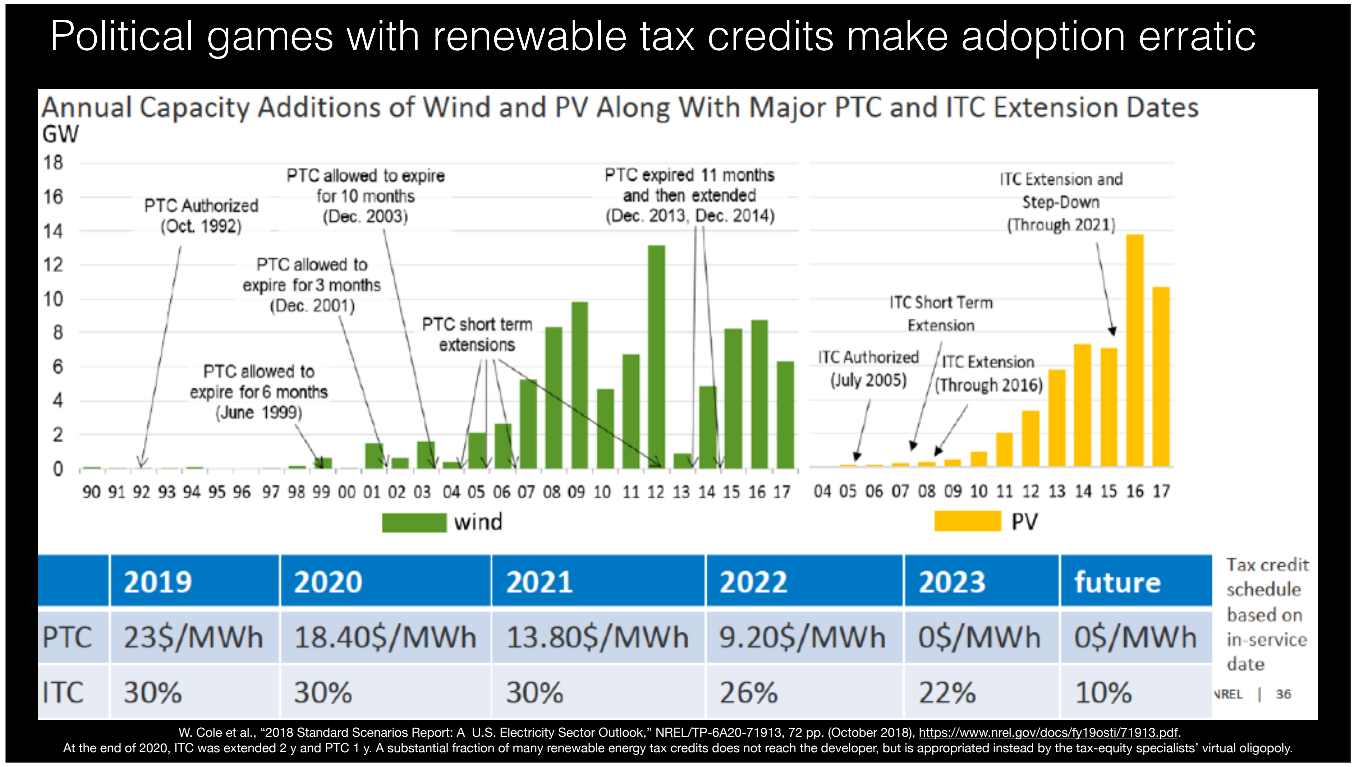
Year	2016	2030
PTC Relative Value	**29%**	**36%**
PTC Absolute Value (2017$)	$\frac{23\$}{\text{MWh}}$	$\frac{23\$}{\text{MWh}}$
ITC Relative Value	30%	30%
ITC Absolute Value (2017$)	$\frac{26\$}{\text{MWh}}$	$\frac{12\$}{\text{MWh}}$

NREL's 2018 Levelized Cost of Energy (LCOE) estimates for *average* US resource conditions with standard 20-y financing

W. Cole et al., "2018 Standard Scenarios Report: A U.S. Electricity Sector Outlook," NREL/TP-6A20-71913, 72 pp. (October 2018), https://www.nrel.gov/docs/fy19osti/71913.pdf

As nonrenewables keep and increase their larger subsidies [the 2017 tax-cut law changed arcane rules to make central-plant power cheaper and renewable power costlier], the planned phaseout of renewable tax credits won't rescue gas. Here's the phaseout pattern for *average* US wind and solar resources, not counting the extensions of a year or two passed at the end of 2020. Of course, developers prefer to build where resources are best, yielding the lower market prices you saw from Berkeley Lab. Conservatively, this comparison counts tax credits at their book value, but in fact the oligopoly of tax-equity finance houses keeps roughly a third, shrinking actual subsidies, so it would be more efficient to pay the developers directly than through a middleman. Tax equity investors' bloodbath over recent Texas hedges may make them prefer that too. *

Political games with renewable tax credits make adoption erratic

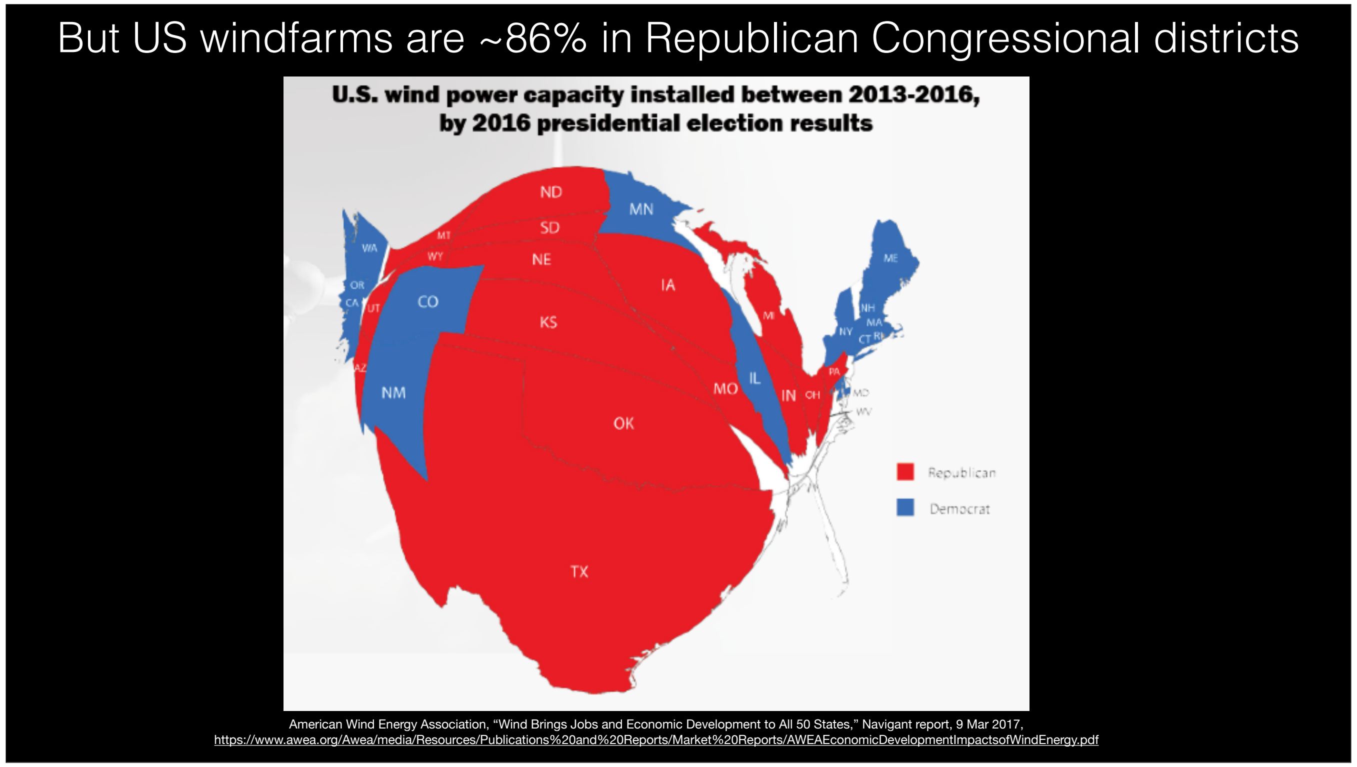

Annual Capacity Additions of Wind and PV Along With Major PTC and ITC Extension Dates

	2019	2020	2021	2022	2023	future
PTC	23$/MWh	18.40$/MWh	13.80$/MWh	9.20$/MWh	0$/MWh	0$/MWh
ITC	30%	30%	30%	26%	22%	10%

Tax credit schedule based on in-service date

W. Cole et al., "2018 Standard Scenarios Report: A U.S. Electricity Sector Outlook," NREL/TP-6A20-71913, 72 pp. (October 2018), https://www.nrel.gov/docs/fy19osti/71913.pdf.
At the end of 2020, ITC was extended 2 y and PTC 1 y. A substantial fraction of many renewable energy tax credits does not reach the developer, but is appropriated instead by the tax-equity specialists' virtual oligopoly.

Renewable tax credits are also unreliable and disruptive because they've become a bargaining chip in unrelated political disputes. This NREL graph shows five expirations and numerous short-term extensions that deterred investment, slowed deployment, and raised costs well above those seen abroad under more-stable policies. *

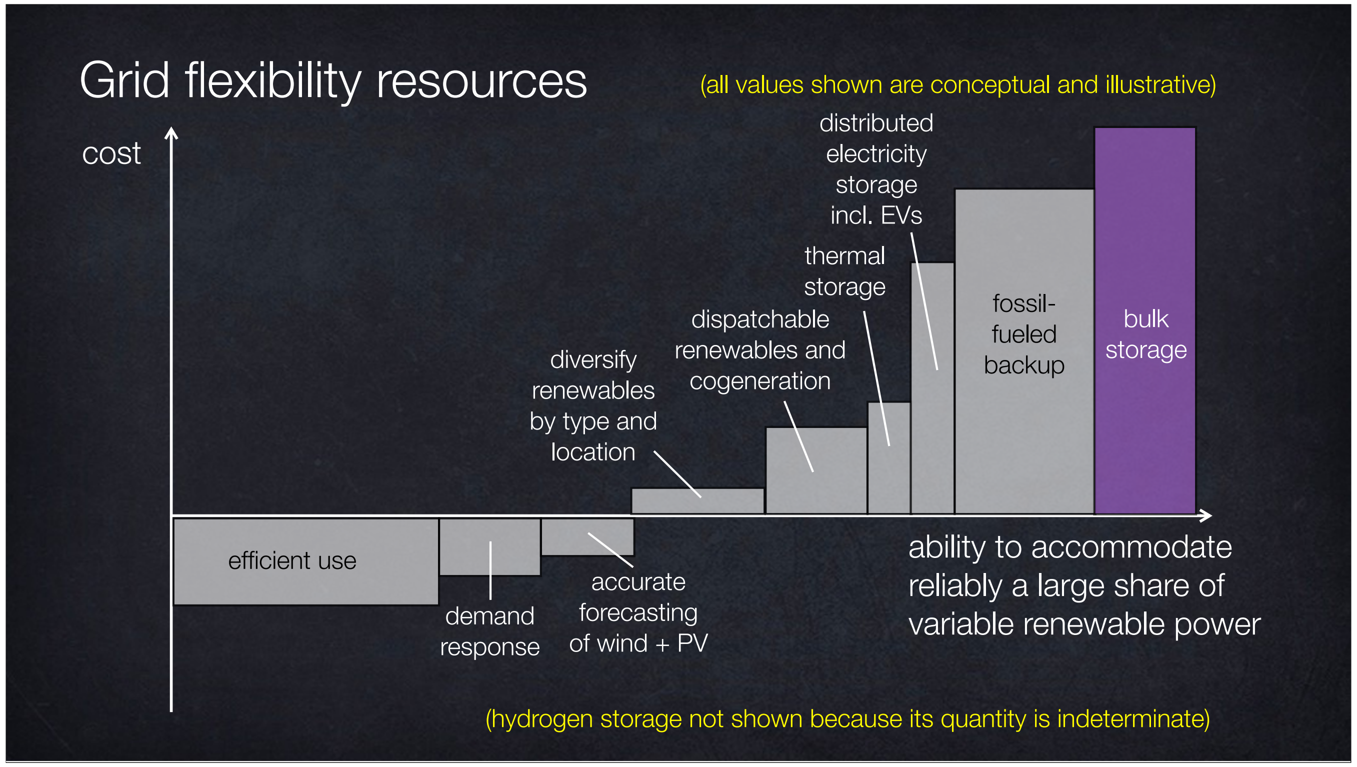


But US windfarms are ~86% in Republican Congressional districts

U.S. wind power capacity installed between 2013-2016, by 2016 presidential election results

American Wind Energy Association, “Wind Brings Jobs and Economic Development to All 50 States,” Navigant report, 9 Mar 2017,
https://www.awea.org/Awea/media/Resources/Publications%20and%20Reports/Market%20Reports/AWEAEconomicDevelopmentImpactsofWindEnergy.pdf

Yet the father of those tax credits and their extensions was Senate Finance Committee Chairman Chuck Grassley (R-IA), whose state is one-third windpowered, and who knows 86% of US windfarms are in Republican Congressional districts, as is most solar power too. Senator Grassley memorably said politicians who claim to favor “all of the above” energy policies often turn out to favor “none of the above and all of the below.” *



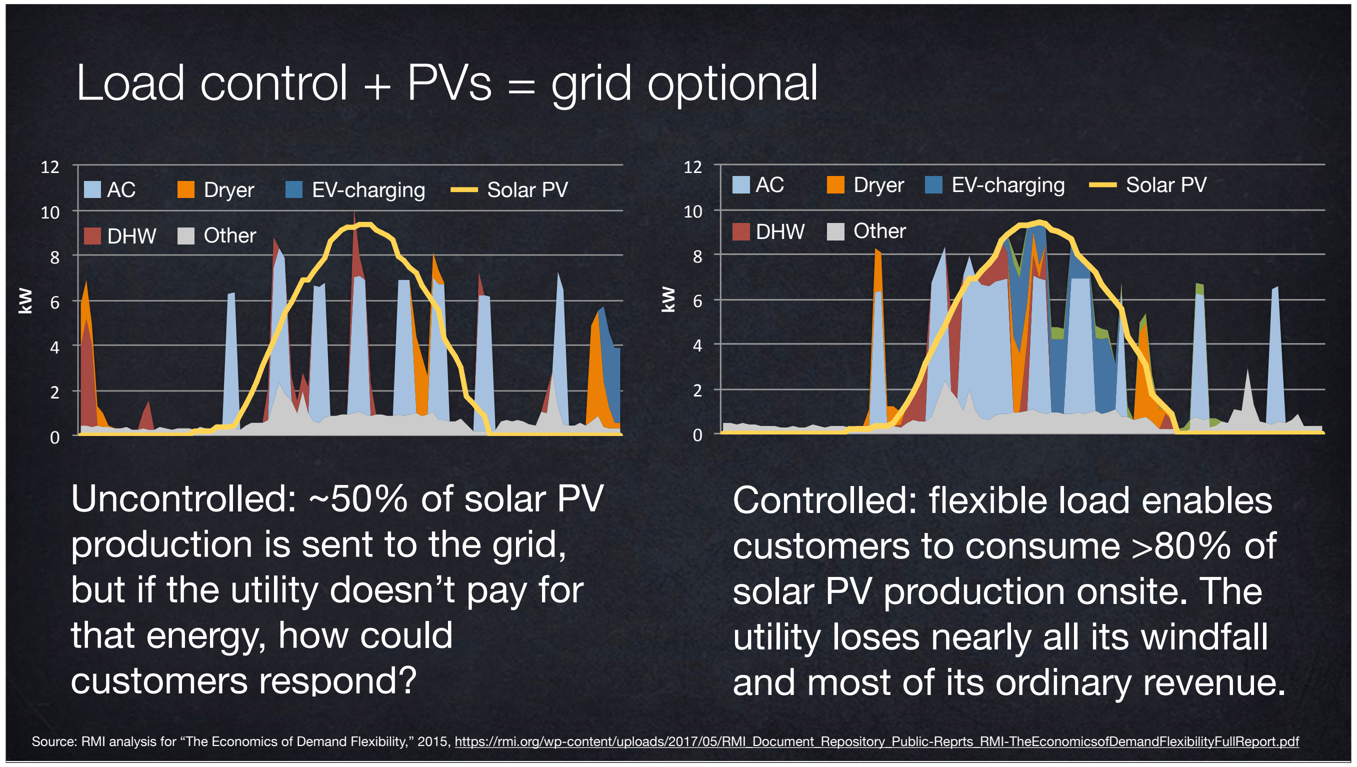
Grid flexibility resources

(all values shown are conceptual and illustrative)

(hydrogen storage not shown because its quantity is indeterminate)

To keep the grid reliable while supply becomes renewable, we can use not just one grid flexibility resource (bulk storage, in magenta) but about *ten*, sketched here conceptually in order of increasing cost. RMI is fleshing out the data, and your actual costs will vary, but bulk storage comes last, not first, so we needn't wait for a storage miracle, and the market isn't waiting. To be sure, behind-the-meter batteries have more benefits than just storing energy, and can often be cost-effective today. But cost-effective doesn't mean competitive: it only means benefits exceed costs, not that there isn't an even cheaper way to get similar benefits. There are at least nine such competitors, and they too are rapidly improving, so it's a crowded horse-race. Yet at battery conferences, everyone says, "My battery is better than your battery," while almost no one asks, "What must any kind of battery compete with?" /

Bulk electrical storage, though often lucrative and effective, is neither necessary nor sufficient for reliably operating a modern renewable-dominated grid. Such grids' more numerous moving parts and more variable output require good forecasting tools and more care, attention, and thoughtfulness. But this is a solvable and solved problem, not an insuperable obstacle. With proper operation, variable and flexible resources can reliably serve steady loads not in the traditional way—giant fossil-fueled and nuclear plants—but with newer resources that meet even better the classical criterion for so-called "baseload" plants: that they have the *lowest operating cost*, so they're dispatched whenever available. Of course, modern grids don't connect a single generator to a single load; all generators serve the grid, and the grid serves all loads. So unless you're on a small desert island, bulk electrical storage isn't generally required. Whether a specific generator runs at a specific time is irrelevant; what matters is the *statistical* reliability of the whole fleet of generators and the lines connecting them. So as BloombergNEF's *2H2020 LCOE Update* concluded (10 Dec 2020), "Variable renewables and back-up [which may be demand-side, renewable, or nonrenewable] are the cheapest new-build option to meet a flat load." Steadily operating big thermal power stations have been dethroned from that traditional role. *



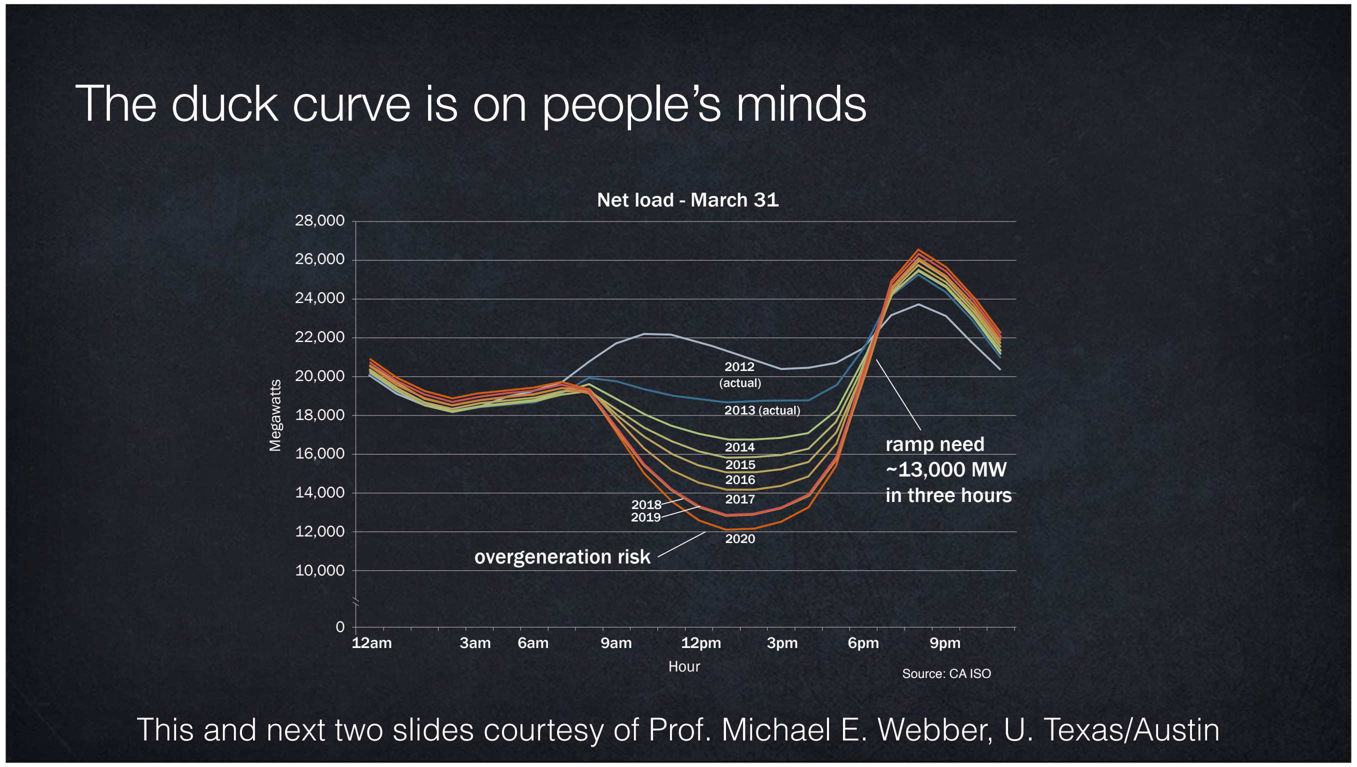
Load control + PVs = grid optional

Uncontrolled: ~50% of solar PV production is sent to the grid, but if the utility doesn't pay for that energy, how could customers respond?

Controlled: flexible load enables customers to consume >80% of solar PV production onsite. The utility loses nearly all its windfall and most of its ordinary revenue.

Source: RMI analysis for "The Economics of Demand Flexibility," 2015, https://rmi.org/wp-content/uploads/2017/05/RMI_Document_Repository_Public-Reprts_RMI-TheEconomicsofDemandFlexibilityFullReport.pdf

* Demand response, the second item from the left in the previous slide, is a powerful resource to which many utilities haven't yet fully adapted. For example, a typical Hawai'ian household uses appliances at various times of the 24-hour day, roughly half while rooftop PVs are operating (the yellow curve). But their main utility, having tried and failed to prohibit solar hookups, then wanted to confiscate leftover solar production without paying for it. * How might angry customers respond? Probably the same vendors who provide their PVs and batteries would offer them smart appliances to move 80–90% of household loads conveniently into the solar hours, costing the utility nearly all its intended windfall *and* most of its ordinary revenue. So this anti-solar tariff, like all six that RMI studied, is a well-aimed boomerang that will actually speed and expand solar adoption by educating and annoying the customers so they leave the grid faster! (Happily, HECO and the PUC are now national leaders after an extensive stakeholder process.) *



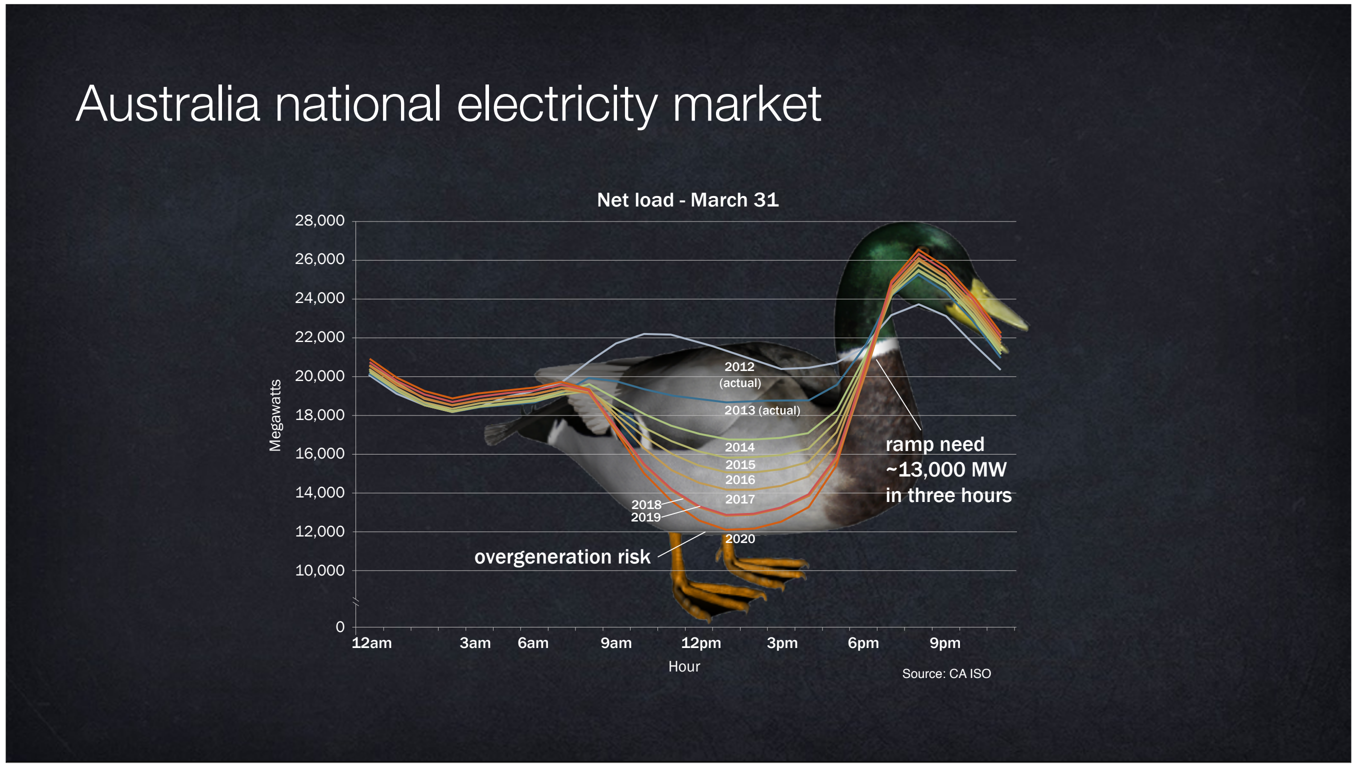
The duck curve is on people's minds

Net load - March 31

Source: CA ISO

This and next two slides courtesy of Prof. Michael E. Webber, U. Texas/Austin

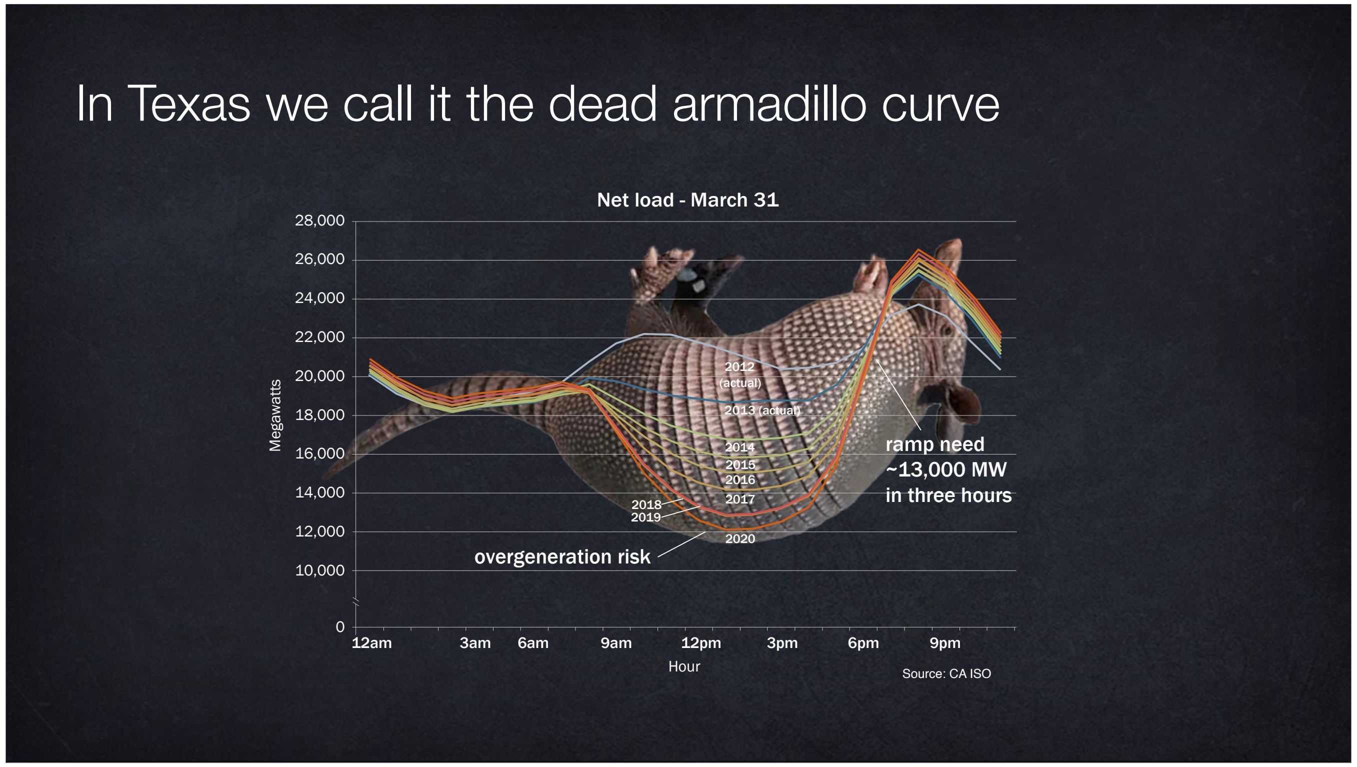
Another illustration of how the demand-response curve is severalfold bigger than normally assumed comes from Texas. An important use of "flexiwatts" is to solve PVs' challenge of requiring other resources to ramp up sharply as strong midday solar generation fades at the end of the day just as people get home and turn stuff on. So in these California load profiles, supply must ramp up steeply… *



Australia national electricity market

Source: CA ISO

…creating what California regulators called the “duck curve”—… *

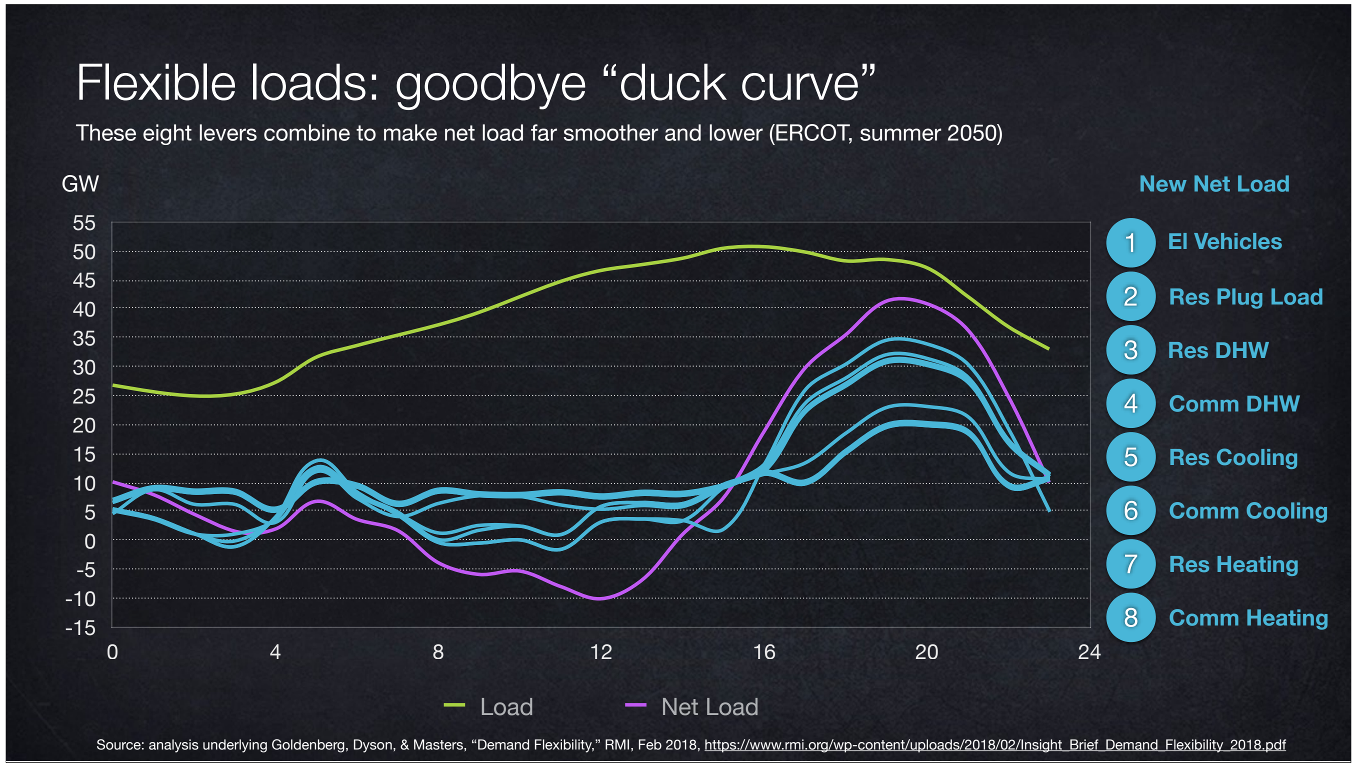


In Texas we call it the dead armadillo curve

Net load - March 31

Source: CA ISO

…or what Texans call the “dead armadillo curve.” So how can we manage this evening ramp-rate challenge, and other kinds of variability in solar and windpower? *



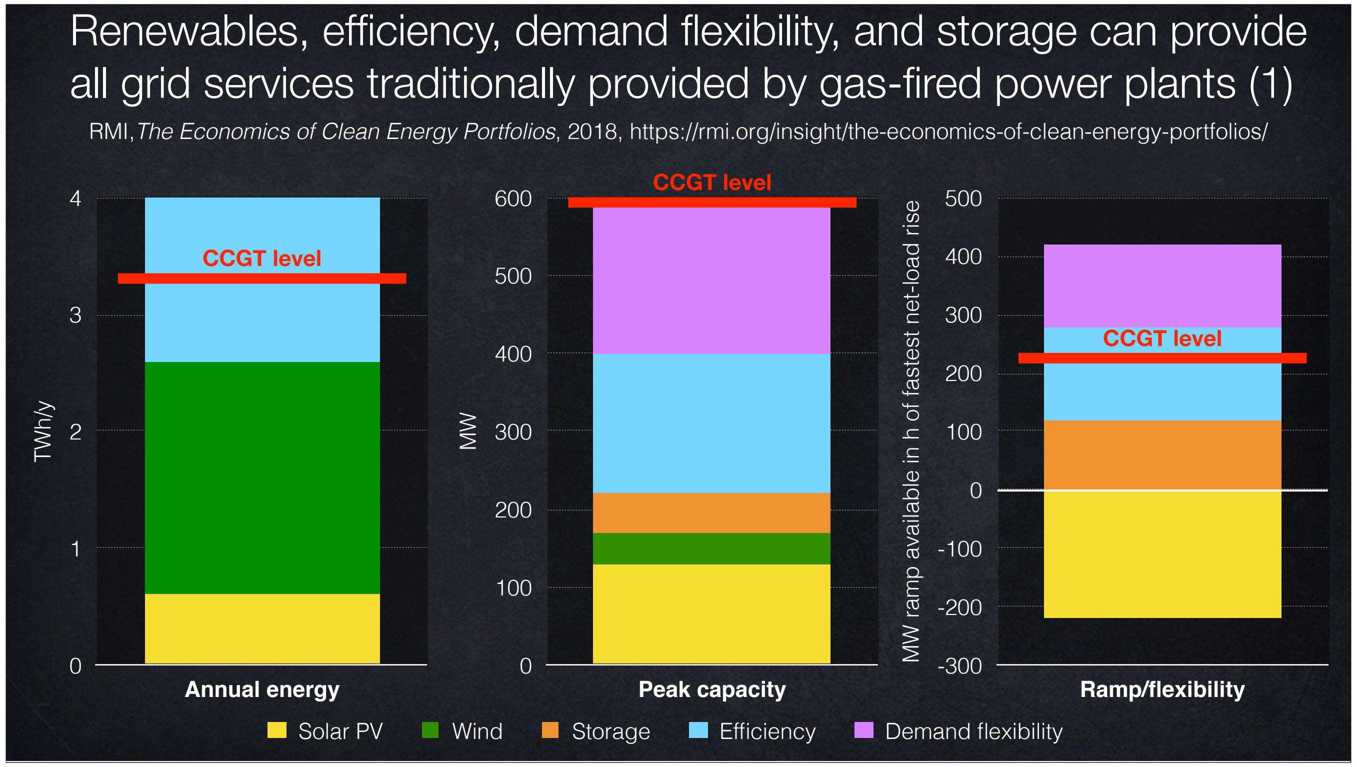
Flexible loads: goodbye “duck curve”

These eight levers combine to make net load far smoother and lower (ERCOT, summer 2050)

Source: analysis underlying Goldenberg, Dyson, & Masters, “Demand Flexibility,” RMI, Feb 2018, https://www.rmi.org/wp-content/uploads/2018/02/Insight_Brief_Demand_Flexibility_2018.pdf

In the 2050 Texas grid, as shown here, the dead armadillo disappears if we combine comprehensive but realistic deployment of demand response in * electric vehicles, * home plug loads, and * residential and * commercial domestic hot water, * plus * space heating * and * space cooling. Together these can conveniently cut the 2050 summer daily load range nearly in half [from ~26 to ~15 GW], save a fourth [24%] of nonrenewable capacity, make renewable energy a third [36%] more valuable, and pay back in about five months. That’s especially valuable in stressed parts of the grid, like Brooklyn and Queens, where ConEd is deferring a $1-billion investment through third-party demand-side solutions.

(If you’ve heard the false statement that renewable failures triggered or contributed significantly to the Texas grid’s mid-February 2021 power failures, please watch the Rutgers U. Center for Research in Regulated Industries 9 March 2021 webinar at https://www.youtube.com/watch?v=XZDabDE4-do, where I present contrary findings, mostly summarized in the last four slides in this deck. I also ascribe primary responsibility (leaving aside institutional and governance failures) to ~35 GW of peak electric heating load from inefficient houses, two-thirds electrically heated. That thesis and emergent solutions are elaborated at https://www.dallasnews.com/opinion/commentary/2021/03/14/like-power-generators-texas-homes-are-not-built-for-winter/.)



Renewables, efficiency, demand flexibility, and storage can provide all grid services traditionally provided by gas-fired power plants (1)

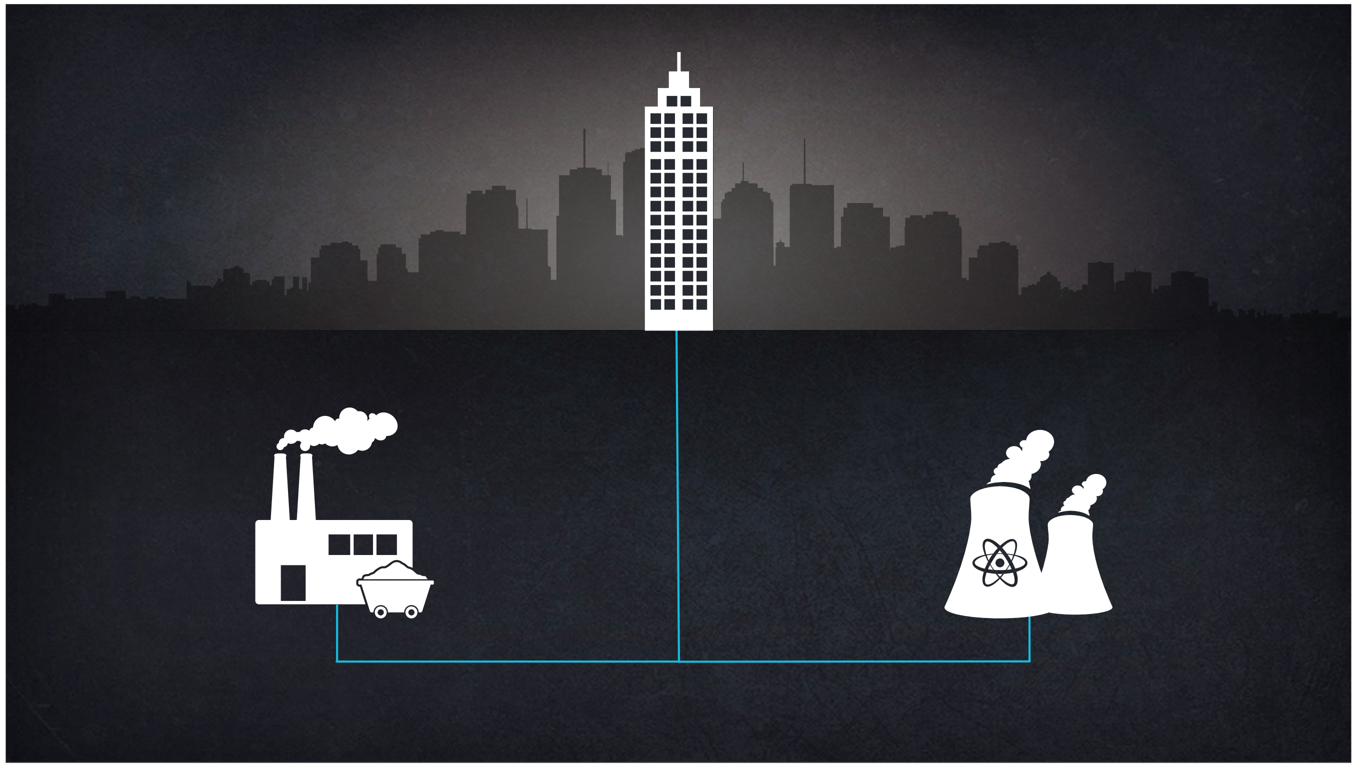
RMI, *The Economics of Clean Energy Portfolios*, 2018, https://rmi.org/insight/the-economics-of-clean-energy-portfolios/

So far we've discussed competition between, say, gas plants and either solar or windpower. But today the keenest competition is not between single technologies but between Clean Energy *Portfolios* combining solar, wind, storage, and efficiency. They can provide not just electrical energy and peak capacity but also ramping and flexibility capabilities, displacing gas-fired power plants in each role, at lower cost, almost everywhere in the US—in the Southeast, ~19% cheaper than combined-cycle gas. On the West Coast, such a portfolio replaces a new combined-cycle plant like this:

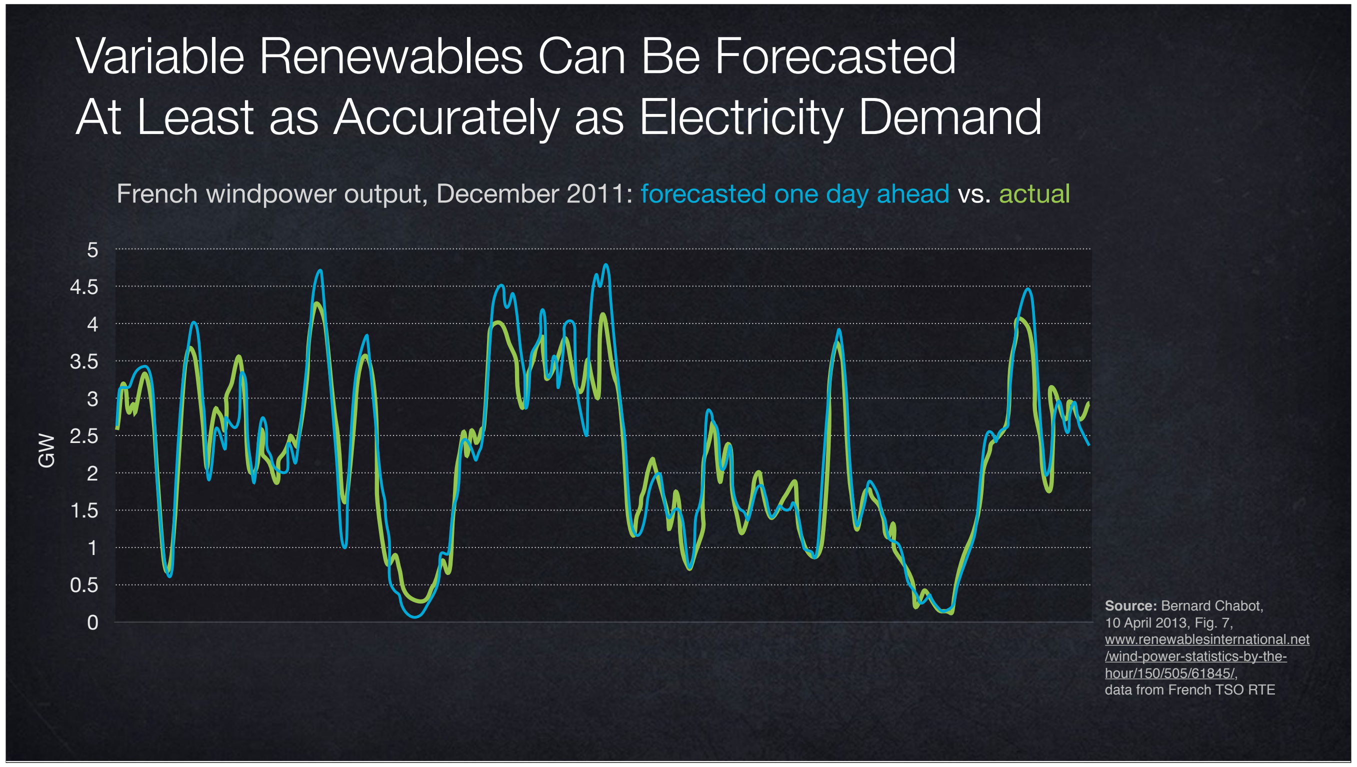
- * renewables and efficiency provide even more low-cost energy;
- * peak needs are met, with significant savings from efficiency and demand flexibility; and
- * storage, efficiency, and demand flexibility provide ramping capacity, including the extra required by the PVs (whose ramping contribution, shown in yellow, is negative).

Clean generators' smart inverters can also readily provide other needed services like voltage and frequency stability and short-circuit duty—faster, better, and cheaper than gas plants can, as California and Australia proved. /

The US already has roughly 100 GW of flexible resources, and they're growing fast. The often-heard argument that we need gas to back up variable renewables is obsolete. More than $100b of proposed new US combined-cycle gas power plants could be stranded [for 2018–30 startup if they replace all retiring thermal capacity and are run at an equivalent capacity factor], plus a half-trillion dollars [$520b undiscounted] of gas-industry investments to fuel them, plus more abroad. This RMI analysis got strong attention in capital markets and has undercut arguments for new gas pipelines. Its 2019–21 updates strengthen the argument. *



Yet we’re still told that only coal, gas, and nuclear stations can keep the lights on, because they’re “24/7,” while windpower and PVs are “variable” and hence unreliable. *

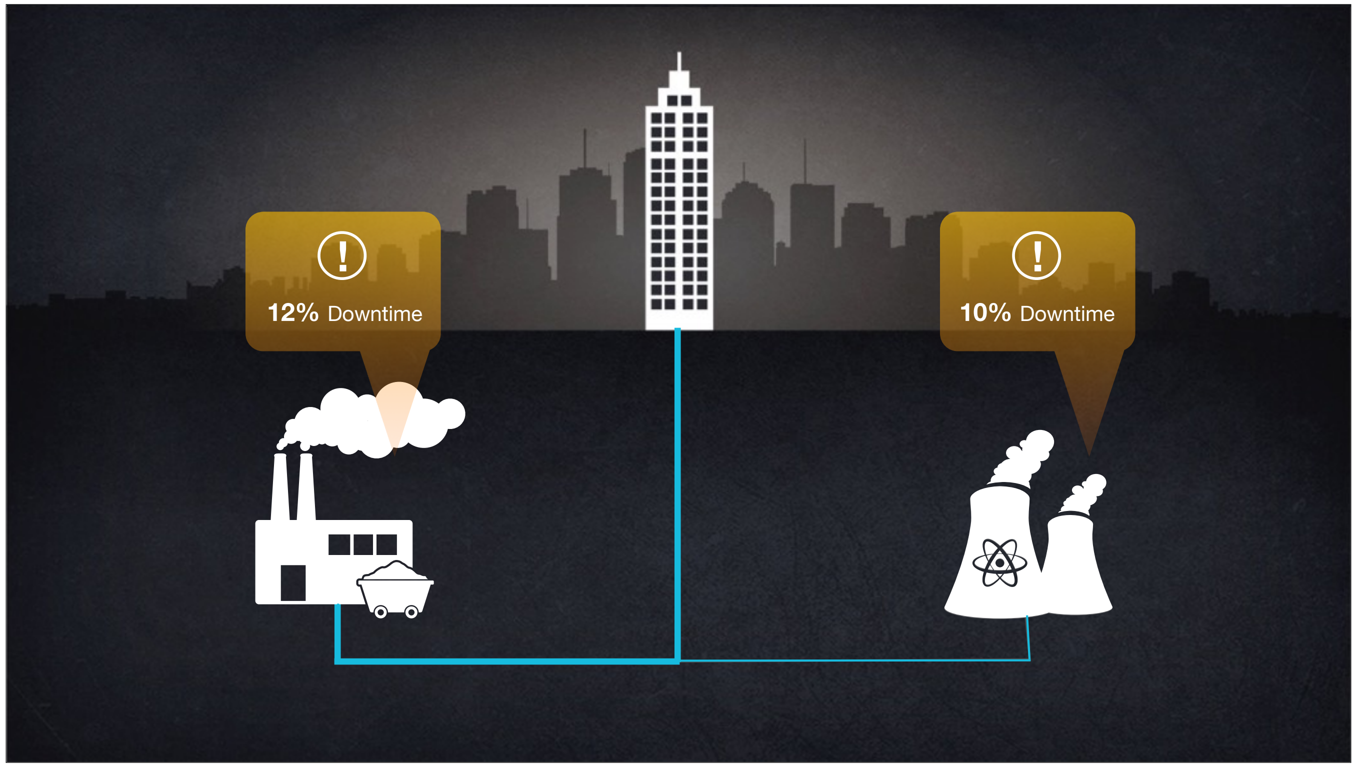


Variable Renewables Can Be Forecasted At Least as Accurately as Electricity Demand

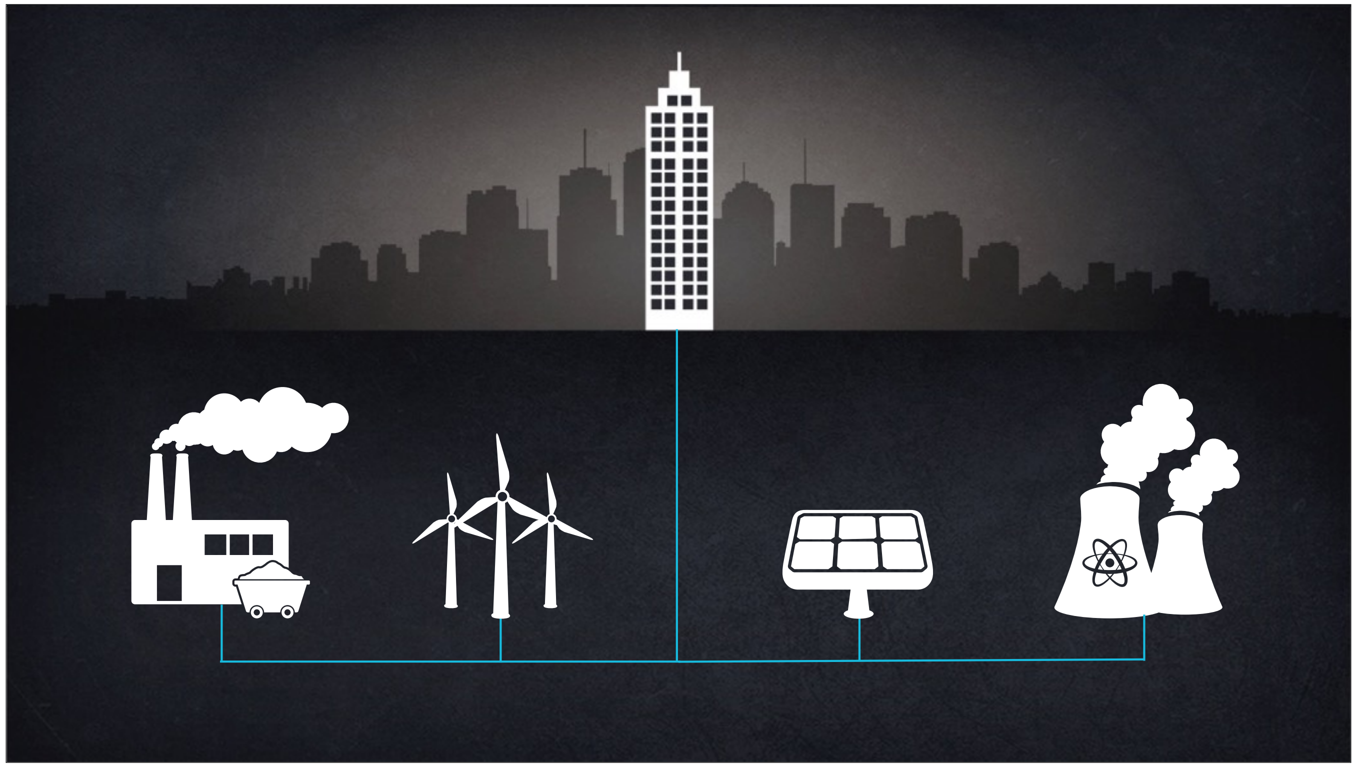
French windpower output, December 2011: forecasted one day ahead vs. actual

Source: Bernard Chabot,
10 April 2013, Fig. 7,
www.renewablesinternational.net/wind-power-statistics-by-the-hour/150/505/61845/,
data from French TSO RTE

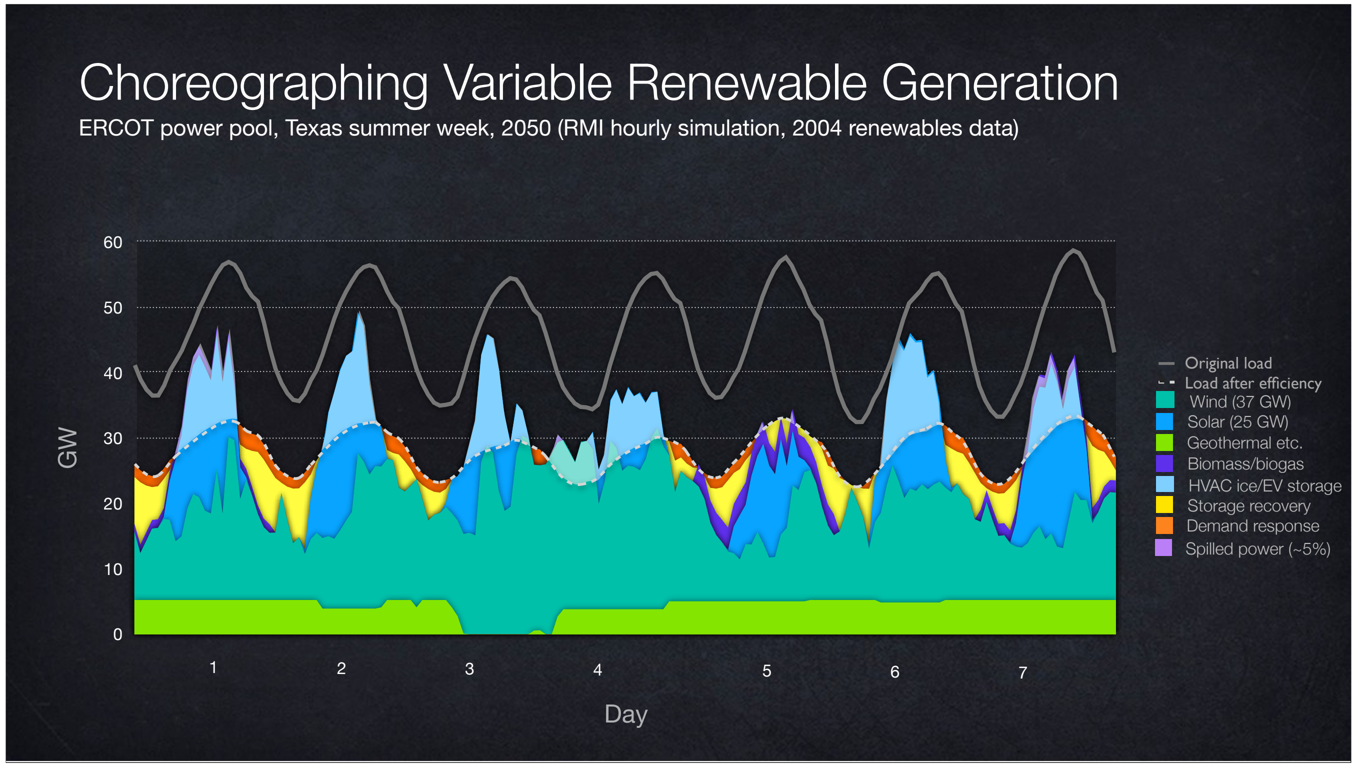
But “variable” doesn’t mean “unpredictable.” Here’s how accurately the French grid operator in one stormy winter month a decade ago * forecast a day ahead the * output of the country’s windfarms. They’d do well to forecast demand that accurately! And forecasting has since improved so much that East Danish wind operators bid day-ahead windpower into the grid’s hourly auction for balancing reserves, [bidding both upward and downward regulation] just as confidently and reliably as fossil-fueled generators do. *



Indeed, we *built* the grid *because no* generator is 24/7. Giant * plants fail too, losing * a billion watts in milliseconds, often abruptly and for weeks or months. * Grids manage this intermittence by backing up failed plants with working plants, * and in exactly the same way, but often at lower cost, grids can manage the forecastable variations of solar and windpower…. *



…by backing up those variable renewables with a portfolio of other renewables, all forecasted, integrated, and diversified by type and location. So in Texas... *

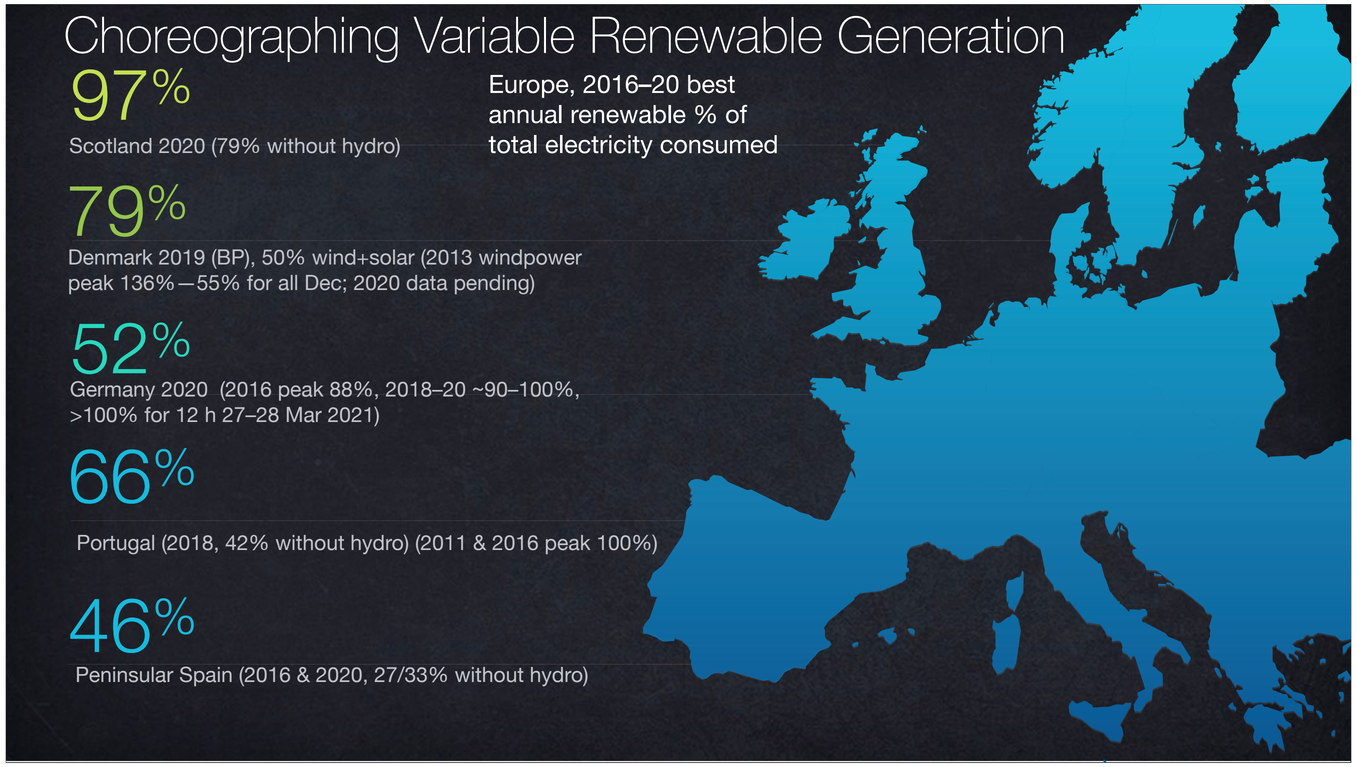


Choreographing Variable Renewable Generation

ERCOT power pool, Texas summer week, 2050 (RMI hourly simulation, 2004 renewables data)

...whose * grid has no big hydro dams and is only 1% interconnected to the rest of the United States, a 2050 summer week's expected loads can get much * smaller and less peaky with efficient use. Then we can make 86% of the annual electricity with * wind and * PVs, and 14% from * *dispatchable* renewables—geothermal, small hydro, solar-thermal-electric, burning ag and municipal and industrial wastes, * burning feedlot biogas in existing gas turbines, burning obsolete energy studies. (Of Germany's 2020 renewable electricity, 30% was dispatchable.) This 100% renewable Texas supply can then match the load by putting surplus electricity into * two kinds of distributed storage that are worth buying anyway—ice-storage air-conditioning and smart charging of electric autos—then * recovering that energy when needed, and * filling the last gaps with unobtrusively flexible demand. * Only ~5% of the annual renewable output is left over, so the economics should be excellent even at today's market prices, let alone lower future prices. *

(An easier-to-understand animation of this graph is at https://www.youtube.com/watch?v=MsgrahFln0s. That 2014 video's data on various countries' renewable shares is updated through 2020 in the following slide; further data will be published throughout 2021.)



Choreographing Variable Renewable Generation

Europe, 2016–20 best annual renewable % of total electricity consumed

97%
Scotland 2020 (79% without hydro)

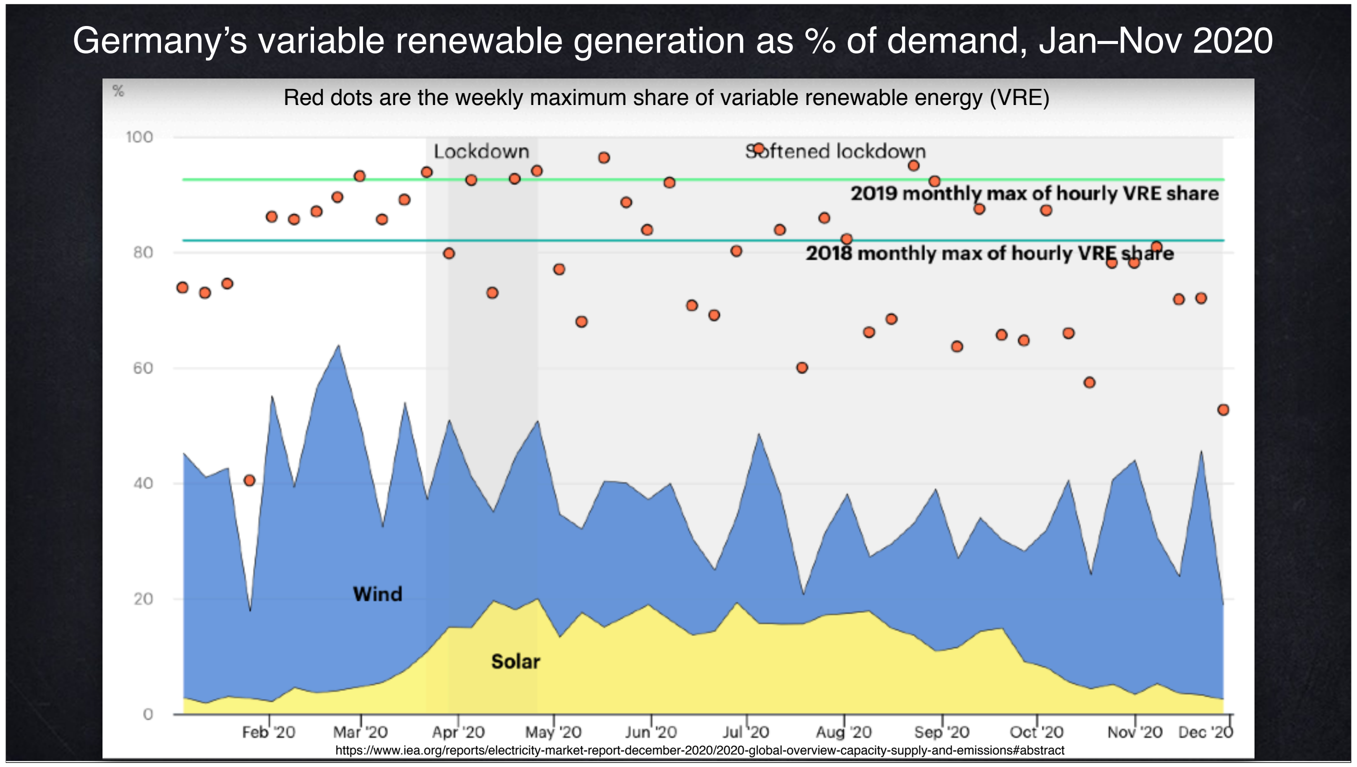
79%
Denmark 2019 (BP), 50% wind+solar (2013 windpower peak 136%—55% for all Dec; 2020 data pending)

52%
Germany 2020 (2016 peak 88%, 2018–20 ~90–100%, >100% for 12 h 27–28 Mar 2021)

66%
Portugal (2018, 42% without hydro) (2011 & 2016 peak 100%)

46%
Peninsular Spain (2016 & 2020, 27/33% without hydro)

Some grid operators do such choreography today. * Germany and Britain are half renewably powered [UK 47%, Germany 52%, both 2020; Italy over one-third, Ireland (2018) and France (2019) one-third]; the whole EU was 38% renewably powered in 2020, surpassing fossil-fueled as well as nuclear generation. * Denmark expects to be 86% renewably powered by this year [2021], and Scotland 100%, both mostly windpowered. Already, they and some other * European countries with * modest or no hydropower meet about * *half to three-fourths or more* of their electricity needs from renewables, adding no bulk storage and with superior reliability—for Denmark and Germany, ~20–25× US reliability. The ultrareliable former East German utility 50Hertz was 60% wind- and solar-powered in 2019, and, says its CEO, could do 60–70% without adding bulk storage; now it targets 100% renewables, all reliably integrated, by 2032. So as my colleague Clay Stranger says, the operators have learned to run these grids the way a conductor leads a symphony orchestra: no instrument plays all the time, * but the ensemble continuously makes beautiful music. *



Germany’s variable renewable generation as % of demand, Jan–Nov 2020

Red dots are the weekly maximum share of variable renewable energy (VRE)

https://www.iea.org/reports/electricity-market-report-december-2020/2020-global-overview-capacity-supply-and-emissions#abstract

In 2020, the maximum percentage of Germany’s electricity demand met by variable renewables (photovoltaics plus windpower) was over half in almost every week, and in about half the weeks reached from 80% to nearly 100%. Nuclear and coal phaseouts (slide 6) continued. The lights stayed on. *

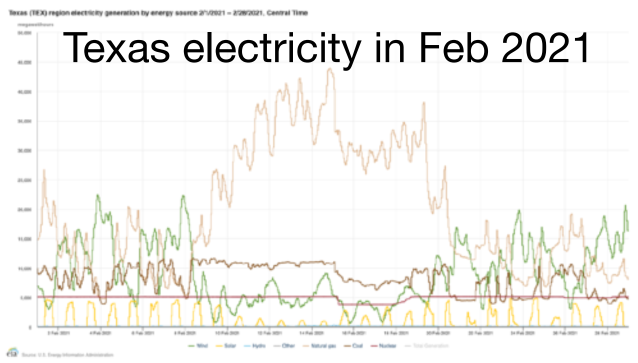
The Texas Power Freeze: First Impressions

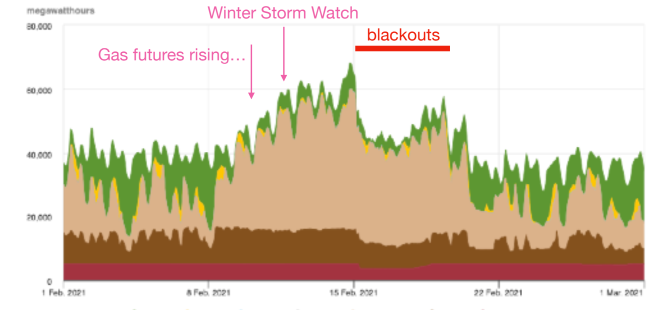
Demand, renewables, interdependencies, and institutions

Amory B. Lovins (www.rmi.org, ablovins@stanford.edu), 9 March 2021, Rutgers Center for Research in Regulated Industries webinar

The full video of the two-hour CRRI webinar is at https://www.youtube.com/watch?v=XZDabDE4-do.
A valuable new analysis by Chris Clack (VCE) is at https://www.vibrantcleanenergy.com/wp-content/uploads/2021/03/VCE-ERCOT-StormUri.pdf.

Texas electricity in Feb 2021





Texas (TEX) region electricity generation by energy source 2/1/2021 – 2/28/2021, Central Time

Source: U.S. Energy Information Administration

https://www.eia.gov/beta/electricity/gridmonitor/expanded-view/custom/pending/GenerationByEnergySource-9/edit

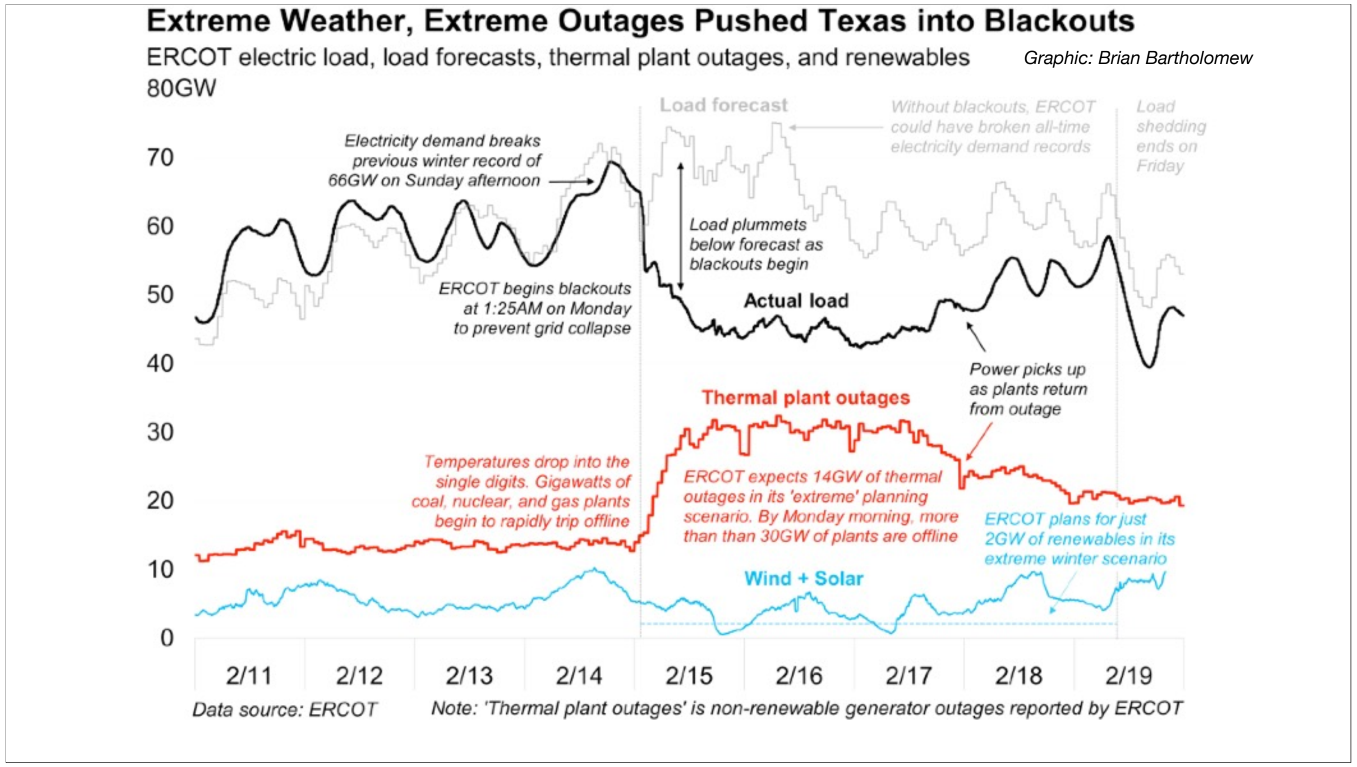
Supply story:

- 1–9 Feb: robust wind (green) and sun (yellow) displaced gas (light brown) and coal (dark brown) whenever available; then warning signals
- 10–14 Feb: ice-storm/cold cut wind, surged gas
- 15–19 Feb: severe weather cut wind output 1 GW below expectation, thermal 21 GW; grid collapse barely averted by blacking out millions for days
- 20–28 Feb: conditions returned to near-normal; years or decades of disputes and recovery began

Demand story:

- Severe (but not worst-ever) cold added ~35.3 GW of peak *heating* load: nearly twice 20-GW max load-shedding or 17.4-GW max gas-fired outages, more than 21-GW total shortfall, almost half total demand
- Cause: inefficient housing/building stock + ~65% electric heat (~80% in new houses)—a menace to occupants' safety and to all Texans' energy supply
- Customer response not properly informed/engaged
- Institutions focused on supply and summer

These graphs show in two styles last month's Texas electricity supply. Early and late February had normal operation, with wind (green) and solar (yellow), whenever available, displacing gas (light brown) and coal (dark brown). But mid-month brought * four days of blackouts—perhaps the costliest disaster ever to hit Texas. Most analyses focus on the supply side: * how two February storms strained, then shriveled, Texas's bountiful gas supply by freezing unwinterized infrastructure, while many electric generators also froze. Gas-plant output fell 17 GW, coal 4, nuclear 1 (just missing 3 more), becalmed and frozen wind 13, and snow-covered solar 1. But the resulting 34-GW coincident generating shortfall, 21 of it thermal, exposed technical, institutional, and governance flaws that mattered only because of a huge *demand* event. * Intense cold boosted normal loads by an estimated *35 GW* of peak *electric heating* load. That's nearly twice the maximum load ERCOT shed, twice the lost gas-fired generation, more than the total shortfall in supply, and nearly half the 77-GW total peak demand that if met would have been 2 GW over the summer record. These vast heating loads came from an often-inefficient building stock (half housing) heated mainly by electricity. In extreme weather, this fragile combination risks hypothermia or heatstroke, and endangers electricity and gas supplies. / Two-thirds of Texas homes were built before there was a state building code. Half have big air leaks and little or no wall insulation, limited attic insulation, and single glazing. / The blackouts could have been abated if not averted by asking Texans the day before to turn thermostats and water-heaters down and appliances off, drain their pipes into containers, leave those out to freeze, then put them back into unplugged refrigerators and freezers to preserve food. But customers were only asked—late, vaguely, ineffectually—to "conserve energy," so they didn't know how to help, nor that they held the power in their hands. Despite days of advance notice from weather forecasters and gas markets, supply- and summer-focused state institutions were unprepared to sustain interlocked supplies or tell retail customers how to mobilize a decisive behavioral rapid response. Instead, leaders blamed each other and scapegoated renewables. So how did those perform? Let's return to Alison's third slide…*



Extreme Weather, Extreme Outages Pushed Texas into Blackouts

ERCOT electric load, load forecasts, thermal plant outages, and renewables

Graphic: Brian Bartholomew

Electricity demand breaks previous winter record of 66GW on Sunday afternoon

ERCOT begins blackouts at 1:25AM on Monday to prevent grid collapse

Load plummets below forecast as blackouts begin

Without blackouts, ERCOT could have broken all-time electricity demand records

Load shedding ends on Friday

Power picks up as plants return from outage

Temperatures drop into the single digits. Gigawatts of coal, nuclear, and gas plants begin to rapidly trip offline

ERCOT expects 14GW of thermal outages in its 'extreme' planning scenario. By Monday morning, more than than 30GW of plants are offline

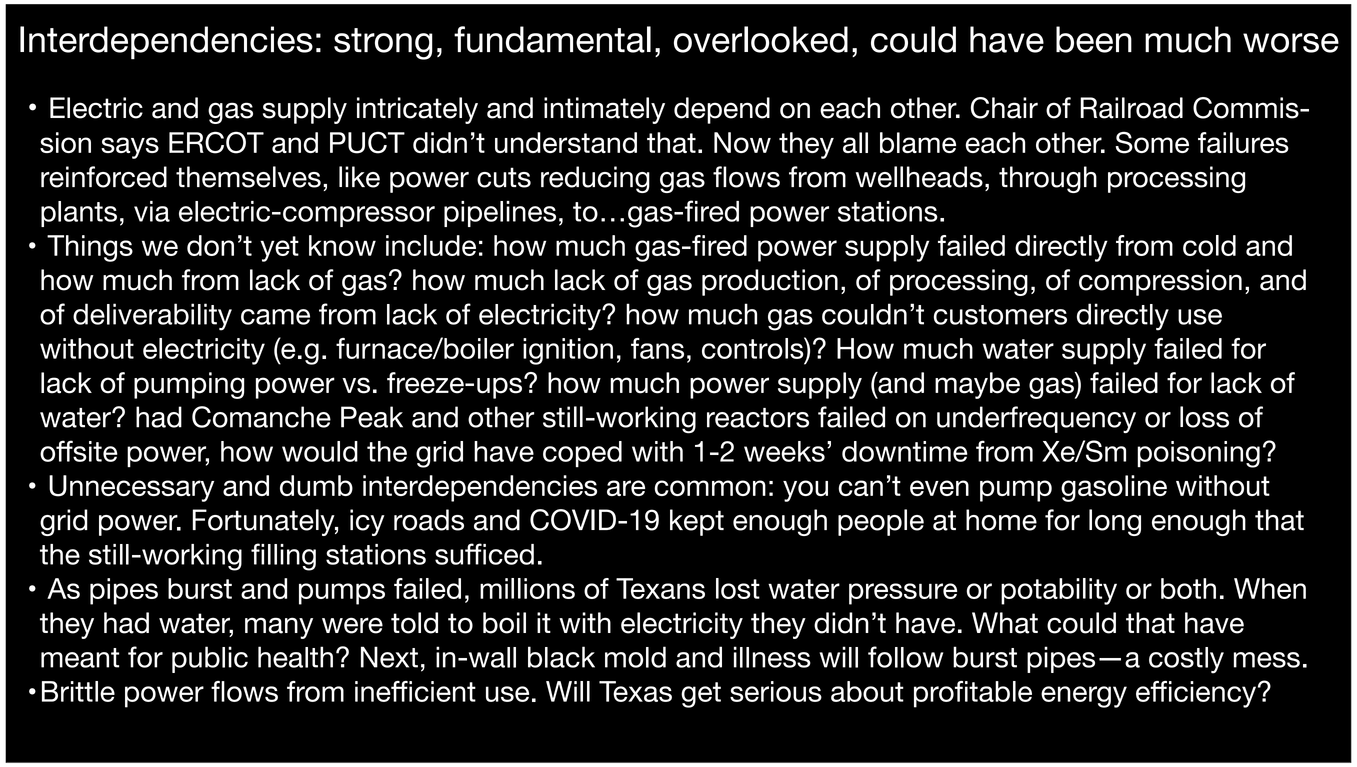
ERCOT plans for just 2GW of renewables in its extreme winter scenario

Data source: ERCOT

Note: 'Thermal plant outages' is non-renewable generator outages reported by ERCOT

[Grid collapse could have persisted for months or more, with incalculable social and economic costs to Texas, the nation, and global markets. That calamity was averted by a few minutes, but at the cost of scores of deaths and vast suffering. Unserved Texas electric energy demand on 15–16 Feb (says IEA) totaled >500× California's scorned load-shed last summer—not counting February's 15 GW of load cuts in 9+ states of the adjacent SPP and MISO power pools, plus nearly 5 million customers in northern Mexico. /]

Wind and solar were initially blamed—128x by Fox News in two days—for triggering the Texas disaster. So was the Green New Deal, not yet adopted anywhere. Yet the aqua line at the bottom shows how wind and solar power actually met ERCOT's 2.1-GW extreme-winter-peak average expectation for all but ten hours, constrained much more by expected and actual low windspeeds than by freezing, but overperforming throughout the rest of the blackout week. Meanwhile, the red curve shows that operable thermal capacity fell from 70 to 45 GW in a few hours—a far larger unpredicted failure. ERCOT initially reported 16–18 GW of wind "outage," later revised to 13, but that only meant production below full nameplate rating. February is normally a low-wind month, so ERCOT's forecast included only 7.1 average GW of windpower, or 1.8 GW in the extreme winter-peak forecast, plus 0.3 GW solar, so renewables actually underperformed contingency expectations *by at most 1.4 GW for one hour 18 hours into the outage, while >30 GW of thermal capacity was down*. The *Wall Street Journal*'s five editorials didn't get this >20x difference. Of course, winterizing the wind turbines could have been a smart investment to earn astronomical prices in the 80-hour crisis, but would have added only a few GW when most needed [Chris Clack's newer analysis cited on slide 52 says a bit more], because, as expected, winds were light. Meanwhile, under 6–8" of snow, shallow-pitched Austin solar panels produced ~60% less on 15–16 Feb, then rebounded; ERCOT solar produced 2–3 GW on 15–18 Feb, then 4–5 the next week while wind returned to a robust 12–20 GW. So look who was most resilient! / Finally, how did these systems interact? *



Interdependencies: strong, fundamental, overlooked, could have been much worse

- Electric and gas supply intricately and intimately depend on each other. Chair of Railroad Commission says ERCOT and PUCT didn’t understand that. Now they all blame each other. Some failures reinforced themselves, like power cuts reducing gas flows from wellheads, through processing plants, via electric-compressor pipelines, to…gas-fired power stations.
- Things we don’t yet know include: how much gas-fired power supply failed directly from cold and how much from lack of gas? how much lack of gas production, of processing, of compression, and of deliverability came from lack of electricity? how much gas couldn’t customers directly use without electricity (e.g. furnace/boiler ignition, fans, controls)? How much water supply failed for lack of pumping power vs. freeze-ups? how much power supply (and maybe gas) failed for lack of water? had Comanche Peak and other still-working reactors failed on underfrequency or loss of offsite power, how would the grid have coped with 1-2 weeks’ downtime from Xe/Sm poisoning?
- Unnecessary and dumb interdependencies are common: you can’t even pump gasoline without grid power. Fortunately, icy roads and COVID-19 kept enough people at home for long enough that the still-working filling stations sufficed.
- As pipes burst and pumps failed, millions of Texans lost water pressure or potability or both. When they had water, many were told to boil it with electricity they didn’t have. What could that have meant for public health? Next, in-wall black mold and illness will follow burst pipes—a costly mess.
- Brittle power flows from inefficient use. Will Texas get serious about profitable energy efficiency?

Strong interconnections between complex systems made this event severe and could well have made it catastrophic. We’ll see more and worse cascading failures if we don’t grasp these linkages. * Most obviously, *gas, electricity, and water all depend on each other*. It’s unclear if Texas regulators understood this—especially if managing interactions means actually regulating when markets fail. * We’ve don’t yet know, for example, how much gas-fired power supply failed directly from cold and how much from lack of gas? how much gas production, processing, compression, and deliverability were cut by lack of electricity? how much gas customers couldn’t directly use without electricity (e.g. furnace/boiler ignition, fans, controls)? how much water supply failed for lack of pumping power vs. freeze-ups? how much power supply (and maybe gas) failed for lack of water? or if Comanche Peak and the other still-working reactors had failed on underfrequency or loss of offsite power, how would the grid have coped with 1–2 weeks’ downtime, as nine Northeastern reactors in 2003 took two weeks to regain 8 lost GW and a few days to regain any? * Texans were also lucky not to have been immobilized by failed filling-station pumps that now foolishly and needlessly depend on grid power. Absent icy roads and pandemic, that immobility would have paralyzed action within a few days. That added a week or two to recovery after recent major storms further north, because first responders and genset owners couldn’t pump fuel. Every grid-powered filling station should untangle pump wiring from the convenience store and pump with battery-backed solar power. * There’s also a long tail of potential public-health consequences from drinking bad water, and in the months and years to come, illness and huge, often uninsured costs from immune-suppressing black mold inside walls soaked by burst pipes. * And most fundamentally, this disaster was caused as much by inefficient electrically-heated houses as it was caused by failed gas supplies and power plants. So when will Texas seriously consider and exploit its immense energy efficiency opportunities, and compare and compete them against supply-side resources? *