Metric and method for comparing investments to decarbonize the electricity system

A Rocky Mountain Institute occasional paper

24 September 2019, www.rmi.org/decarb

Amory B. Lovins (corresponding author)
Cofounder and Chairman Emeritus
c/o Rocky Mountain Institute
22830 Two Rivers Road
Basalt, CO 81621, United States
ablovins@rmi.org, +1 970 927 3129

and

Titiaan Palazzi
(Rocky Mountain Institute 2014–18)
titiaan.palazzi@gmail.com, (970) 930-5350

Introduction

Effective climate protection requires judicious, not indiscriminate, investment to save the most carbon per dollar and per year—tracking not only carbon but also cost and speed. This paper proposes a Climate Effectiveness metric focusing on relative cost—carbon (in the form of CO_2) avoided per dollar spent—and briefly summarizes empirical evidence on relative speed.

We present a transparent, flexible, and rigorous method for comparing different investments to displace coal-fired power plants, which produce ~38% of the world's electricity. Our approach can be adapted to compare any resources (not only to coal plants), anywhere, for any type of emissions. The data, location, and options to be compared can be easily changed from our illustrative base case. This comparison shows that if a new combined-cycle power plant (CCGT)—burning natural gas that costs \$6/GJ or /million BTU and is 3% emitted[1]—has a Climate Effectiveness Index (CEI) of 1.0, then a new nuclear power plant has a CEI ~0.5–1.1; unsubsidized utility-scale photovoltaics or onshore windpower ~2; new cogeneration roughly 1–5; and using electricity more efficiently about 30–150. An international analysis simultaneously published elsewhere[2] shows that such efficiency costs severalfold less than just *operating* most existing nuclear power plants, so closing such economically-distressed plants and reinvesting their saved operating cost in efficiency could save more carbon than continuing to run them.

This analysis applies the bedrock economic concept of *opportunity cost*—an outcome foregone because one investment is made instead of another. You cannot spend the same dollar on two different things at the same time, so each choice excludes other choices and outcomes. Thus if you buy a kilowatt-hour (kWh) of retail electricity generated without releasing fossil carbon, say at a price of nine cents, and use it to displace a kWh generated by burning coal, its accounting cost to you is nine cents. But if you could instead have *saved* three kWh of coal-fired electricity for three cents each (a typical-to-high cost for electricity providers' efficiency programs), then the *opportunity* cost of buying the zero-carbon kWh for nine cents, instead of three kWh of savings for a total of nine cents, is that two kWh of coal-fired electricity were unnecessarily generated, releasing carbon that wouldn't have been released if you had bought the cheaper efficiency instead. Displacing coal-fired electricity by any means that costs more or takes longer than it could have done will burn more coal and release more carbon than it should have done.[3] Decades of efforts to point this out[4,5,6,7,8,9] have received little attention or response, since nuclear-power advocates are eager that this point not be understood. However, ref. 2 may at last help get it properly considered. This paper is a brief practical guide to applying it.

This approach will yield better results than the common but flawed two-step decision process of first considering a subset of options (typically carbon-free ways to generate electricity) and then selecting the least costly. That approach can omit important options, such as efficient end-use, or cogeneration of electricity plus useful heat; it can also choose an option that is carbon-free but unnecessarily costly, saving less carbon per dollar than other options not considered (typically efficiency). Avoiding such mistakes requires a direct metric of "Climate Effectiveness" ($kgCO_2$ saved/\$) that combines carbon intensity ($kgCO_2/kWh$) with the retail customer's cost of electricity (\$/kWh) or the service it provides. This combination reunites cost-based technology choices with their climate implications, revealing opportunity costs that considering just one of those parameters inevitably hides.

Such a combined metric exists: the reciprocal of our metric is one-thousandth of \$/tC (metric ton of elemental carbon, which weighs 27% as much as the carbon dioxide containing it). McKinsey and Company pioneered that metric in its 2007– supply curves showing how much carbon can be abated at what cost in various sectors and geographies. However, those costs are opaque, incomplete, and outdated, so few decisionmakers rely on them. We therefore use high-quality, transparent, up-to-date, easily updateable data, based on observed market prices that reflect actual investor risks and business models. Rather than relying on outdated historic data or on complex projective models, we use the latest (generally 2018) empirical price data from the United States, where technologies are mature, market mechanisms well developed, and data independently published.[10]

Without assuming any future price trends, which would generally strengthen the case, a decisionmaker wanting to replace a kWh of coal-fired electricity can thus see how much carbon each alternative investment will save per dollar spent to buy it. Such comparisons reveal solutions severalfold to >50-fold more climate-effective than many options now being bought based on misleading metrics or on non-economic considerations.[11] Carbon-free substitutes—nuclear, renewables, efficiency—all save directly the same amount of carbon per kWh of coal power displaced, so they would all be equally advantaged by pricing carbon (and cogeneration partly so). But these substitutes are not all equally climate-*effective,* because they have different costs (and perhaps speeds). Cheaper options save more carbon *per dollar spent.* That matters too.

Main investment choices to displace coal-fired power plants

Using electricity more efficiently accounted for most (all except structural change) of the savings that cut the 30 International Energy Agency member nations' 2010–17 electricity demand growth by more than four-fifths, from 1.6 to 0.3%/y, and shrank electricity demand for 18 of those nations.[12] U.S. electricity demand flattened a decade ago[13], about a decade later than primary energy demand, leaving a larger overhang of unbought efficiency[14]; yet three-fourths of U.S. 2010 electricity use could still be saved at an average cost roughly one-tenth the price of retail electricity.[15] Cumulative U.S. energy savings in all forms during 1975–18 were 30 times as large as the cumulative increase in U.S. renewable energy supplies—yet their headline ratio is the opposite, because renewables are visible, but energy is invisible, and unused energy is almost unimaginable. No wonder most assessments of ways to displace coal-fired electricity examine only other kinds of *generators*, not the *savings* that are far cheaper than either. Yet any sensible comparison will include and symmetrically compete both demand- *and* supply-side resources.

On the supply side, rapidly falling prices, cheaper finance, and improving performance let modern renewables (*i.e.* excluding big hydro) capture 68% of the 2018 global market for net additions of generating capacity, or 75% if big hydro were included.[16] Those net additions during 2010–19 were greater for solar than for coal power and greater for windpower than for gas power.[17] Of the net additions in 2018, 96% of modern and 85% of total renewable capacity was solar photovoltaics (PV) and windpower. We therefore emphasize those two options and omit the other types of renewable generators that added 9 net GW in 2018—geothermal, waste-burning, solar-thermal-electric, and small-hydro, tidal, and wave energy.[18] However, we do consider building-scale and industrial-waste-heat cogeneration, illustrating that even options that emit some CO_2 may be worth considering alongside options that emit none.

For simplicity and transparency, our model doesn't directly support comparisons between portfolios that combine more than one kind of technology, especially if they interact. However, such combinations often work better and cost less than single technologies, and can be deployed with greater speed and confidence via a more-diversified portfolio of methods and risks. In general, if multiple single technologies are each more climate-effective than a given alternative, they will probably become even more advantageous when combined with each other. The advantages may include complementarity—for example, solar and windpower are often available at different times—and use of otherwise wasted resources, such as surplus industrial heat that operators currently pay to throw away.

This paper expresses all monetary values in levelized form (using real discount rates around 5%/y) and in 2018 U.S. dollars, with supply- and demand-side costs directly comparable.

Step-by-step calculation

Our analysis simply divides

the amount of carbon [dioxide] avoided by displacing each kWh of coal-fired electricity

by

the cost of displacing that kWh with a different resource

to obtain our Climate Effectiveness metric—

carbon [dioxide] saved per dollar spent for that displacement.

For consistency, we compare all resources per kWh delivered to the retail meter. That delivery from remote U.S. power plants incurs average grid losses of 5.1% and an average grid cost of 4.1¢/kWh per kWh delivered[19]—less for large and more small customers. Both these adjustments apply to coal, nuclear, combined-cycle gas, utility-scale PV, and windpower, but not to onsite resources (cogeneration and efficiency), whose power is already delivered. We add 0.5¢/kWh for firming and grid integration costs of PV and windpower[20], but conservatively omit the arguably larger corresponding costs of fossil-fueled and nuclear power plants (see "Spurious Arguments" section below).

This calculation needs two inputs. First, we need to know how much carbon is avoided when a kWh of coal-fired electricity is replaced by a kWh generated or saved by some other resource. Avoided carbon equals the carbon emitted by generating a kW-h from coal (currently averaging ~1.053 $kgCO_2$ in the U.S.—over twice the 0.45 $kgCO_2/kWh$ national average for all generation[21]—but varying widely between different power plants, types of coal, and countries), minus any carbon emitted by the substitute resource. We conservatively neglect all sources' indirect emissions[22], which are small for renewables (except hydropower due to the rotting of flooded vegetation) and for nuclear (assuming today's uranium ores and enrichment methods). Also conservatively, we omit the methane emitted by the coal fuel cycle, which IPPC's global-average evidence suggests[23] may raise pulverized-coal plants' average climate effects by ~7%. Direct greenhouse-gas emissions are negligible for nuclear, renewables, and efficiency. A typical new U.S. gas-fired CCGT emits ~0.36 $kGCO_2$ per kWh generated, plus ~0.1 $kgCO_2$-equivalent for each 1% of burned methane that previously escaped from the upstream gas supply system. Cogeneration calculations are more complex because costs and emissions (including any escaping methane) must be allocated between the joint production of electricity and of useful heat, so rather than detailing them here, we assume typical values.

Second, we need to know the costs of competing alternative resources. Locally specific data are best, but lacking them, you can use sound *and up-to-date* regional or national averages. The latest authoritative assessment by the 170-year-old financial firm Lazard[24] shows the following 2018-$ ¢/kWh cost ranges for electricity sent out to the grid from new U.S. power plants ordered in 2018, without tax credits for solar and windpower but tacitly retaining all the generally larger permanent subsidies to fossil-fueled and nuclear[25] plants and their fuel cycles:

- Coal: 6.0–14.3, of which 2.7–4.5 (average 3.6) ¢/kWh is operating cost
- Nuclear: 11.2–18.9, of which 2.4–3.1 (average 2.8) ¢/kWh is operating cost (though the Nuclear Energy Institute says[26] this 2018 average operating cost was 3.2¢/kWh)
- Gas combined-cycle: 4.1–7.4 based on a $3.45/million BTU fuel-price forecast; since future fuel prices are unknowable, we assume $4–8/GJ values (1 million BTU = 1.0548 GJ), similar to the range of official forecasts for 2050, yielding a CCGT cost range of 4.6–7.9¢/kWh with $4/GJ gas and 7.2–10.7¢/kWh with $8/GJ gas
- Utility-scale solar (PV): 3.6–4.6
- Onshore windpower: 2.9–5.6

We checked these values against other authoritative sources:

- Lazard's coal-plant range agrees closely with Bloomberg New Energy Finance's 6.4–16.1¢/kWh for recent market transactions. So does gas combined-cycle at BNEF's 3.8–7.6¢/kWh.
- Lazard's nuclear cost range, based on unstated data, is far below BNEF's market-price range of 19.5–34.4¢/kWh. In fairness, though, no new nuclear plant recently completed anywhere has a scrutable, detailed, transparent, and publicly available cost analysis.
- For utility-scale PV, BNEF's subscriber database of offtaker prices (accessed 18 Dec 2018) showed a price range of 2.16–3.0¢/kWh; for onshore windpower, 2.55–3.56¢/kWh. These subsidized prices are below Lazard's unsubsidized price estimates (stated above) by margins consistent with the 2018 market value of both technologies' temporary and

phasing-out U.S. subsidies. Lawrence Berkeley National Laboratory's exhaustive annual assessment of the U.S. long-term fixed prices set by Power Purchase Agreements signed in 2018 shows median subsidized prices of 2.33¢/kWh for utility-scale PV and 1.11¢/kWh for windpower. LBNL also estimates unsubsidized median PV levelized cost in 2018 at 3.9¢/kWh, consistent with Lazard. Solar and windpower prices have continued to fall in 2019, so any estimate more than a year old is too old for valid comparison.

We used other industry data sources for three other alternatives:

- Building-scale gas-fired cogeneration: 6.3–8.2¢/kWh with \$4/GJ gas, 8.7–10.7¢/kWh with \$8/GJ gas (capital cost from MIT's *Future of Natural Gas* study, other parameters from industry experts)
- Industrial cogeneration from recovered waste heat: 3–4¢/kWh (from a leading expert)
- Efficient use of electricity: 1.4–3.2¢/kWh (from three broad, detailed, and independent assessments of U.S. utility programs[27])

Four worked examples

Now, equipped with the needed data, let's illustrate our two-step analysis for four cases:

1. If we're building, say, a new **windfarm** to displace an existing coal plant, then excluding all subsidies to both, we'll pay 2.9 to 5.6¢/kWh for the windpower, plus its assumed 0.5¢/kWh firming cost. We convert those wholesale prices at the power station into retail prices at the meter by adjusting for 5.1% grid loss and adding 4.1¢/kWh delivery cost. Then the windpower costs [(2.9 to 5.6¢/kWh) + 0.5¢/kWh firming cost + 4.1¢/kWh grid cost]/(1–0.051) = \$0.079 to \$0.107 per delivered kWh. This substitution avoids the coal-fired kWh's emission of ~1.053 kg of CO_2. Dividing that avoided emission by its cost—delivered windpower's price range in dollars—the Climate Effectiveness has a range of 1.053 $kgCO_2$/\$0.107 to 1.053 $kgCO_2$/\$0.079, or 9.8–13.3 $kgCO_2$/\$. Windpower's average long-term subsidized market price in 2018 was 1.1¢/kWh, for a Climate Effectiveness of 17.5.
2. If instead we buy a **gas-fired** CCGT, and its gas price over its operating life turns out to be equivalent today ("levelized cost") to \$6/GJ (\$5.69/million BTU), then its delivered cost will be [(5.9 to 9.4¢/kWh) + 4.1¢/kWh]/(1–0.051) = \$0.105 to \$0.14 per delivered kWh. Dividing those costs by the avoided 0.689 $kgCO_2$ (the difference in direct

emissions between a typical coal plant and a typical new combined-cycle gas plant) yields a Climate Effectiveness range of 4.9–6.6. But this assumes the gas supply system has no leaks, flares, engineered vents, or other emitters of the potent greenhouse gas methane. If, for example, 4% of the methane throughput were emitted (a rather high estimate but not implausible with some fracked gas systems), the Climate Effectiveness would be more than halved, and it would fall below zero (worse than a coal plant) at roughly 7% methane emissions. Methane emissions are poorly measured, and many official estimates rest on guesswork, not actual measurements. Non-gas resources avoid the resulting uncertainties and hence climate risks.

3. Replacing the coal plant with a new **nuclear** plant at Lazard's 11.2–18.9¢/kWh would incur a delivered cost around $0.16–0.24/kWh, so the displaced 1.053 kgCO_2 would be achieved with Climate Effectiveness 4.3–6.5. That's slightly less climate-effective than a combined-cycle gas plant, which emits CO_2 (hence saving much less carbon) but costs far less—illustrating the importance of tracking both carbon and dollars. BNEF's market-based 19.5–34.4¢/kWh nuclear cost yields even lower Climate Effectiveness, 2.6–4.2.
4. Replacing the coal plant with **more-efficient use** of electricity costs 0.72–3.2¢/kWh. (Reported utility program costs averaged 1.4–3.2¢/kWh and their biggest and most recent study found an average of 2.3¢, but the 0.72¢/kWh cost included partial integrative design and corresponded, if fully adopted, to quadrupled U.S. electric end-use efficiency—equivalent to nearly four times U.S. nuclear output.). There is no firming or delivery cost nor grid loss. Climate Effectiveness is thus 1.053 kgCO_2/($0.0072 to $0.032) or 33–146, or for the 2.3¢/kWh average cost, 46.

Climate opportunity cost

The third and fourth of these examples shows that efficiency, at the average utility program cost (2.3¢/kWh), is about 7–18 times less costly at the meter than a new nuclear power plant (after adjusting for the nuclear plant's average 4.1¢/kWh delivery cost and 5.1% grid loss). NEI's 3.2¢/kWh NEI average operating cost and its third- and fourth-quartile 2014–16 average operating costs of 4.2 and 5.3¢/kWh, adjusted for delivery cost and loss, and all including zero cost for original construction or financing, makes nuclear operation cost respectively 3.3, 3.6, and 4.1 times the average efficiency cost that U.S. utilities recently paid. Thus, as ref. 2 explains, closing those distressed nuclear plants and reinvesting their saved operating cost (let alone any avoided subsidies) in efficiency would save far more carbon than continuing to run them. Even new unsubsidized onshore windpower in favorable areas, or market-priced (currently subsidized) new wind or solar in most areas, would be more climate-effective than operating most existing nuclear plants. Those who believe continued nuclear operations help protect the climate are therefore counting carbon but not dollars. Climate-effective investment requires counting both.

Such comparisons don't include the avoided operating cost of the displaced coal plant, because that term equally benefits all alternatives and therefore would presumably not change their relative value. However, avoided coal-plant operating costs add to the total societal value that the substitution creates. Our method includes all operating costs for all alternatives, though operating costs are nearly zero for efficiency and renewables, small for industrial cogeneration from recovered waste heat, and around or above coal operating costs only for nuclear.

Our method can be easily adapted to comparing any other resources and emissions.

Spurious arguments

Many advocates claim that certain un- or underpriced attributes of coal-fired, nuclear, and sometimes gas-fired power plants give them special value meriting preferential choice, operation, or pricing. Reference 9 comprehensively rebuts such claims and specific ones based on cost[28], scaling rate[29], grid stability[30], or other rationales.[31,32] The current U.S. Secretary of Energy's novel claim of resilience benefits was disproven by testimony[33] to the Federal Energy Regulatory Commission, which later unanimously rejected the Secretary's view.

The common claim (and still the official position of the U.K. government) of an "absolute" nuclear-power requirement to overcome the supposedly insuperable "intermittence" of variable renewables (PVs and windpower) reflects a common misunderstanding of how grids work.[34,35] In brief, one generator does not serve one load; rather, a portfolio of generators collectively serves the grid, which then serves all loads, so any failed generator is instantly backed up by all the rest. This 19th-century grid concept, now updated with telecommunications, fast power electronics, and digital grid management, works well regardless of whether generators are large or small, renewable or not, and variable or steady. Because modern renewable portfolios are more distributed, granular, and diversified, they tend to have lower backup requirements and costs than lumpy central thermal stations. The concept of “intermittence” is thus best applied to those plants’ awkward and unpredictable forced outages.

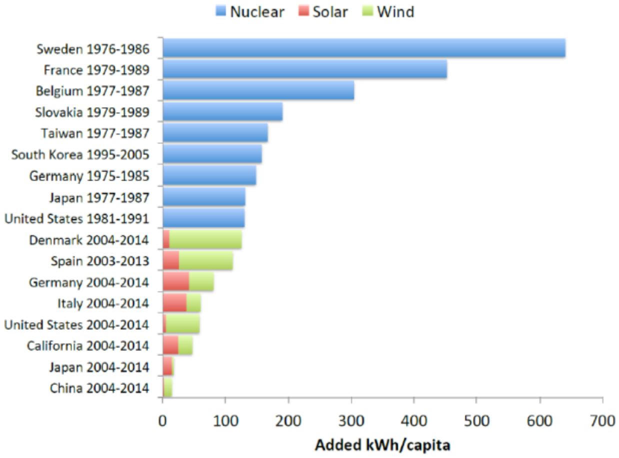
Although bulk storage of electricity is currently the costliest of ten kinds of grid flexibility resources (ref. 34) and is not needed even for 100%-renewable power supply of the isolated, hydro-free grid of Texas[36], it is becoming cheaper and is already gaining a prominent place in electricity investments. For example, a new analysis of all 68 GW of gas-fired combined-cycle power plants proposed to be built in the U.S. found that 90% by 2035 and 100% by 2040 couldn’t compete with “clean portfolios” combining PVs, windpower, demand-side management, and storage.[37] To avoid this risk of prestranded assets, portfolio purchases are already displacing replacing new combined-cycle gas plants with PVs, wind, and storage even in such gas-rich and climate-skeptical markets as Oklahoma.

Some economic theorists suggest that a snapshot of current renewable prices understates long-term prices at the very large quantities needed to stabilize climate, because the best sites and some critical resources will become scarcer, and theory says higher quantity raises price (“supply curves slope upwards”). In fact, suitable solar and wind resources are so enormously larger than conceivable human needs, and critical resources are so substitutable and abundant[38] (their price indeed crashed soon after the rare-earths stock-hyping scare), that these arguments lack foundation. For example, the windpower advances achieved just during 2012–18 more than offset the slight upturn in U.S. onshore windpower prices calculated by the U.S. Department of Energy for 2012 turbines if their output grows to more than four times today’s total electricity production. In other words, the best available official analysis, engineering evidence, and commercial experience show that contrary to traditional economic theory, renewable quantities sufficient to serve all long-term electricity demand many times over come with falling real costs, because a few years’ technical advances routinely exceed decades of predicted “depletion.” This behavior is not true of all technologies: from first commercial use to today, real nuclear power costs rose by severalfold but fell about a thousandfold for PVs, because of different fundamental processes. Similar increasing returns also apply to modern electric efficiency, even in very large quantities.[39]

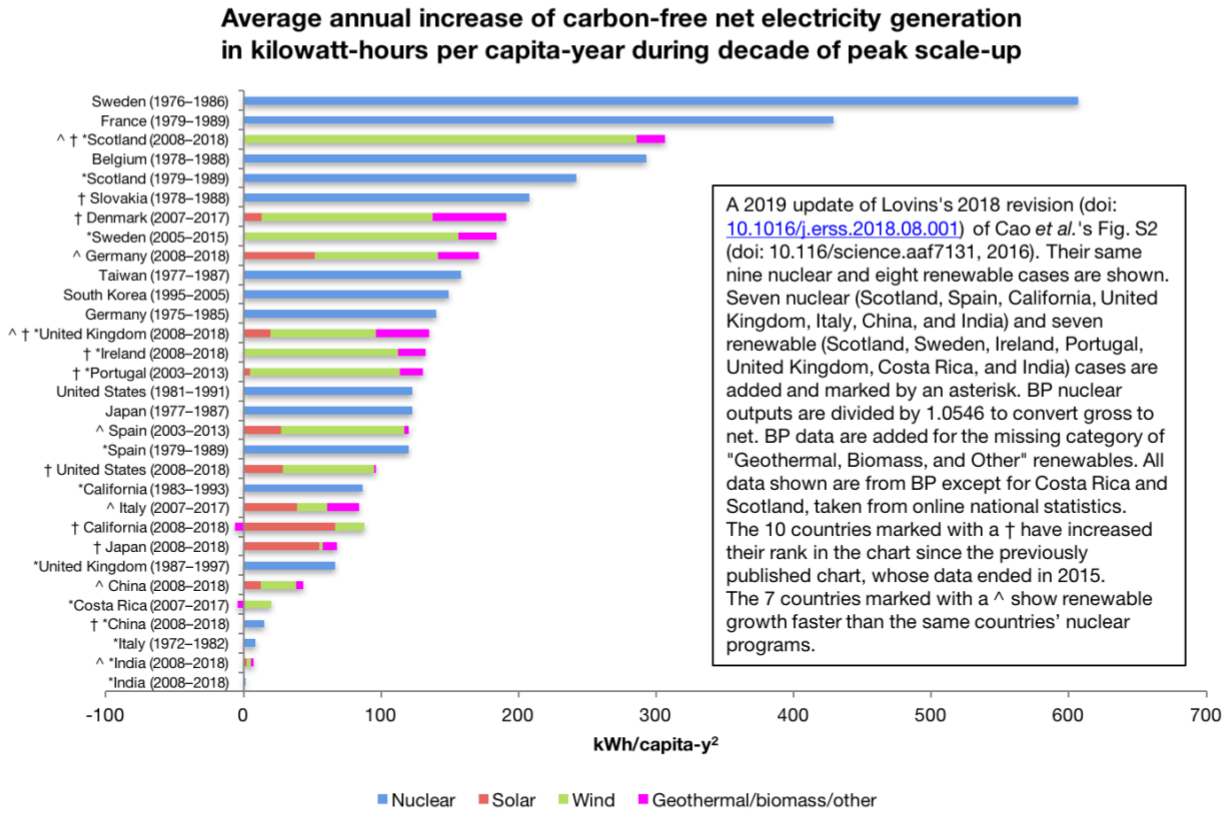
The best long-term analyses indeed show that centuries-old scarcity-based economic theories have diminishing relevance. The newer theory and practice of expanding returns (price falls with volume, due to innovation, learning, and mass production)—with convincing evidence refined by such thought leaders as W. Brian Arthur and Doyne Farmer—is best illustrated by such modern technologies as computing, telecommunications, and renewables. As IPCC found in 2007,[40] "A robust analytical finding…is that the economic benefits of technology improvements (i.e. from cost reductions) are highly non-linear, arising from the cumulative nature of technological change, from interpendence and spillover effects, and from potential increasing returns to adoption." The twelve years since have dramatically strengthened that finding.

Relative deployment speeds

The often-heard claim of nuclear power's uniquely rapid deployment speed[41], allegedly vital for climate protection, is unsupported by historical data. It is an artifact of misleading methodology, misinterpreted and cherry-picked data, and other analytic errors.[42,43,44] Perhaps its best-known form is variants of this graph (recolored here in colors similar to its rebuttal's):[45]



The casual reader could easily conclude that all nuclear programs add electrical supply faster than any renewable program. However, that conclusion would be wrong. Correcting the graph's seven classes of errors but using exactly the same database, period, and methodology yields very different results (ref. 44). Updating with three more years' data, through 2018, further strengthens the conclusion that neither nuclear power nor modern renewables enjoys a consistent speed advantage, but renewables are pulling ahead: in seven of the ten countries where both kinds of programs are directly compared, renewables outpaced nuclear growth, as the following graph shows:

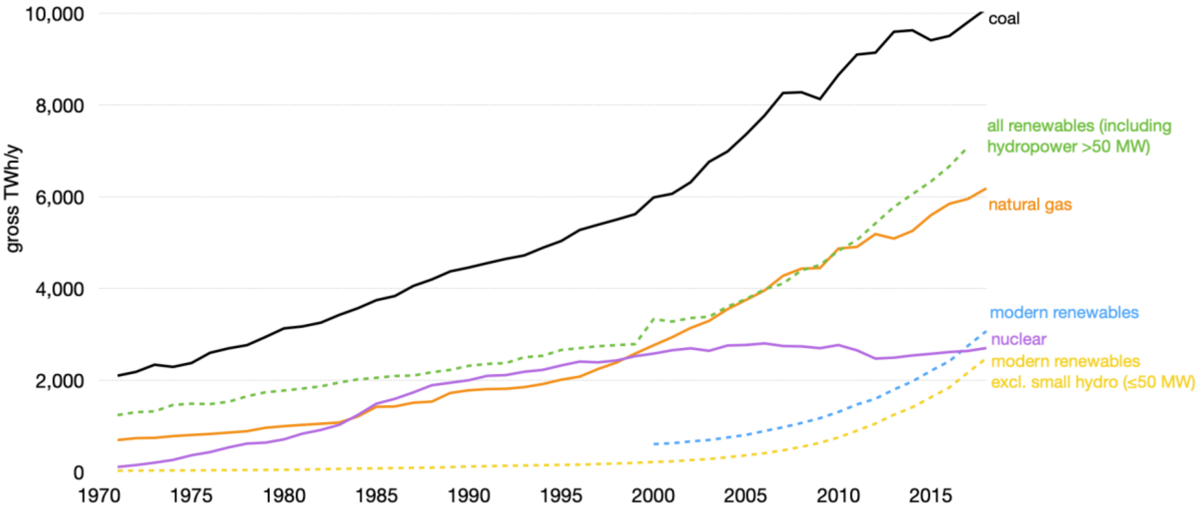


A 2019 update of Lovins's 2018 revision (doi: 10.1016/j.erss.2018.08.001) of Cao *et al.*'s Fig. S2 (doi: 10.116/science.aaf7131, 2016). Their same nine nuclear and eight renewable cases are shown. Seven nuclear (Scotland, Spain, California, United Kingdom, Italy, China, and India) and seven renewable (Scotland, Sweden, Ireland, Portugal, United Kingdom, Costa Rica, and India) cases are added and marked by an asterisk. BP nuclear outputs are divided by 1.0546 to convert gross to net. BP data are added for the missing category of "Geothermal, Biomass, and Other" renewables. All data shown are from BP except for Costa Rica and Scotland, taken from online national statistics. The 10 countries marked with a † have increased their rank in the chart since the previously published chart, whose data ended in 2015. The 7 countries marked with a ^ show renewable growth faster than the same countries' nuclear programs.

Both these graphs use the original authors' (Cao *et al.*'s) severely criticized per-capita methodology, which is better suited to comparing countries than technologies—hence Cao *et al.*'s choice of low-population countries like Sweden, Belgium, and Slovakia to show rapid nuclear growth, while conversely China's world-dominating renewables growth is shown as unimportant because of that nation's vast population. But the simplest and clearest way to compare technologies is to compare their *global* output growth—making irrelevant and unnecessary any distinctions between different countries' populations and other conditions.

Graphing the global data through 2018 and comparing the slopes of the various curves (which are individual, not stacked) confirms that modern renewables (which exclude hydropower >50 MW) are growing faster than nuclear power ever did (in the mid-1980s, but it's been in global eclipse for the past ~15 years and now, lacking a business case, is in slow-motion collapse[46])—and also faster than gas-fired electricity has sustained. Thus modern renewables' global output—electricity production, not installed capacity—has lately been growing faster than any other source of electricity in history. Claims that this is impossible are therefore unconvincing. Claims that it cannot continue belie observed market realities.

Worldwide electricity generation by source, 1971–2018



A B Lovins *et al.*, "Relative deployment rates of renewable and nuclear power: a cautionary tale of two metrics," *El. Res. & Soc. Sci.* **38**:188–192 (2018), doi:10.1016/j.erss.2018.01.05. BP 2019 data. Preliminary 2018 coal & gas data from IEA, "Global Energy & CO_2 Status Report 2018," Mar 2019, https://webstore.iea.org/global-energy-co2-status-report-2018. Small hydro in 2018 est'd from 2017 data.

Nuclear power's speed disadvantage is even greater than this simple graphical comparison implies. As Ref. 2 explains, a national nuclear power program takes about three times as long to launch as a comparable renewables program (due to "formative phases" for institution-building, recruitment, and training), then has physical construction times several to many times longer. Thus more CO_2 is released while waiting for nuclear plants to come online.

A striking confirmation of today's swift energy transformation comes from Japan[47], where government policy constrains solar power and severely restricts onshore windpower in order to try to preserve market space for restarting the surviving portion of the nuclear capacity shut down after the March 2011 Fukushima disaster. By the end of FY2018 (31 March 2019), 9 of 37 reactors had restarted and were making 6% of electricity, leaving a 223 TWh/y gap from pre-Fukushima output levels. Yet meanwhile, in just eight years, demand fell sharply: electrical savings (–246 TWh/y) plus renewable growth (+70 TWh/y) filled 97% of the need both to replace that lost nuclear output and to power Japan's 9% GDP growth during FY2010–18. (Meanwhile, gas-fired generation rose +35 TWh/y and coal-fired +9 TWh/y, offset almost exactly by –43 TWh/y of displaced oil-fired generation.) Thus to displace the 71% of FY2018 electricity still made from fossil fuels and help to meet Japan's climate targets, further nuclear restarts must overcome stiff competition from both efficiency and renewables.

We hope our method will help inform timely and cost-effective coal-displacing choices.

---

[1] Through leaks, flares, and engineered vents: 3% is a fair and probably low approximation of recent global estimates, approximating IPCC's literature range of 0.8–5.5% in *Assessment Report 5*, Working Group III, p 538 (2013). As measurements expand, the latest observations are gradually rising through this range.

[2] A.B. Lovins, "Climate Change and Nuclear Power," *World Nuclear Industry Status Report 2019* (M. Schneider, A. Froggatt, eds.), 24 Sep 2019, www.worldnuclearreport.org.

[3] An economist would also emphasize marginal costs to society, and hence subtract the avoided cost of not burning the coal from the accounting cost of whatever displaced it. That could save the U.S. operator around 3.6 cents per kWh displaced (or probably more if major repairs and upgrades required for continued operation were consistently included). From a societal standpoint, though, you could still respend the six cents of net societal benefit to save two kWh for three cents each. And each kWh of coal-fired electricity you thereby displace saves another ~3.6 cents of operating cost that could in turn be reinvested in more efficiency, repeating the cycle. Here we ignore such second- and higher-order cascading effects, but avoided thermal-plant operating costs do make the *net* accounting cost of any cheaper alternative (typically efficiency, windpower, or solar power) generally less than zero, *i.e.* profitable. This does not depend on the capital cost of building the existing coal-fired station, since that cost is already sunk and you can make decisions only about the future, not the past.

[4] B. Keepin, G. Kats, "Greenhouse warming: comparative analysis of nuclear and efficiency abatement strategies," *En. Pol.* **16**(6), 538–561 (1988).

[5] A. Lovins, "Mighty mice," *Nucl. Eng. Intl.* **12**, 44–48 (2005), https://www.rmi.org/mighty-mice.

[6] A. Lovins, I. Sheikh, A. Markevich, "Nuclear power: climate fix or folly?," 2009, https://rmi.org/insight/nuclear-power-climate-fix-or-folly/.

[7] A. Lovins, "Profitable solutions to climate, oil, and proliferation," *Ambio* **39**, 236–248 (2010), https://rmi.org/insight/profitable-solutions-to-climate-oil-and-proliferation/.

[8] B. Sovacool et al., " Comment on "Prevented Mortality and Greenhouse Gas Emissions from Historical and Projected Nuclear Power," *Envtl. Sci. Tech.* **47**, 6715–6717, 22 May 2013, http://dx.doi.org/10.1021/es401667h.

[9] A. Lovins, "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, preprint at https://d231jw5ce53gcq.cloudfront.net/wp-content/uploads/2017/07/ElJ6May2017_preprint.pdf, lay summary at https://www.rmi.org/news/fourteen-alleged-magical-properties-coal-nuclear-plants-dont-shouldnt-paid-extra-providing/. See also exchange in Oct and Dec issues: "Response to D. Murphy & M. Berkman, 'Efficiency and nuclear energy: Complements, not competitors, for a low-carbon future'" [*El. J.* **30**(8):54–57 (Oct. 2017)], *El. J.* **30**(8):58–62 (Oct. 2017), https://doi.org/10.1016/j.tej.2017.09.012 and "Response to Dean Murphy and Mark Berkman's 'Response to Amory Lovins' reply comments,'" [*El. J.* **30**(8):63–64 (Oct. 2017)], *El. J.* **30**(10):80–81 (Dec. 2017), https://doi.org/10.1016/j.tej.2017.11.013.

[10] Our resource prices for fossil-fueled and nuclear central power stations come from two authoritative sources—the annual compilation by leading financial house Lazard (version 12.0, Nov. 2018), checked against the market prices in Bloomberg New Energy Finance's subscriber database. Lazard adopts lower nuclear operating costs than the average reported by the Nuclear Energy Institute, and lower nuclear fixed costs than reported by BNEF. Since future natural-gas prices are unknowable, we parameterize them over a twofold range consistent with 2050 USEIA forecasts. We adopt Lazard's 2018 costs for utility-scale photovoltaics and onshore windpower, both without their temporary and phasing-out tax incentives, and compare both with two BNEF market-price databases and with Lawrence Berkeley National Laboratory's annual compilations of Power Purchase Agreement long-term fixed contractual prices, as well as with the National Renewable Energy Laboratory's exhaustive 2019 *Annual Technology Baseline* parametrics and with unsubsidized foreign auction-clearing prices (such as Mexico's Nov. 2017 $19/MWh for utility-scale photovoltaics and $17 for onshore windpower). We adopt literature price ranges for typical industrial or in-building cogeneration, and three independent compilations of US utilities' measured costs of energy efficiency programs, cross-checking against national analyses by the National Academies (2009) and Rocky Mountain Institute (2011). We do not assume the severalfold-larger and -cheaper efficiency costs found across all sectors in A. Lovins, "How big is the energy efficiency resource?," *Envtl. Res. Ltrs.* **13**:090401, https://doi.org/10.1088/1748-9326/aad965.

[11] An interesting example is well-documented evidence that the U.K. Government's uniquely ardent and durable commitment to nuclear energy reflects a desire to reduce apparent nuclear expenditures for national defense by

---

charging them, without disclosure, to all electricity customers: *e.g.* A. Stirling, P. Johnstone, "Are Hidden Military Pressures for Cross-Subsidies Driving Major UK Energy Infrastructure Decisions?," written evidence by Science Policy Research Unit (U. of Sussex), 2017. As stated in its endnote p, former U.S. Secretary of Energy Ernest Moniz has confirmed similar U.S. practices. Conservative economic and accounting principles would instead imply that if a country requires military nuclear capabilities, then all the resulting costs, including those of attracting and retaining career staff and sustaining required industrial capacities, should be transparently charged to military accounts and budgets, rather than subsidized from civilian electricity purchases as a concealed subvention that distorts civilian energy choices. Stirling and Johnstone updated the argument in SPRU Working Paper SWPS 2018-13 (Aug 2018), "A Global Picture of Industrial Interdependencies Between Civil and Military Nuclear Infrastructures," www.sussex.ac.uk/spru/research/swps.

[12] International Energy Agency, *World Energy Outlook 2018*, p. 28. www.iea.org/weo2018/.

[13] J. Koomey, "An Update On Trends In US Primary Energy, Electricity, And Inflation-Adjusted GDP Through 2018," 29 Mar 2019, https://www.koomey.com/post/183799578018.

[14] A. Lovins, "A Complex Current: Why are we saving electricity only half as fast as fuels?," *Solutions J* **11**(1):4–9, Spring, May 2018, RMI, https://medium.com/solutions-journal-spring-2018/a-complex-current-f837b95c289c.

[15] A. Lovins, Rocky Mountain Institute, *Reinventing Fire*, Chelsea Green (Vermont), 2011; see p. 204, Fig. 5-23.

[16] UNEP/Frankfurt School/BNEF, "Global Trends in Renewable Energy Investment 2019," 5 Sep 2019, https://wedocs.unep.org/bitstream/handle/20.500.11822/29752/GTR2019.pdf?sequence=1&isAllowed=y,

[17] *Id.*, p. 17, Fig. 6, also showing +283 GW of hydro in all sizes, –2 GW for oil-fired, and –7 GW for nuclear. Modern renewables at the end of 2018 totaled 21% of global power capacity and 12.9% of global power generation. The output fraction is smaller because different technologies have different capacity factors (the actual sent-out fraction of theoretical full-time output). However, that difference is often overstated. In 2018, for example, U.S. utility-scale generators' capacity factors averaged 42.8% for conventional hydropower, 37.4% for windpower, 26.1% for photovoltaics, 23.6% for solar thermal, 73.3% for landfill gas and municipal solid waste, 49.5% for other biomass including wood, and 77.3% for geothermal (www.eia.gov/electricity/monthly/epm-table_grapher.php?t=epmt_6.07_b), compared with 92.6% for nuclear (*id.*) and with 54.0% for coal and 57.6% for natural-gas combined cycle (www.eia.gov/electricity/monthly/epm-table_grapher.php?t=epmt_6.07_a). In general, technical improvements and dispatch competition are tending to increase renewable and decrease nonrenewable capacity factors.

[18] Only electric generators are counted here—not also the 4.2% of world Total Final Energy Consumption (IEA), or ~16 EJ/y, of recently identified modern renewable heat—comparable to the world's total 2017 output of wind plus PVs: A. Lovins *et al.*, "Recalibrating Climate Prospects," *Envtl. Res. Ltrs.*, in review, 2019.

[19] USEIA, *Annual Energy Outlook 2019*, 2018 projection, Table A8, p 19; grid losses from *AEO* data browser.

[20] For example, R. Wiser & M. Bolinger's *2019 Wind Technologies Market Report*, LBNL, DOE/GO-102019-5191, Aug 2019, p 74, says integration costs are generally "near or below" that value for wind capacity "up to and even exceeding 40 percent of the peak load" (Fig. 62 then shows values up to 69%). The PV literature is similar.

[21] USEPA, "Emission Factors for Greenhouse Gas Inventories," 9 Mar 2018, https://www.epa.gov/sites/production/files/2018-03/documents/emission-factors_mar_2018_0.pdf.

[22] IPCC, *Climate Change 2014: Mitigation of Climate Change* (*Assessment Report 5*, Working Group III), p 539, 2014.

[23] EPA (ref. 21) lists 11 gCH_4 per million BTU. At the climate-relevant IPCC equivalence of ~86 over 20 years (EPA now shows only the 100-year equivalence factor of 25), that's equivalent to 1% of the direct CO_2 emissions. However, EPA gives the same methane emissions for every category of coal, suggesting poor data quality, and the methane factor seems ~20x smaller than found by EPA's assessment of 1995 U.S. coal-industry emissions (https://www3.epa.gov/ttn/chief/ap42/ch14/related/mine.pdf).

[24] Lazard, "Levelized Cost of Energy Analysis—Version 12.0," Nov 2018, https://www.lazard.com/media/450784/lazards-levelized-cost-of-energy-version-120-vfinal.pdf.

[25] D. Koplow, "Nuclear Power: Still Not Viable without Subsidies," Union of Concerned Scientists, 2011, https://www.ucsusa.org/nuclear-power/cost-nuclear-power/nuclear-power-subsidies-report.

[26] Nuclear Energy Institute, ""Nuclear by the Numbers," 20 Mar 2019, www.nei.org/CorporateSite/media/filefolder/resources/fact-sheets/nuclear-by-the-numbers.pdf.

[27] By the American Council for an Energy-Efficient Economy (2014), E Source (2014), and LBNL (2014), broadly consistent with the National Academies (2009) and considerably costlier than found in ref. 15.

---

[28] C. Frank, "The net benefits of low and no-carbon electricity technologies," *Brookings Global Economy & Development Working Paper 73* (2014).

[29] J. Hansen, "Renewable Energy, Nuclear Power and Galileo: Do Scientists Have a Duty to Expose Popular Misconception?," http://www.columbia.edu/~jeh1/mailings/2014/20140221_DraftOpinion.pdf (2014).

[30] S. Brand, S. *Whole Earth Discipline* (Penguin Books, 2010), rebutted in A. Lovins, "Nuclear nonsense," 2009, www.rmi.org/insight/nuclear-nonsense/.

[31] S. Qvist, S., B. Brook, "Environmental and health impacts of a policy to phase out nuclear power in Sweden," *En. Pol.* **84**, 1–10 (2015).

[32] P. Kharecha, J. Hansen, "Prevented mortality and greenhouse gas emissions from historical and projected nuclear power," *Env. Sci. Technol.* **47**(9), 4889–4895 (2013).

[33] A. Lovins, Comments to Federal Energy Regulatory Commission on Grid Resiliency Pricing Rule, Docket No. RMI8-1-000, submission number 813728 and two small errata 813743, 23 Oct 2017, consolidated as https://www.rmi.org/wp-content/uploads/2017/11/FERC_Comments_ABLovins_October_2017.pdf.

[34] A. Lovins, "Reliably integrating variable renewables: moving grid flexibility resources from models to results," *El. J.* **30**(10):58–93 (Dec 2017), http://dx.doi.org/10.1016/j.tej.2017.11.006.

[35] T. Brown *et al.*, "Response to 'Burden of proof: A comprehensive review of the feasibility of 100% renewable-electricity systems'," *Ren. Sust. En. Revs.* **92**:834-847 (Sep. 2018), https://doi.org/10.1016/j.rser.2018.04.113.

[36] A. Lovins, "The storage necessity myth: how to choreograph high-renewables electricity systems," 8 Jul 2014, https://www.youtube.com/watch?v=MsgrahFln0s.

[37] C. Teplin, M. Dyson, A. Engel, G. Glazer, "The Growing Market for Clean Energy Portfolios," 9 Sep 2019, https://rmi.org/insight/clean-energy-portfolios-pipelines-and-plants.

[38] A. Lovins, "Clean energy and rare earths: Why not to worry," *Bulletin of the Atomic Scientists*, 23 May 2017, https://thebulletin.org/2017/05/clean-energy-and-rare-earths-why-not-to-worry/.

[39] A. Lovins, "How big is the energy efficiency resource?," ref. 10.

[40] IPCC, *Fourth Assessment Report*, §2.7.1.3.

[41] See notes 4–9 in Lovins, Palazzi, Laemel, Goldfield, below.

[42] A. Lovins, "Nuclear power: deployment speed," *Science* **354**:1112–1113 (2 Dec 2016), https://doi.org/10.1126/science.aal1777.

[43] A. Lovins, T. Palazzi, R. Laemel, E. Goldfield, "Relative Deployment Speed of Renewable and Nuclear Power: A Cautionary Tale of Two Metrics," *En. Res. & Soc. Sci.* **38:**188–192, 22 Feb 2018, https://doi.org/10.1016/j.erss.2018.01.005. See also the following reference.

[44] A. Lovins, Corrigendum to "Relative Deployment Speed of Renewable and Nuclear Power: A Cautionary Tale of Two Metrics," En. Res. & Soc. Sci. 46:381-383 (Oct 2018), online 27 Aug 2018, https://doi.org/10.1016/j.erss.2018.08.001.

[45] J. Cao *et al.*, "China-U.S. cooperation to advance nuclear power," *Science* **353**:547–548, 5 Aug 2016.

[46] M. Schneider, A. Froggatt, eds., *World Nuclear Industry Status Report 2019*, 24 Sep 2019, www.worldnuclearreport.org.

[47] R. Zissler, "Remarkable Progress in Japan's Electricity Consumption and Generation Since FY2010," 13 Sep 2019, Renewable Energy Institute (Tōkyō), https://www.renewable-ei.org/en/activities/column/REupdate/20190913.php.