Four Nuclear Myths

A commentary on Stewart Brand's *Whole Earth Discipline* and on similar writings

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Public discussions of nuclear power, and a surprising number of articles in peer-reviewed journals, are increasingly based on four notions unfounded in fact or logic: that

1. variable renewable sources of electricity (windpower and photovoltaics) can provide little or no reliable electricity because they are not "baseload"—able to run all the time;
2. those renewable sources require such enormous amounts of land, hundreds of times more than nuclear power does, that they're environmentally unacceptable;
3. *all* options, including nuclear power, are needed to combat climate change; and
4. nuclear power's economics matter little because governments must use it anyway to protect the climate.

For specificity, this review of these four notions focuses on the nuclear chapter of Stewart Brand's 2009 book *Whole Earth Discipline*, which encapsulates similar views widely expressed and cross-cited by organizations and individuals advocating expansion of nuclear power. It's therefore timely to subject them to closer scrutiny than they have received in most public media.

This review relies chiefly on five papers[1–5], which I gave Brand over the past few years but on which he has been unwilling to engage in substantive discussion. They document[6] why expanding nuclear power is uneconomic, is unnecessary, is not undergoing the claimed renaissance in the global marketplace (because it fails the basic test of cost-effectiveness ever more robustly), and, most importantly, *will reduce and retard climate protection*. That's because—the empirical cost and installation data show—new nuclear power is so costly and slow that, based on empirical U.S. market data, it will save about 2–20 times less carbon per dollar, and about 20–40 times less carbon per year, than investing instead in the market winners—efficient use of electricity and what *The Economist* calls "micropower," comprising

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[1] A.B. Lovins, "Mighty Mice," *Nuclear Engineering International*, pp. 44–48, Dec. 2005, www.rmi.org/images/PDFs/Energy/E05-15_MightyMice.pdf, summarizing ref. 2. A World Nuclear Association critique and my response are at www.neimagazine.com/comments.asp?sc=2033302.

[2] "Nuclear Power: Economics and Climate-Protection Potential," RMI Publ. #E05-14, 6 Jan. 2006, www.rmi.org/images/PDFs/Energy/E05-14_NukePwrEcon.pdf.

[3] A.B. Lovins, I. Sheikh, & A.M. Markevich, "Forget Nuclear," *RMI Newsletter*, Apr. 2008, www.rmi.org/sitepages/pid467.php, summarizing refs. 4 and 5.

[4] —, "Nuclear Power: Climate Fix or Folly?," RMI Publ. #E09-01, Dec. 2008, www.rmi.org/images/PDFs/Energy/E09-01_NuclPwrClimFixFolly1i09.pdf, updating and expanding ref. 3.

[5] A.B. Lovins & I. Sheikh, "The Nuclear Illusion," draft-18 preprint posted by permission May 2008 at www.rmi.org/images/PDFs/Energy/E08-01_AmbioNucIllusion.pdf, draft-20 revision to be published in early 2010 in *Ambio* (Royal Swedish Academy of Sciences).

[6] Particularly in refs. 2, 4, and 5; ref. 4 is the best starting-point for most readers, with ref. 5 as its detailed backup. A more recent short article assesses "new" ("Gen 4") reactor types, which look broadly comparable to today's Gen 2–3 reactors in waste production, might in some respects be safer, are generally as or more proliferative, and lack the economic and other advantages often claimed for them, *e.g.* by Brand at pp. 113–114: A.B. Lovins, "'New' Nuclear Reactors, Same Old Story," *RMI Solutions J.*, Spring 2009, www.rmi.org/sitepages/pid601.php.

distributed renewables (renewables with mass-produced units, *i.e.*, those other than big hydro dams) and cogenerating electricity together with useful heat in factories and buildings.

These economic arguments are the core of any rational nuclear debate, because if nuclear power isn't necessary, competitive, and effective at climate protection, then one needn't debate its other attributes. Readers are therefore invited to explore the cited papers, starting with ref. 4.

Typically of such writings, Brand's alternatives to nuclear and coal power comprise only:

- energy efficiency—praised but quickly dismissed, without analysis, as insufficient by itself to replace all existing coal plants and all future developing-country power needs;
- solar thermal electric power (normally with overnight heat storage), mentioned but not analyzed despite its very large competitive potential;[7] and
- windpower and photovoltaics, both rejected on the flawed bases described below.

Other than a mention of big hydro dams, his slate of climate alternatives arbitrarily excludes:

- all other renewables, even though dispatchable renewables (those operable whenever desired and with high technical reliability)—small hydro, geothermal, biomass/waste combustion, etc.—now have about the same global installed capacity as photovoltaics plus windpower, but greater annual output because they have higher capacity factors;[8]
- cogeneration (combined-heat-and-power), which is larger today than distributed renewables, has vast further potential[9], and avoids or eliminates carbon emissions at similar or lower cost (it typically saves at least the normal fuel, carbon, and money); and
- fuel-switching, which could cheaply displace one-third of U.S. coal-fired power now.[10]

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[7] A simple introduction is at http://en.wikipedia.org/wiki/Concentrating_solar_power. In spring 2008, J. Romm's assessment found a practical potential to scale up and mass-produce 50–100+ GW/y of concentrating solar power indefinitely (www.salon.com/news/feature/2008/04/14/solar_electric_thermal/print.html) at a busbar cost Sandia National Laboratory estimated in 2008 at ~8–10¢/kWh once 3 GW has been made. The current order pipeline, with scores of projects (by some counts ~180 contemplated in just Spain and the U.S.), is a substantial multiple of 3 GW and may exceed 40 GW. Some innovators also believe costs around or below 6¢/kWh are coming into view. CSP capacity coming online in 2009 appears competitive with new nuclear capacity. Of course, large-scale deployment in deserts would require dry cooling due to water scarcity—as is similarly or more true for nuclear or coal plants.

[8] All these and other micropower data, documented to standard industry sources, are posted at RMI's longstanding database: see www.rmi.org/sitepages/pid256.php, Publ. #E05-04. The 2008 renewable data will be posted shortly, and the latest cogeneration data in late 2009. The 2008 capacity factor of the global installed base is ~66% for all micropower, ~83% for non-biomass cogeneration, ~60% collectively for geothermal/small hydro/biomass/ waste, ~40% and rising for all distributed renewables, ~0.26 for wind, ≥0.17 for PV, and 80% for nuclear power.

[9] For example, untapped U.S. industrial cogeneration potential is at least comparable to U.S. nuclear capacity and output: O. Bailey and E. Worrell, "Clean Energy Technologies: A Preliminary Inventory of the Potential for Electricity Generation," LBNL-57451, Apr. 2005, http://repositories.cdlib.org/lbnl/LBNL-57451/. See also P. Lemar Jr., "The potential impact of policies to promote combined heat and power in U.S. industry," *En. Pol.* **29**(14):1243–1254 (Nov. 2001). Cogeneration potential in buildings is unmeasured but very large, and is not confined to large buildings; *e.g.*, Honda has sold over 100,000 home cogeneration systems, and VW has just entered the market with LichtBlick, which plans a German 2-GW "virtual decentralized power plant" to firm renewable power. Old but still useful estimates of European industrial and building CHP potential are in F. Krause *et al.*, *Fossil Generation: The Cost and Potential of Low-Carbon Resources Options in Western Europe*, IPSEP, 1994, http://files.me.com/jgkoomey/c49xzn.

The central issue is: *What are nuclear power's competitors?* If the competitors can be artificially restricted to just coal and gas-fired plants, then at least coal, perhaps gas too, can be excluded on climate grounds, and gas perhaps also on price-volatility or supply-security grounds, so nuclear stands unchallenged. In this central-plants-only world, nuclear power will also be advantaged by carbon pricing. But if, as the data show, *all three* kinds of thermal power plants have been reduced in total to minority global market share and nuclear to just a few percent market share by smaller, more agile, and generally cheaper *decentralized* supply-side competitors (let alone by demand-side rivals), then those alternatives are real, are large, and have costs, speeds, and carbon consequences that must be compared with those of new nuclear plants. Moreover, these alternatives are equally advantaged (or largely so in the case of fueled cogeneration) by carbon pricing, which thus wouldn't change nuclear power's competitive disadvantage against them.

Nuclear advocates are eager to avoid head-to-head comparisons with these market winners, so they, including Brand, typically seek to exclude from consideration as unrealistic all non-nuclear alternatives to coal—typically by invoking one or more of the four myths listed on page one above. Before addressing those myths, it's useful to offer energy efficiency as an example of why such arbitrary exclusions predetermine the outcome, rather in the way dictators can rig their reelection not by stuffing or miscounting the ballot boxes but simply by keeping their most formidable opponents off the ballot. The importance of the other excluded alternatives is similarly explored in refs. 1–5 and their citations.[11]

Energy efficiency

On p. 84, Brand praises energy efficiency and agrees it can do much more, but then drops it as an option by asserting that it "can't replace all the coal-fired plants that have to be shut down, and it can't generate power[12] for the burgeoning energy demand of the growing economies in China, India, Africa, and Latin America." This unanalyzed and undocumented claim is hard to reconcile with strong evidence left unmentioned, *e.g.*:

- If each of the United States used electricity as productively as the top ten states actually did in 2005 (adjusted for each state's economic mix and climate), 62% of U.S. coal-fired

[10] Noted gas expert R.A. Hefner's *The Grand Energy Transition* (Sept. 2009 rev. edn., Wiley, Sept. 2009) notes that simply dispatching existing U.S. combined-cycle gas-fired plants before coal-fired plants would displace about one-third of all U.S. coal-fired electricity, lowering CO_2 emissions by several hundred million tonnes a year, without building any new capacity. This would increase operating costs by ~2¢/kWh—many times less than substituting new nuclear plants (refs. 4–5).

[11] I assume that readers interested in the economic arguments are acquainted with both the long-term and the recent economic history of nuclear power. Basic readings are: I.C. Bupp & J.-C. Derian, *The Failed Promise of Nuclear Power*, Basic Books (NY), 1981; J.G. Koomey & N.E. Hultman, "A reactor-level analysis of busbar costs for U.S. nuclear plants, 1970–2005," *En. Pol.* **35**(11):5630–5642 (Nov. 2007), http://dx.coi.org/10.1016/j.enpol.2007.06.005; F. Krause *et al.*, *Nuclear Power: The Cost and Potential of Low-Carbon Resource Options in Western Europe*, IPSEP, 1994, http://files.me.com/jgkoomey/b7fi62; MIT, *The Future of Nuclear Power: An Interdisciplinary MIT Study*, 2003, http://web.mit.edu/nuclear power/; Keystone Center, *Nuclear Power Joint Fact-Finding*, June 2007, www.keystone.org/spp/documents/FinalReport_NJFF6_12_2007(1).pdf; and for France, ref. 83.

[12] Nobody claims that efficiency can "generate power," but rather that it displaces the need to generate part of the power currently needed to do a given task. "Negawatts" are functionally equivalent, not identical, to megawatts.

electricity would become unnecessary.[13] McKinsey found that by 2020, the U.S. could actually and very profitably save 1,080 TWh/y—half of today's coal-fired generation.[14]

- Late-1980s efficiency technologies, if systematically installed throughout the U.S. economy, could save ~75% of U.S. electricity (*vs*. the 50% made by coal-fired plants) at an average cost ~1¢/kWh (less than the *operating* cost of an existing coal or nuclear plant, even if the plant and grid were free)[15]; or, according to the U.S. utilities' think-tank, could save ~40–60% at an average cost ~3¢/kWh[16] (cheaper than the delivered price of existing coal-fired electricity). The difference between these two findings was largely methodological, not substantive.[17]
- Today's efficiency potential is even bigger and cheaper, both because efficiency technology keeps improving faster than it's applied, and because we now know how to get expanding rather than diminishing returns to investments in energy efficiency—how to make large (often at least tenfold) energy savings cost *less* than small or no savings.[18]
- Developing countries tend to have greater efficiency *potential* than developed countries.[19] They have a keener *need* to exploit this potential because they can ill afford such waste—especially of electricity, the most capital-intensive sector, whose production gobbles about one-fourth of global development capital.[20] And they have a greater *opportunity* to become efficient, because they are building their infrastructure the first time, and it's easier to build it right than fix it later. That's why energy efficiency (both electric and direct-fuel) cut China's energy demand growth by ~70% during 1980–2001. Since 2004, China's top strategic goal for national development has been energy efficiency—now being vigorously implemented—because leaders like Wen Jiabao understand that otherwise China can't afford to develop: energy supply will eat the capital budget.

It's also fallacious to reject any single resource (efficiency, wind, solar, or whatever) because it can't do the *entire* job. As Brand agrees, energy needs a diverse portfolio, not a single "silver bullet." Yet having arbitrarily rejected efficiency as unable to meet *all* global needs for

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[13] S. Doig *et al*., "Assessing the Electric Productivity Gap and the U.S. Efficiency Opportunity," RMI, 2009, ert.rmi.org/research/cgu.html; the 62% is an equivalent-TWh/y figure and doesn't reflect hourly dispatch.

[14] McKinsey Global Energy and Materials, *Unlocking Energy Efficiency in the U.S. Economy*, July 2009, www.mckinsey.com/clientservices/ccsl/. An authoritative U.S. government study also shows encouraging potential: M. Brown *et al*., "Scenarios for a Clean Energy Future," *En. Pol*. **29**(14):1179–1196 (Nov. 2001), LBNL-48031.

[15] COMPETITEK, *The State of the Art* series, 1986–92, RMI, 6 vols., 2,509 pp., 5,135 notes. Condensed versions were republished by E SOURCE as the *Technology Atlas* series,, www.esource.com/public/products/prosp_atlas.asp.

[16] A. Fickett, C. Gellings, & A.B. Lovins, "Efficient Use of Electricity," *Sci. Amer*. **263**(3):64–74 (1990).

[17] A.B. Lovins, "Least-Cost Climate Stabilization," *Ann. Rev. En. Envt*. **16**:433–531 (1991), citing ORNL/CON-312.

[18] A.B. Lovins, "Energy End-Use Efficiency," RMI Publ. #E05-16, 2005 white paper commissioned by S. Chu for InterAcademy Council (~90 National Academies), www.rmi.org/images/PDFs/Energy/E05-16_EnergyEndUseEff.pdf; "Advanced Energy Efficiency," Stanford Engineering School lectures, spring 2007, www.rmi.org/stanford.

[19] This emerges clearly from *e.g*. McKinsey's January 2009 analysis of how to abate global greenhouse-gas emissions by ~70% at an average cost of just €4 per ton of CO_2: www.mckinsey.com/clientservice/ccsi/. (That analysis, however, doesn't yet include integrative design (ref. 18).)

[20] Conversely, saving electricity can take four orders of magnitude less capital—three in intensity and one in velocity—than supplying more electricity, turning the capital-hungry power sector into a net *exporter* of capital to fund other development needs: A.J. Gadgil, A.H. Rosenfeld, D. Aresteh, & E. Ward, "Advanced Lighting and Window Technologies for Reducing Electricity Consumption and Peak Demand: Overseas Manufacturing and Marketing Opportunities," LBL-30890 Revised, *Procs. IEA/ENEL Conf. Adv. Technols. El. Demand-Side Mgt*. **3**:6-135–6-152 (Sorrento, 2–5 Apr. 1991), LBNL; www.rmi.org/images/PDFs/Energy/E91-23_NegawattRevolution.pdf.

displacing coal and powering economic development, he fails to count any lesser achievement that could stretch other alternatives' contribution to the portfolio—unless it's nuclear.

The "baseload" myth

Brand rejects the most important and successful renewable sources of electricity for one key reason stated on p. 80 and p. 101. On p. 80, he quotes novelist and author Gwyneth Cravens's definition of "baseload" power as "the minimum amount of proven, consistent, around-the-clock, rain-or-shine power that utilities must supply to meet the demands of their millions of customers."[21] (Thus it describes a pattern of aggregated[22] customer *demand*.) Two sentences later, he asserts: "So far [baseload power] comes from only three sources: fossil fuels, hydro, and nuclear." Two paragraphs later, he explains this dramatic leap from a description of *demand* to a restriction of *supply*: "Wind and solar, desirable as they are, aren't part of baseload because they are intermittent—productive only when the wind blows or the sun shines. If some sort of massive energy storage is devised, then they can participate in baseload; without it, they remain supplemental, usually to gas-fired plants."

That widely heard claim is fallacious. The manifest need for some amount of steady, reliable power[23] is met by generating plants *collectively, not individually*. That is, *reliability is a statistical attribute of all the plants on the grid combined.*[24] If steady 24/7 operation or operation at any desired moment were instead a required capability *of each individual power plant*, then the grid couldn't meet modern needs, because *no* kind of power plant is perfectly reliable. For example, in the U.S. during 2003–07, coal capacity was shut down an average of 12.3% of the time (4.2% without warning); nuclear, 10.6% (2.5%); gas-fired, 11.8% (2.8%).[25] Worldwide through 2008, nuclear units were unexpectedly unable to produce 6.4% of their energy output.[26] This inherent intermittency of nuclear and fossil-fueled power plants requires many different plants to back each other up through the grid. This has been utility operators' strategy for reliable supply throughout the industry's history. Every utility operator knows that power plants provide energy to the grid, which serves load. The simplistic mental model of one plant serving one load is valid only on a very small desert island. The standard remedy for failed plants is other interconnected plants that are working—not "some sort of massive energy storage [not yet] devised."

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[21] In utility operators' parlance, "baseload" actually refers to resources with the lowest operating cost, so they are dispatched whenever available. This definition embraces essentially all efficiency and renewables, since their operating cost is below even that of nuclear plants. Economic ("merit-order") dispatch next uses nuclear, then coal, then gas-fired plants, in order of their increasing operating cost. Utility resource planners use "baseload" to refer to resources of lowest *total* cost—information that guides acquisition rather than operation. "Baseload" is also often but erroneously applied by laypeople to the big thermal plants that traditionally produce relatively steady output.

[22] Some loads are actually steady; others only appear so because of the way they're aggregated with other loads.

[23] The need for steady power depends on what it's used for, not particularly on urbanization as Brand says. If he has evidence that urbanization must increase the steady portion of electricity demand more than the peaky portion, that would be a surprising and important discovery, and he should document it. I've never seen such evidence.

[24] Jim Harding, who led strategic planning for Seattle City Light, says it has no "baseload" resources in Brand's sense; its assets' system capacity factor is around 25%, comparable to a mediocre wind turbine's. Yet retail electricity prices are relatively low and the system is highly reliable. If Brand were right, this would be impossible.

[25] North American Electric Reliability Corporation availability reports, www.nerc.com/page.php?cid=4|43|47.

[26] IAEA, "Lifetime Unplanned Capability Loss Factor," www.iaea.org/programmes/a2/index.html, accessed 7 Sep. 2009. The lost output varied from 1.3% in South Korea to 22.9% in Pakistan; the U.S. figure was 7.1%, France 7.6%. The global average in 2008 was 5.3% (www.iaea.org/programmes/a2/index.html).

Modern solar and wind power are *more* technically reliable than coal and nuclear plants; their technical failure rates are typically around 1–2%. However, they are also *variable* resources because their output depends on local weather, forecastable days in advance with fair accuracy and an hour ahead with impressive precision.[27] But their inherent variability can be managed by proper resource choice, siting, and operation.[28] Weather affects different renewable resources differently; for example, storms are good for small hydro and often for windpower, while flat calm weather is bad for them but good for solar power. Weather is also different in different places: across a few hundred miles, windpower is scarcely correlated, so weather risks can be diversified. A Stanford study found that properly interconnecting at least ten windfarms can enable an average of one-third of their output to provide firm baseload power.[29] Similarly, within each of the three power pools from Texas to the Canadian border, combining uncorrelated windfarm sites can reduce required wind capacity by more than half for the same firm output, thereby yielding fewer needed turbines, far fewer zero-output hours, and easier integration.[30]

A broader assessment of reliability tends not to favor nuclear power. Of all 132 U.S. nuclear plants built—just over half of the 253 originally ordered—21% were permanently and prematurely closed due to reliability or cost problems. Another 27% have completely failed for a year or more at least once. The surviving U.S. nuclear plants have lately averaged ~90% of their full-load full-time potential—a major improvement[31] for which the industry deserves much credit—but they are still not fully dependable. Even reliably-running nuclear plants must shut down, on average, for ~39 days every ~17 months for refueling and maintenance. Unexpected failures occur too, shutting down upwards of a billion watts in milliseconds, often for weeks to months. Solar cells and windpower don't fail so ungracefully.

Power plants can fail for reasons other than mechanical breakdown, and those reasons can affect many plants at once. As France and Japan have learned to their cost, heavily nuclear-dependent regions are particularly at risk because drought, earthquake, a serious safety problem, or a terrorist incident could close many plants simultaneously. And nuclear power plants have a unique further disadvantage: for neutron-physics reasons, they can't quickly restart after an emergency shutdown, such as occurs automatically in a grid power failure. During the August

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[27] Michael Eckhart (former strategic planning head of GE's Power Systems sector) makes the intriguing point that a simple-cycle combustion turbine has a ~97% probability of coming online within 30 minutes of coldstart, while Danish utility operators have demonstrated the ability to predict wind force with 98% accuracy within a 30-minute window. So which resource is more reliable and which is more intermittent?

[28] This has been well-known for over 20 years: see *e.g.* M. Grubb, *En. Pol.* **16**(6):594–607 and **19**(7):670–688 (1988). Indeed, Edward Kahn at LBNL and Sir Martin Ryle, then the Astronomer Royal, analyzed it in the 1970s.

[29] C.L. Archer & M.Z. Jacobson, "Supplying Baseload Power and Reducing Transmission Requirements by Interconnecting Wind Farms," *J. Appl. Meteorol. & Climatol.* **46**(11):1701–1717 (2007).

[30] See RMI publications "Intermittent Renewables in the Next Generation Utility," PowerGen-RE, Feb. 2008, www.rmi.org/images/PDFs/Energy/RMI_PowerGen_090924.pdf; "Spatial and Temporal Interactions of Wind and Solar in the Next Generation Utility," Solar 2008, May 2008, www.rmi.org/images/PDFs/Energy/Solar_2008_in_NGU_090924.pdf; "Spatial and Temporal Interactions of Wind and Solar in the Next Generation Utility: Expanded Analysis," Windpower 2008, June 2008. http://www.rmi.org/images/PDFs/Energy/RMI_Windpower_NGU_090924.pdf.

[31] The U.S. fleet's lifetime average rose to 78.7% through 2008, *vs.* 77.1% globally and 76.9% for France: www.iaea.org/programmes/a2/index.html. The 2008 global average was 80.0%, the lowest value since 1999 (www.iaea.org/programmes/a2/index.html). Assuming 90% for the average new plant seems a stretch.

2003 Northeast blackout, nine perfectly operating U.S. nuclear units had to shut down. Twelve days of painfully slow restart later, their average capacity loss had exceeded 50%. For the first three days, just when they were most needed, their output was less than 3% of normal.[32]

To cope with nuclear or fossil-fueled plants' large-scale intermittency, utilities must install a ~15–20% "reserve margin" of extra capacity, some of which must be continuously fueled, spinning ready for instant use. This is as much a cost of "firming and integration" as is the corresponding cost for firming and integrating windpower or photovoltaic power so it's dispatchable at any time.[33] Such costs should be properly counted and compared for *all* generating resources. Such a comparison generally favors a diversified portfolio of many small units that fail at different times, for different reasons, and probably only a few at a time: diversity provides reliability even if individual units are not so dependable.

Reliability as experienced by the *customer* is what really matters, and here the advantage tilts decisively towards decentralized solutions, because ~98–99% of U.S. power failures originate *in the grid*. It's therefore more reliable to bypass the grid by shifting to efficiently used, diverse, dispersed resources sited at or near the customer. This logic favors onsite photovoltaics, onsite cogeneration, and local renewables over, say, remote windfarms or thermal power plants, if complemented by efficient use, optional demand response, and an appropriate combination of local diversification and (if needed) local storage, although naturally the details are site-specific.

The big transmission lines that remote power sources rely upon to deliver their output to customers are also vulnerable to lightning, ice storms, rifle bullets, cyberattacks, and other interruptions. These vulnerabilities are so serious that the U.S. Defense Science Board has recommended that the Pentagon stop relying on grid power altogether.[34] The bigger our power plants and power lines get, the more frequent and widespread regional blackouts will become. In general, nuclear and fossil-fueled power plants require transmission hauls at least as long as is typical of new windfarms, while solar potential is rather evenly distributed across the country.

For all these reasons, a diverse portfolio of distributed and especially renewable resources can make power supplies *more* reliable and resilient. Of course the weather-caused variability of windpower and photovoltaics must be managed, but this is done routinely at very modest cost. Thirteen recent U.S. utility studies show that "firming" variable renewables, even up to 31% of total generation, generally raises windpower's costs by less than a half-cent per kWh, or a few percent.[35] Without exception, ~200 international studies have found the same thing.[36] Indeed, the

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[32] Author's analysis from U.S. Nuclear Regulatory Commission data posted at www.nrc.gov/reading-rm/doc-collections/event-status/reactor-status/2003/index.html and www.nrc.gov/info-finder/reactor/.

[33] This is often done by hydropower (like BPA's 0.3¢/kWh firming rate), but demand-response "virtual peakers" are comparably cheap and can be very large: FERC has found up to 188 GW of U.S. demand-response potential, the resource may well be even larger, and of the 10 GW just bid into the PJM pool's auction, 7 GW cleared the market.

[34] *More Fight, Less Fuel*, Feb. 2008, www.acq.osd.mil/dsb/reports/2008-02-ESTF.pdf.

[35] M. Bolinger & R. Wiser (LBNL), *2008 Wind Technologies Market Report*, July 2009, p. 49, http://eetd.lbl.gov/ea/ems/re-pubs.html. See also www.awea.org/pubs/factsheets/Backup_Power.pdf, which illustrates the tiny amount of net variability—on a one-hour timescale, just ~1–2% of the renewable capacity—that large additions of variable renewables would impose on various U.S. power systems, and how any extra fuel burned by the resulting reserve capacity would be about a thousandth of the fuel that those renewables displace.

latest analyses are suggesting that a well-diversified and well-forecasted mix of variable renewables, integrated with dispatchable renewables and with existing supply- and demand-side grid resources, will probably need *less* storage or backup *than has already been installed to cope with the intermittence of large thermal power stations*. Utilities need only apply the same techniques they already use to manage plant or powerline outages and variations in demand—but variations in renewable power output are more predictable than those normal fluctuations, which often renewables' variations don't augment but cancel. Thus, as the U.S. Department Energy pithily summarizes, "When wind is added to a utility system, no new backup is required to maintain system reliability."[37]

This is not just a computational finding but a practical reality. In 2008, five German states got 30–40% of their annual electricity from windpower—over 100% at windy times—and so do parts of Spain and Denmark, without reliability problems. Denmark is 20% windpowered today and aims for ~50–60% (the rest to come from low- or no-carbon cogeneration). Ireland, with an isolated small grid (~6.5 billion watts), plans to get 40% of its electricity from renewables, chiefly wind, by 2020 and 100% by 2035. Three 2009 studies found 29–40% British windpower practical.[38] The Danish utility Dong plans in the next generation to switch from ~15% renewables (mainly wind) and ~85% fossil fuel (mainly coal) to the reverse. A German/Danish analysis found that diversifying supplies and linking grids across Europe and North Africa could yield 100% renewable electricity (70% windpowered) at or below today's costs.[39] Similar all-renewable scenarios are emerging for the United States and the world, even without efficiency.[40]

Brand nonetheless concludes that "wind power remains limited by intermittency to about 20 percent of capacity (so that 94 gigawatts [the global windpower capacity at the end of 2007] is four-fifths illusory), while nuclear plants run at over 90 percent capacity these days; and there is still is no proven storage technology that would make wind a baseload provider." That view has long been known to be unfounded. There is no 20% limit, in theory or in practice, for technical or reliability or economic reasons, in any grid yet studied.[41] The "fourth-fifths illusory" remark also appears to reflect confusing an imaginary 20% limit on windpower's share of electrical

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[36] A useful summary is the European Wind Energy Association's March 2009 study *Integrating Wind*; see also EWEA's *The Economics of Wind Energy* (www.ewea.org) and Bolinger & Wiser, ref. 35. See also *Small Is Profitable*, ref. 45, and citations in ref. 5.

[37] "Wind Energy Myths," DOE/GO-102005-2137, May 2005, www.nrel.gov/docs/fy05osti/37657.pdf, item 5. Backup and storage are functionally equivalent for purposes of this discussion.

[38] Summarized and referenced at www.claverton-energy.com/wind-energy-variability-new-reports.html.

[39] G. Czisch & G. Giebel, "Realisable Scenarios for a Future Electricity Supply based 100% on Renewable Energies," Risø-R-1608(EN), www.risoe.dk/rispubl/reports/ris-r-1608_186-195.pdf; G. Giebel, N.G. Mortensen, & G. Czisch, "Effects of Large-Scale Distribution of Wind Energy In and Around Europe," www.iset.uni-kassel.de/abt/w3-w/projekte/Risoe200305.pdf.

[40] *E.g.*, M.Z. Jacobson & M.A. Delucchi, "A Path to Sustainable Energy by 2030," *Sci. Am.*, Nov. 2009, pp. 58–65; on PVs, V. Fthenakis, J.E. Mason, & K. Zweibel, *En. Pol.* **37**:387–399 (2009).

[41] This is a hoary myth. Around the 1970s and early 1980s, before the issue was well analyzed, many people *assumed* a limit of 5–10%, then 15%, then 20%, then 25%, then 30%…but all such limits have dissolved on closer scrutiny. For example, the West Danish system operator reports that as he gained experience with windpower, he became confidently able to manage nearly five times more of it than he had thought possible 7–8 years earlier; he was just learning to treat fluctuating windpower the same way he'd always treated fluctuating electricity demand (EWEA, "Wind Power Technology: Operation, Commercial Developments, Wind Projects, and Distribution," ~2004, www.ewea.org/documents/factsheet_technology2.pdf, p. 10).

output with windpower's *capacity factor* (how much of its full-time full-power output it actually produces). Anyhow, capacity factor averaged 35–37% for 2004–08 U.S. wind projects, is typically around 30–40% in good sites, and exceeds 50% in the best sites.[42] Proven and cost-effective bulk power storage is also available if needed.[43]

Even if Brand were right that variability limits windpower's potential contribution, that would be irrelevant to windpower's climate-protecting ability. Grid operators normally[44] dispatch power from the cheapest-to-run plants first ("merit order" or "economic dispatch"). Windpower's operating cost is an order of magnitude below coal's, because there's no fuel—just minor operating and maintenance costs. Therefore, whenever the wind blows, wind turbines produce electricity, and coal (or sometimes gas) plants are correspondingly ramped down, saving carbon emissions. Coal makes 50% of U.S. electricity, so on Brand's own assumption of a much smaller (20%) windpower limit, windpower saves coal and money no matter when the wind blows. To put it even more simply, physics requires that electricity production and demand exactly balance at all times, so electricity sent out by a wind turbine must be matched by an equal decrease in output from another plant—normally the plant with highest operating cost, *i.e.* fossil-fueled.

Further layers of fallacy underlie Brand's amiable dismissal of solar power (pp. 101–102):

- For photovoltaics (PVs) to become "a leading source of electricity" does not require numerous "breakthroughs, sustained over decades"; it requires only the sort of routine scaling and cost reduction that the similar semiconductor industry has already done. Just riding down the historic Moore's-Law-like "experience curve" of higher volume and lower cost—a safe bet, since a threefold cost reduction across today's PV value chain is already in view—makes PVs beat a new coal or nuclear plant within their respective lead times. That is, if you start building a coal, gas, or nuclear power plant in, say, New Jersey, and next door you start at the same time to build a solar power plant of equal annual output, then by the time the thermal plant is finished, the solar plant will be producing cheaper electricity, will deliver ~2.5× a coal plant's onpeak output, will have

[42] Bolinger & Wiser, ref. 35, pp. 37–39.
[43] Europe has ≥38 GW of hydroelectric pumped storage, the U.S. ≥20 GW, with much more being built. The U.S. has demonstrated compressed-air storage in solution-mined salt caverns, and the economics look promising: S. Succar & R.H. Williams, "Compressed Air Energy Storage: Theory, Practice, and Applications for Wind Power," Apr. 2008, www.princeton.edu/~cmi/research/Capture/Papers/SuccarWilliams_PEI_CAES_2008April8.pdf. Demand response (influencing *when* customers use electricity) provides cheap and abundant "virtual peakers" to firm variable renewables. The coming electrification of light vehicles will add large and lucrative opportunities for distributed storage (move.rmi.org/innovation-workshop-category/smart-garage.html). And in practically any utility system, the simplest method of integrating variable renewables is just to dispatch them when they're available, ramping down costlier fueled plants. This requires no new technology—only running plants differently—and this is widely done in Europe. U.S. operators are already developing the tools: see, *e.g.*, NERC, "Accommodating High Levels of Variable Generation," 16 Apr. 2009, www.nerc.com/files/IVGTF_Report_041609.pdf.
[44] The main exception is that since nuclear plants are best and safest run steadily, some regulators, *e.g.*, in California, allow them to be dispatched instead of cheaper-to-run renewables, so the nuclear plants needn't ramp down their output when renewables are abundant: their inflexibility makes it hard to ramp their output up and down rapidly or economically. Such favoritism sometimes causes available windpower to be "spilled" (lost). The resulting economic penalty improperly falls on wind, not on nuclear, operators, helping the latter to suppress fair competition without compensation. Some key Midwest utilities simply refuse to buy cheap and available windpower in order to protect their profits from old coal and nuclear plants; so far, state regulators have condoned this anticompetitive practice.

enjoyed more favorable financing because it started producing revenue in year one, and will have been made by photovoltaic manufacturing capacity that can then reproduce the solar plant about every 20 months[45]—so you'd be sorry if you'd built the thermal plant.

- Photovoltaics' business case, unlike nuclear's, needn't depend on government subsidies or support. Well-designed photovoltaic retrofits are already cost-effective in many parts of the United States and of the world, especially when integrated with improved end-use efficiency and demand response (*e.g.*, PowerLight's 2002 retrofit of three acres of PVs on the Santa Rita Jail[46]) and when financed over the long term like power plants, *e.g.*, under the Power Purchase Contracts that many vendors now offer. PVs thrive in markets with little or no central-government subsidy, from Japan (2006–08) to rural Kenya, where electrifying households are as likely to buy them as to connect to the grid.
- Photovoltaics are highly correlated with peak loads; they often exhibit 60% and sometimes 90% Effective Load Carrying Capacity (how much of their capacity can be counted on to help meet peak loads). PV capacity factors can also be considerably higher than Brand's assumed 0.14, especially with mounts that track towards the sun: modern one-axis trackers get ~0.25 in New Jersey or ~0.33–0.35 in sunny parts of California.[47]
- Solar power, Brand asserts, does not work well at the infrastructure level (*i.e.*, in substantial installations feeding power to the grid; the largest installations in spring 2009 produced about 40–60 peak megawatts each). This will surprise the California utilities that recently ordered 850 megawatts of such installations, the firms whose reactor-scale PV farms are successfully beating California utilities' posted utility price in 2009 auctions, the firms that are sustaining ~60–70% annual global growth in photovoltaic manufacturing, and their customers in at least 82 countries. Global installed PV capacity reached 15.2 GW in 2008, adding 5.95 GW (110% annual growth) of sales and 6.85 GW of manufacturing (the rest was in the pipeline).[48] That's more added capacity than the world nuclear industry has added in any year since 1996, and more added annual output than the world nuclear industry has added in any year since 2004. About 90% of the world's PV capacity is grid-tied. Its operators think it works just fine.

The belief that solar and windpower can do little because of their variability is thus exactly backwards: these resources, properly used, can actually become major or even dominant ways to displace coal and provide stable, predictable, resilient, constant-price electricity. What, then, of Brand's other main objection—that these renewable resources take up too much land?

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[45] T. Dinwoodie (SunPower Corp., Systems, Founder and CTO), "Price Cross-Over of Photovoltaics vs. Traditional Generation," 2008. In 2008, the National Renewable Energy Laboratory expected 2010 U.S. PV power to cost 13–18¢/kWh residential, 9–12¢ commercial, and 10–15¢ for utility power; NREL's targets for 2015, respectively 8–10¢, 6–8¢, and 5–7¢, now look likely to be achieved sooner. In contrast, NREL says the current market price ranges for retail grid power are about 6–17¢, 5–15¢, and 4–8¢ respectively. I calculate the delivered cost of power from a new nuclear plant at ~15–22¢ or higher (2007 $; see refs. 5–6). This comparison omits many hidden economic benefits of PVs and other distributed renewables that collectively increase their economic value by often about tenfold: A.B. Lovins, *Small Is Profitable*, 2002, www.smallisprofitable.org.

[46] By first retrofitting a white roof and electricity-saving improvements, the jail operator maximized the solar surplus available on sunny afternoons to sell for the best price. Thus the $9-million project would have made money even without $5-million California subsidies, because its 25-year present-valued benefits were $15 million. Today's PV-system prices are even more favorable.

[47] T. Dinwoodie (SunPower), personal communication, 1 Oct. 2009. Two-axis trackers produce more but cost more.

[48] See *e.g.* www.solarbuzz.com/Marketbuzz2009-intro.htm.

The "footprint" myth

Land footprint seems an odd criterion for choosing energy systems: the amounts of land at issue are not large, because global renewable energy flows are so vast that only a tiny fraction of them need be captured. For example, economically exploitable wind resources, after excluding land with competing uses, are over twice total national electricity use in the U.S. and China; before land-use restrictions, the economic resource is over 6× total national electricity use in Britain, over 10× in the U.S., and 35× worldwide—all at 80-meter hub height, where there's less energy than at the modern ≥100 m.[49] Just the 300 GW of windpower now stuck in the U.S. interconnection queue could displace half of U.S. coal power. Photovoltaics, counting just one-fifth of their extractable power over land to allow for poor or unavailable sites, could deliver over 150 times the world's total 2005 electricity consumption,[50] The sunlight falling on the Earth every ~70 minutes equals humankind's entire annual energy use. An average square meter of land receives each year as much solar energy as a barrel of oil contains, and that solar energy is evenly distributed across the world within about twofold.[51] The U.S., "an intense user of energy, has about 4,000 times more solar energy than its annual electricity use. This same number is about 10,000 worldwide[, so] …if only 1% of land area were used for PV, more than ten times the global energy could be produced…."[52]

Nonetheless, if we assume that land-use *is* an important metric, a closer look reveals that the land-use argument is backwards: correcting Brand's (and many others'[53]) estimates supports the opposite of their footprint conclusion.[54]

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[49] C.L. Archer & M.Z. Jacobson, "Evaluation of global windpower," www.stanford.edu/group/efmh/winds/global_winds.html. Class ≥3 sites (≥6.9 m/s), normally competitive with new coal power at zero carbon price, could yield ~72 TW at 80-m hub height. Contrary to the widespread impression that the best lower-49-states wind areas are only in the Great Plains, the East Coast, and certain West Coast sites, the data show that the Great Lakes wind resource, conveniently near upper Midwest load centers, is also Class 6±1. (It needs marine cables and engineering plus ice protection, but is much closer than Dakotas windpower.) The underlying data are in *J. Geophys. Res.* **110** (2005), D12110, doi:10.1029/2004JD005462, www.stanford.edu/group/efmh/winds/2004jd005462.pdf. The global windpower potential will become far larger even just on land if tethered high-altitude wind-turbine R&D projects succeed.

[50] M.Z. Jacobson, "Review of solutions to global warming, air pollution, and energy security," *En. & Envtl. Sci.* **2**:148–173 (2009), www.stanford.edu/group/efmh/jacobson/PDF%20files/ReviewSolGW09.pdf.

[51] World Energy Council, www.worldenergy.org/publications/survey_of_energy_resources_2007/solar/720.asp. Variation within the continental U.S. is smaller: Buffalo gets only one-fourth less and Arizona one-fourth more annual sunlight than Kansas City—less than regional differences in conventional energy prices (ref. 72). For detailed U.S. solar resource data, see http://rredc.nrel.gov/solar/pubs/redbook/.

[52] USDOE and Electric Power Research Institute, *Renewable Energy Technology Characterizations*, TR-109496, 1997, www.nrel.gov/docs/gen/fy98/24496.pdf, at p. 4-19. See also ref. 40.

[53] Including U.S. Senator Lamar Alexander, who predicts that renewables, if unchecked, will "consume" an area bigger than Nebraska: "Energy 'Sprawl' and the Green Economy," *Wall St. J.*, 18 Sep. 2009, http://online.wsj.com/article/SB10001424052970203440104574404762971139026.html; "The Perils of 'Energy Sprawl," 5 Oct. 2009, http://alexander.senate.gov/public/index.cfm?FuseAction=Speeches.Detail&Speech_Id=0a6f9273-5dbc-4c37-99b6-a9940780c51d.

[54] A cautionary note: land-use analyses assess land transformation (m^2)—land altered from a reference state—or land occupation (m^2-y)—the product of area occupied times duration of occupancy—for various energy outputs or capacities. The results can be hard to interpret if durations are long, effects are partly irreversible, or impacts are incommensurable. For example, the facilities and activities on a nuclear or coal system's land are often more

On p. 81, Brand cites novelist and author Gwyneth Cravens's claim that "A nuclear plant producing 1,000 megawatts [peak, or ~900 megawatts average] takes up a third of a square mile." But this direct plant footprint omits the owner-controlled exclusion zone (~1.9–3.1 mi^2).[55] Including all site areas barred to other uses (except sometimes a public road or railway track), the U.S. Department of Energy's nuclear cost guide[56] says the nominal site needs 7 mi^2, or 21× Cravens's figure. She also omits the entire nuclear fuel cycle, whose first steps—mining, milling, and tailings disposal—disturb nearly 4 mi^2 to produce that 1-GW plant's uranium for 40 years using typical U.S. ores.[57] Coal-mining to power the enrichment plant commits about another 22 mi^2-y of land disturbance for coal mining, transport, and combustion,[58] or an average (assuming full restoration afterwards) of 0.55 mi^2 throughout the reactor's 40-y operating life. Finally, the plant's share of the Yucca Mountain spent-fuel repository (abandoned by DOE but favored by

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permanent and damaging than windpower or solar installations, which can readily be removed altogether. Most metrics used here are, or are converted to, occupancy (simple land areas) to reduce the risk of unit confusion.

[55] Ref. 52, p. 161. By international norms, the minimum buffer zone is 200 ha or 0.77 mi^2: GEN IV International Forum, *Cost Estimating Guidelines for Generation IV Nuclear Energy Systems*, Ref. 3.03b, 29 Sep. 2006, http://nuclear.inl.gov/deliverables/docs/emwgguidelines_ref3.03b.pdf. We don't count here the ~10-mile radius typical of the Emergency Planning Zone in which public activities are permitted.

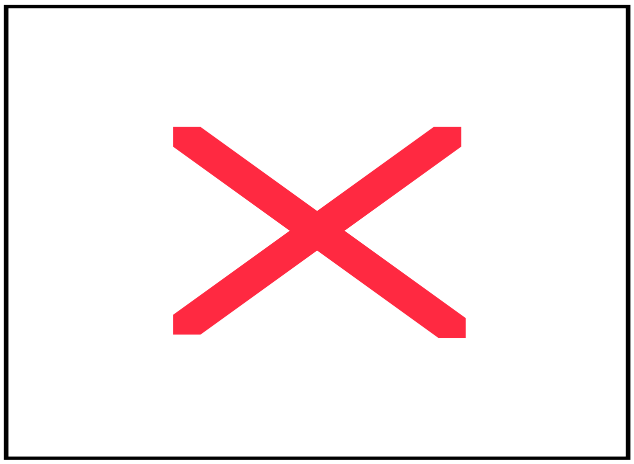
[56] J.G. Delene, K.A. Williams, & B.H. Shapiro, "Nuclear Energy Cost Data Base," DOE/NE-0095 (1988), cited in ref. 57. H.C. Kim & V. Fthenakis, both of Brookhaven National Laboratory, give a similar figure of 52 m^2/GWh or, for our nominal 1-GW plant, 6.3 mi^2: "The Fuel Cycles of Electricity Generation: A Comparison of Land Use," *Mater. Res. Soc. Symp. Proc. Vol. 1041*, 1041-R05-03 (2008). Their ref. 63 expands this analysis to include the full nuclear fuel cycle.

[57] D.V. Spitzley & G.A. Keoleian, "Life Cycle Environmental and Economic Assessment of Willow Biomass Electricity: A Comparison with Other Renewable and Non-Renewable Sources," Rpt. #CSS04-05R, 2004, Center for Sustainable Systems, University of Michigan (Ann Arbor), cite at p. 57 some 2000 DOE data (www.eia.doe.gov/cneaf/nuclear/page/umtra/title1map.html) showing that 18 U.S. decommissioned uranium mines and mills disturbed an average of 0.025 ha/tU_3O_8 for 15 years. However, those 18 operations ran from the 1940s to 1970, and during 1948–70, the average U.S. ore milled contained 0.453% U_3O_8 (author's analysis from USEIA, *Uranium Industry Annual 1992*, DOE/EIA-0478(92), http://tonto.eia.doe.gov/FTPROOT/nuclear/047892.pdf, p. 37). Through the mid-1980s, the modern ore grade reflecting most of the U.S. resource base averaged ~0.1% U_3O_8 (G.M. Mudd & M. Diesendorf, "Sustainability of Uranium Mining and Milling: Toward Quantifying Resources and Eco-Efficiency," *Environ. Sci. Technol.* **42**:2624–2630 (2008), Fig. 1). Assuming, probably conservatively, a constant stripping ratio over the decades, the historical land-use of ~0.025 ha/tU_3O_8 should therefore be adjusted to a modern U.S. value ~4.5× higher, or ~0.112 ha/tU_3O_8. According to www.wise-uranium.org/nfcm.html, a modern EPR-class reactor (4.0% enrichment, 45 GWd/t burnup, 0.9 capacity factor, 0.36 thermal efficiency) uses ~219 tU_3O_8/y on standard assumptions, or 8,769 tU_3O_8/40 y—hence a lifetime total of 986 ha, or 3.8 mi^2, for the nominal 1-GW plant. (That figure would be comparable at Australian ore grades; higher at South African; and lower for Canadian, especially for two extraordinarily high-grade but short-lived deposits: see E.A. Schneider & W.C. Sailor, "Long-Term Uranium Supply Estimates," *Nucl. Technol.* **162**:379–387 (2008).) Ref. 63 is in excellent agreement at 3.66 mi^2. As a cross-check of reasonableness, at a nominal 0.1% ore grade and 91.5% recovery, the modern 1-GW nuclear plant's uranium consumption over 40 y will produce roughly 8.94 million short tons of mill tailings. The tailings piles at 26 uranium mills reported at p. 7 of EIA's 1992 *Uranium Industry Annual* averaged 46,327 ston tailings per acre (24 ft thick), committing 193 acres or 0.30 mi^2 for the 1-GW plant's tailings; at the modern 0.1% ore grade this would be ~1.35 mi^2. Adding the mine area and waste rock disposal (a typical stripping ratio is ~5, and it swells when removed, so it can't all go back in the excavated area) obtains reasonable agreement.

[58] The traditional U.S. method of enrichment (coal-fired gas diffusion, 0.3% tails assay) would use during the 1-GW plant's 40-year life ~10 TWh to power separative work of ~4.3 million SWU. According to Spitzley & Keoleian, average U.S. pulverized-coal-fired electricity averages a land commitment of 580 ha-y/TWh, so we must add another ~5,800 ha-y or 22 mi^2-y to power the enrichment—less with centrifugal enrichment or with less land-intensive electricity sources. Such a reduced modern estimate, from ref. 63, is presented below.

Brand) plus its exclusion zone adds[59] another 3 mi^2. Though this sum is incomplete,[60] clearly Brand's nuclear land-use figures are too low by more than 40-fold[61]—or, according to an older calculation done by a leading nuclear advocate, by more than 120-fold.[62]

This is strongly confirmed by a new, thorough, and authoritative assessment I found after completing the foregoing bottom-up analysis. Scientists at the nuclear-centric Brookhaven National Laboratory and at Columbia University, using Argonne National Laboratory data and a standard lifecycle assessment tool, found[63] that U.S. nuclear-system land use totals 119 m^2/GWh, or for our nominal 1-GW plant over 40 y, 14.5 mi^2—virtually identical to my estimate of at least 14.3 mi^2. Here's their summary of "Land transformation during the nuclear-fuel cycle," Fig. 1:



[59] The Yucca Mountain high-level waste repository, according to D. Bodansky's data cited by Spitzley & Keoleian (ref. 57), commits 6.2 km^2 × (40 y × 23 t spent fuel/y / 70,000 t facility capacity); but those authors failed to notice that this counts only the facility's direct footprint. Dr. Bodansky omitted its permanently withdrawn, DOE-controlled exclusion zone of ~600 km^2 (232 mi^2, 150,000 acres; see Final EIS, pp. 4-5 and 2-79), thus understating its land-use by 97× as ~0.08 rather than the correct ~7.7 km^2 for the nominal 1-GW plant. (That plant's lifetime spent-fuel output of ~920 t represents 1.3% or 1.5% of Yucca Mountain's 63,000 tHM or ~21 PWh of authorized capacity.) Kim & Fthenakis (ref. 56) derive 29 m^2/GWh, or 3.5 mi^2 for our nominal 1-GW plant.

[60] I have not found reliable data, other than old DOE data in Fig. 1, on the minor land-uses for uranium conversion, enrichment, or fuel fabrication facilities including exclusion zones, nor for any land commitment for cooling water.

[61] That is, (7 + 3.8 + 0.55 + 3) / 0.33 = 14.35, which is 43× Cravens's 0.33. As a cross-check, using slightly different global-average nuclear data, Jacobson (ref. 50) uses the Spitzley & Keoleian data to calculate a land commitment of ~20.5 km^2/847 MW reactor at 85.9% capacity factor, or 25.4 km^2 using our assumptions here but excluding enrichment fuel and the Yucca Mountain exclusion zone. That's 9.8 mi^2 (29× Cravens's number), or, adjusted to 0.1%U ore, 16.1 mi^2 or 48× Cravens's claim. Another paper using the Spitzley & Keoleian data (R.I. McDonald *et al.*, "Energy Sprawl or Energy Efficiency: Climate Policy Impacts on Natural Habitat for the United States of America," PLoSONE, 2009, www.plosone.org/article/info:doi/10.1371/journal.pone.0006802#pone.0006802-Spitzley2, cited in ref. 53), expresses its nuclear land-use as 1.9–2.8 km^2/TWh/y, or 5.8–8.5 mi^2 for our nominal 1-GW plant, but shows no derivation, and I have not been able to reproduce its results from its stated sources.

[62] W. Häfele *et al.*, *Energy in a Finite World*, International Institute for Applied Systems Analysis (Laxenburg), 1977, & Ballinger (Cambridge MA), 1981, Vol. 1, p. 286, found that the total area disturbed by the LWR system is ~0.7 mi^2 for fixed facilities, plus ~0.5 mi^2/y for the fuel cycle using 0.203%U ore, which would be ~1 mi^2/y at the modern U.S. norm of 0.1%U ore. (I've adjusted the IIASA figures for the 14% lower uranium use per TWh in today's EPRs and for 90% nuclear capacity factor.) This implies ~41 mi^2 for the 1-GW nuclear plant over its 40-y lifetime, which is 2.9 times my conservative estimate or 123× Cravens's claim.

[63] V. Fthenakis & H.C. Kim, *Renewable and Sustainable Energy Reviews* **13**:1465–1474 (2009), Fig. 1, assuming 50% underground and 50% openpit mining, 70% centrifuge and 30% gas-diffusion enrichment, and apparently counting all terms except disposal sites for low- and medium-level wastes, which neither they nor I can quantify from available data. Erroneously in my view, though, they count windpower area spread across, not occupied.

Of this 119 m^2/GWh of land-use, Brand counts only 2.7 m^2/GWh—1/16th of the power-plant site—or 2.3%. Not that he's unaware of the concept of a fuel cycle, which he bemoans for coal.

His land-use errors for renewables, however, are in the opposite direction. "A wind farm," he says, "would have to cover over 200 square miles to obtain the same result [as the 1-GW nuclear plant], and a solar array over 50 square miles." On p. 86 he quotes Jesse Ausubel's claim[64] of 298 and 58 square miles respectively. Yet these windpower figures are ~100–1,000× too high, because they include the undisturbed land *between* the turbines—~98–99+% of the site[65]—which is typically used for cultivation, grazing, wildlife, or other uses (even solar collection) and is in no way occupied, transformed, or consumed by windpower. For example, the turbines that make 13% of Iowa's electricity rise amidst farmland, often cropped right up to the base of each tower, though wind royalties are often more profitable than crops. Saying that wind turbines "use" the land between them is like saying that the lampposts in a parking lot have the same area as the parking lot: in fact, ~99% of its area remains available to drive, park, and walk in.

The area actually *used* by 900 average MW of windpower output—unavailable for other uses—is only ~0.2–2 mi^2, not "over 200" or "298."[66] Further, as noted by Stanford's top renewables

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[64] Ausubel's charming essay "Renewable and nuclear heresies," *Intl. J. Nuclear Governance, Economy & Ecology* **1**(3):229 (2007), claims energy sources that use material amounts of land are not green because some Greens think human land-use shouldn't increase. Its untransparent but clearly flawed analysis has been heavily criticized privately and publicly, *e.g.* www.newscientist.com/blog/environment/2007/07/just-how-much-land-does-solar-power.html.

[65] According to the European Wind Energy Association's 2009 treatise *The Economics of Wind Energy*, ref. 36, p. 48. The American Wind Energy Association at www.awea.org/faq/wwt_environment.html#How%20much%20land%20is%20needed%20for%20a%20utility-scale%20wind%20plant gives the older and more conservative figure "5% or less", and notes that the land the turbines spread across can decrease by up to 30× on a hilly ridgeline (from 60 to 2 nominal acres/peak MW), though some such sites may require maintained roads, taking back some of the turbine-spread land savings. In a 23 Sep. 2009 online *Wall Street Journal* letter, AWEA gives a 2–5% range and states that "for America to generate 20% of its electricity from wind, the amount of land actually used is about half the size of Anchorage, Alaska, or less than half the amount currently used for coal mining today." DOE / EPRI's 1997 data (ref. 52), reflecting early California practice before turbine layout was well understood, mentions 5–10%. J.G. McGowen & S.R. Connors' thorough "Windpower: A Turn of the Century Review," *Ann. Rev. En. Envt.* **25**:147–197 (2000), at p. 166, give 3–5% for U.S. windfarms in the 1990s, but find 1% typical of U.K. and 1–3% of continental European practice, with "farm land…cultivated up to the base of the tower, and when access is needed for heavy equipment, temporary roads are placed over tilled soil." I consider 1–2% typical of modern practice where land is valued enough to use attentively.

[66] Wind turbines on flat ground are typically spaced 5–10 diameters apart (*e.g.*, in an array designed at 4×7 diameters) so they don't unduly disturb each other's windflow. (Spacing over water or on ridges is often much closer.) A typical modern wind turbine with its infrastructure has a nominal footprint of ~1/4 to 1/2 acre for roads, installation, and transformers (NREL, *Power Technologies Energy Data Book*, Wind Farm Area Calculator, www.nrel.gov/analysis/power_databook/calc_wind.php) and has a peak capacity ~2–5 megawatts, hence an average capacity ~0.6–2 megawatts. That's 0.2–2 mi^2 of actual equipment and infrastructure footprint to match a 1-GW nuclear plant's annual output. As a more rigorous cross-check, a nominal 1.5-MW, 77-m-diameter, 80-m-hub-height turbine in a Class ≥3 wind site would nominally be sited 6 turbines per km^2 (ref. 50, p. 17), so 667 of them would match the peak output and (at 35% wind *vs.* 90% nuclear capacity factor) 1,715 would match the annual output of a 1-GW nuclear plant. Including roads, 1,715 turbines would physically occupy a nominal 1–2% (EWEA, ref. 65) of the area they spread across, which is 1,715/6 = 286 km^2 or 110 mi^2. That 1–2% occupied area is thus 2.9–5.7 km^2 or 1–2 mi^2. Even in probably the highest official land-use estimate, which generously assumes about a thousand times the minimal physical footprint, the Bush Administration's *20% Wind Energy by 2030*, at pp. 110–111, found that 305 GW of U.S. windpower could disturb ~1,000–2,500 km^2 of land, or 1.3–3.2 mi^2/installed GW, or at 35% capacity factor, 3.3–8.1 mi^2/1-GW-reactor-equivalent—still 37–90 times lower than Ausubel's claim of 298 mi^2.

expert, Professor Mark Jacobson,[67] the key variable is whether there are permanent roads. Most of the infrastructure area, he notes, is *temporary* dirt roads that soon revegetate. Except in rugged or heavily vegetated terrain that needs maintained roads, the long-term footprint for the tower and foundation of a modern 5-MW tubular-tower turbine is *only ~13–20 m²*. That's just ~0.005 mi² of actual windpower footprint to produce 900 average MW:[68] not ~50–100× but *22,000–34,000×* smaller than the unused land that such turbines spread across. Depending on site and road details, therefore, Brand overstates windpower's land-use by 2–4 orders of magnitude.

His photovoltaic land-use figures are also at least 3.3–3.9× too high (or ≥4.3× *vs*. an optimized system), apparently due to analytic errors.[69] Moreover, ~90% of today's photovoltaics are mounted not on the ground but on rooftops and over parking lots, using *no* extra land—yet ~90% are also tied to the grid.[70] PVs on the world's urban roofs alone could produce many times the world's electricity consumption.[71] The National Renewable Energy Laboratory found that:

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[67] Ref. 50.

[68] With each 5-MW turbine at 35% capacity factor producing 1.75 average MW, 514 turbines would produce 900 average MW to match the 1-GW nuclear plant. Each turbine has a direct footprint (foundation and tower) of ~20 m², so 514 turbines directly occupy ~20 x 514 = 10,280 m² or ~0.004 mi². We round up to 0.005 to allow for transformers; the cables are always underground. This footprint is normal for flat open sites not needing permanent roads.

[69] In an *average* U.S. site, PVs spreading across 15 mi², but not actually using much or most of it, would produce the same annual grid electricity as a 1-GW nuclear plant from flat horizontal solar cells like the 19.3%-efficient Model 315 in SunPower's current catalog (that firm's prototypes in May 2008 also achieved 23.4%, heading for market ~2010). The math is simple. The U.S. receives annual-average, 24/7/365 sunlight of 1,800 kWh/m²y (one-fifth of full equatorial sea-level noon irradiance), so a 19.3%-efficient module captures an average of 347 kWh/m²y or 40 average WDC/m². AC output is nominally ~23% lower due to practical losses (dirt, fill fraction, wiring and conversion losses, mismatch, system availability, heat: http://rredc.nrel.gov/solar/codes_algs/PVWATTS/system.html), yielding 31 average WAC/m². Now derate generously by another 25%, to 23.1 average WAC/m², to allow ample access space for maintenance (possibly shared with other uses). Thus horizontal flat PVs spread across 3/4 of 900,000,000/23.1 = 39 million m² or 15 mi² will produce 900 average MWAC in an average U.S. site. Tracking collectors could reduce the module area by ~25–36%, or southwestern Nevada siting by ~22%, or both; simply tilting up the panels at the local latitude saves ~16%, but some space is still needed between the panels for access, so for simplicity and conservatism I've used the horizontal model in this illustration. NREL (ref. 72) found that the most efficient packing of tilted 15%-efficient PV modules can spread across 10 km²/GW_p, or 17.4 mi² to match the annual output of our nominal 1-GW nuclear plant; at our 19.3% efficiency that would be 13.5 mi². In excellent agreement, CTO Tom Dinwoodie (personal communication, 2 Oct. 2009) confirms that in a typical U.S. site, SunPower's land-efficient one-axis/backtracking T0 tracker typically yields 0.3 capacity factor at 0.4 ground cover ratio (the ratio of panel area to total land area), so a nuclear-matching PV farm at 20% module efficiency and 80% DC/AC efficiency would spread across 17.8 mi² (or 5.9 if it matched the nuclear plant in capacity rather than in energy). Also consistent with these figures, J.A. Turner (NREL), *Science* **285**:687–689 (30 July 1999), showed that 10%-efficient PVs occupying half of a 100×100-mile square in Nevada could produce all 1997 annual U.S. electricity. But the phrase "occupying half of" is conservative: PVs normally get mounted not *on* the ground but well *above* it, leaving the space between ground mounts available for other uses such as grazing. (The moving shade can reportedly benefit both grass and sheep.) Mounting poles punched into the ground can make actual land-use a very small fraction of the total site areas calculated here, and livestock graze right up to the poles. Two-axis trackers, though typically less cost-effective than one-axis, have an even smaller footprint because they're PVs-on-a-pole, analogous to wind turbines. For comparison, concentrating solar thermal power systems spread across roughly one-third more area than PVs for the same annual (but firm) output, and require cooling, though this can use dry towers. Other revealing land-use comparisons are at www.sourcewatch.org/index.php?title=Concentrating_solar_power_land_use.

[70] Ref. 50, which conservatively projects that 30% of long-term PV capacity will be roof-mounted.

[71] According to Lawrence Berkeley National Lab's world-class roof expert Dr. Hashem Akbari (www.climatechange.ca.gov/events/2008_conference/presentations/2008-09-09/Hashem_Akbari.pdf), the world's dense cities occupy 1% of the earth's land area, or ~1.5 trillion m². About one-fourth of that, or 0.38 million km², is

> In the United States, cities and residences cover about 140 million acres of land. We could supply every kilowatt-hour of our nation's current electricity requirements simply by applying PV to 7% of this area—on roofs, on parking lots, along highway walls, on the sides of buildings, and in other dual-use scenarios. We wouldn't have to appropriate a single acre of new land to make PV our primary energy source!…[I]nstead of our sun's energy falling on shingles, concrete, and under-used land, it would fall on PV—providing us with clean energy while leaving our landscape largely untouched.

and concludes: "Contrary to popular opinion, *a world relying on PV would offer a landscape almost indistinguishable from the landscape we know today*."[72] This would also bypass the fragile grid, greatly improving reliability and resilience.

Summarizing, then, the square miles of land area used to site and fuel a 1-GW nuclear plant at 90% capacity factor, *vs*. PV and wind systems with the same annual output, are:

mi^2/900 av. MWe	*Brand's claim*	*Evidence-based literature findings*
Nuclear	0.33	≥14.3 (ABL); 14.5 (BNL)
Windpower	>200 to 298	In flat open sites, ~0.2–2 (max. 5) actually used with permanent roads; without permanent roads, ~0.005
Photovoltaics	>50 to 58	≤15 with horizontal panels in av. U.S. sites; ≤13.5 if optimized; 0 if on structures

Thus *windpower is far* less *land-intensive than nuclear power*; *photovoltaics spread across land comparable to nuclear if mounted on the ground in average U.S. sites, but much or most of that land (shown in the table) can be shared with lifestock or wildlife, and PVs use* no *land if mounted on structures, as ~90% now are*. Brand's "footprint" is thus the opposite of what he claims.

These comparisons don't yet count the land needed to produce the materials to build these electricity supply systems—because doing so wouldn't significantly change the results. Modern wind and PV systems are probably no more, and may be less, cement-, steel-, and other basic-materials-intensive than nuclear systems—consistent both with their economic competitiveness and with how quickly their output repays the energy invested to make them. For example, a modern wind turbine, including transmission, has a lifecycle embodied-energy payback of under 7 months;[73] PVs' energy payback ranges from months to a few years (chiefly for their aluminum

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roofs. So ignoring all parking structures, and all smaller cities' or non-urban roofs, and assuming that just one-fourth of the big-city roof area has suitable orientation, pitch, shading, and freedom from obstructions, PVs just on the world's urban roofs could produce ~106 PWh/y, or 5.8× global 2005 electricity use. (This assumes the same 75% module derating factor as before, and global-average horizontal surface irradiance of 170 W/m^2 (WEC, ref. 51, but most big cities are at relatively low latitudes with more sun.) Large land areas now occupied by old landfills and Superfund sites, or overwater, could also be covered with PVs without displacing any useful activity.

[72] NREL, "PV FAQs: How much land will PV need to supply our electricity?," DOE/GO-102004-1835 (2004), www.nrel.gov/docs/fy04osti/35097.pdf, italics in original.

[73] Vestas, "Life cycle assessment of offshore and onshore sited wind power plants based on Vestas V90-3.0 MW turbines," Vestas Wind Systems A/S, 2006, www.vestas.com/Files/Filer/EN/Sustainability/LCA/LCAV90_juni_2006.pdf, assuming 105-m hub height onshore. See also www.vestas.com/en/about-vestas/principles/sustainability/wind-turbines-and-the-environment/life-cycle-assessment-(lca).aspx.

and glass housings);[74] and adding indirect (via materials) to direct land-use increases PV systems' land-use by only a few percent,[75] just as it would for nuclear power according to the industry's assessments. Indeed, a gram of silicon in amorphous solar cells, because they're so thin and durable, produces more lifetime electricity than a gram of uranium does in a light-water reactor—so it's not only nuclear materials, as Brand supposes, that yield abundant energy from a small mass. Their risks and side-effects, however, are different. A nuclear bomb can be made from a lemon-sized piece of fissile uranium or plutonium, but not from any amount of silicon.

The "portfolio" myth

Brand's third big argument for needing nuclear expansion (p. 82) is "…portfolio—the idea that climate change is so serious a matter, we have to do *everything* simultaneously to head it off as much as we can." This common view misinterprets the portfolio concept, which comes from financial economics. Investors combine multiple asset classes so that market conditions bad for one kind will be neutral or good for other kinds, improving overall risk/reward performance.[76] But investors assemble financial portfolios judiciously, not indiscriminately. They don't buy one of every kind of asset simply because it exists; some kinds are too costly or risky, and buying them would preclude buying more attractive ones. Diversified energy portfolios are similar: a balanced mix of options needn't and generally shouldn't include everything available.

There is no analytic basis for Brand's assumption that *all* energy options are necessary, nor is it sensible. It's no good claiming we need *all* options just because one feels the climate problem is urgent; we have only so much money. The more urgent you think it is to protect the climate, the more important it is to spend each dollar to best effect by choosing the fastest and cheapest options—those that will displace most carbon soonest.

The only evidence Brand offers for his assumption of nuclear necessity is a famous 2004 paper by Stephen Pacala and Robert Socolow,[77] supposedly showing that we need nuclear power *and* every other climate-protecting option—in all, seven "stabilization wedges," each of which is one-seventh of the greenhouse-gas abatement needed to stabilize CO_2 concentration in the

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[74] See *e.g.*, Ref. 63's citations 27, 34, and 35.

[75] *E.g.*, Kim & Fthenakis, ref. 56, Fig. 3. Ref. 63 states that using U.S. average solar irradiance (1800 kWh/m^2y) and a 30-y assumed life, the indirect land-use for PV balance-of-system is 7.5 m^2/GWh, plus for the installed PV array itself, 18.4, 18, and 15 m^2/GWh for multi-, mono-, and ribbon-Si. Scaled to 900 average MW for 40 y, these would correspond respectively to 0.9, 2.2, 2.2, and 1.8 mi^2. For comparison, that paper calculates 30–60-y direct land-use as 164–463 m^2/GWh with optimal tilt but ~10% efficiency. These direct land-uses correspond to 20–56 mi^2/900 average MW—higher than my ~10 because the paper assumes half my empirical array efficiency and uses layouts with severalfold less dense packing (*id.*; Ref. 52, p. 4-30). Their analysis confirms that PVs produce about two-fifths more electricity per unit of land (over 30 y at 13% efficiency and average U.S. irradiance) than typical U.S. coal-fired power plants do.

[76] More formally, for a given level of expected return, a portfolio minimizes total variance by diversifying amongst assets with poorly correlated risks. Prof. Harry Markowitz shared the Sveriges Riksbank Prize in Economic Sciences in Memory of Alfred Nobel for coinventing portfolio theory in 1952. The late Dr. Shimon Awerbuch, formerly of the International Energy Agency, applied it extensively to electricity portfolio planning. I summarized those applications at length in RMI's 2002 *Economist* book of the year *Small Is Profitable: The Hidden Economic Benefits of Making Electrical Resources the Right Size* (ref. 45).

[77] *Science* **305**:968–972 (2004), www.sciencemag.org/cgi/content/abstract/305/5686/968; the wedges are shown in a tabular format and more fully described at www.princeton.edu/~cmi/resources/wedgesumtb.htm.

atmosphere at 500 parts per million over the next 50 years. One of the seven wedges described is a tripling of the world's current nuclear capacity over 50 years. All seven, says Brand, "could reduce greenhouse gas emissions to a tolerable level, but only if all the wedges are pursued extremely aggressively at the same time, starting yesterday."

The Pacala and Socolow paper doesn't say that: quite the contrary. It presents not seven but 15 wedges, including three from end-use efficiency, one from power-plant efficiency, one from fuel-switching to gas, one each from windpower and photovoltaics, another from wind hydrogen, one from biofuels, three from carbon capture and storage, and two from farm and forest practices. Pacala and Socolow's list of 15 wedges "is not exhaustive": at least eight more wedges were soon added.[78] Brand also overlooks the paper's headline that "the portfolio as a whole is large enough that not every element has to be used." (That could be why Al Gore's movie left out the nuclear wedge.) As Socolow recently reiterated,[79] "…there are enough options for the portfolio that none is indispensable. Thus, climate change mitigation can succeed without nuclear power…." Moreover, Pacala and Socolow explicitly did not consider costs, so their paper offers no advice on "best buys first." Thus it provides *no evidence that a nuclear wedge is needed at all*, let alone that it's a worthy buy. Rather, they show 14 (now at least 22) *other* ways to do nuclear's carbon-reduction job (a nice big number, because we'll probably need upwards of ten wedges to get CO_2 concentration to or below 350 ppm, not 550, and time is of the essence.[80]) Brand rejects or omits all those non-nuclear options and chooses nuclear instead. This choice is particularly perverse because, as refs. 2–6 show, his choice would *harm* climate protection.

Why is that? The central message of those five papers he's failed to address[1–5] is that *the non-nuclear competitors he rejects or ignores have been demonstrated empirically to save carbon more cheaply and quickly*. Nuclear expansion, the papers show, is about the *least* effective way to displace carbon (or achieve any of its other professed goals); the only reason one would choose it is to keep the dying nuclear industry alive as an "option." But having failed to make its way in the market for a half-century, that "option" has become prohibitively costly, requiring continuous and increasingly heroic intensive-care interventions. In the U.S. it's now so expensive that no nuclear plant can be built unless the taxpayers pick up all its cost or risk or both, because private investors are unwilling to hazard their own money. With a two-reactor plant costing well over \$10 billion, perhaps \$15+ billion, so even the biggest U.S. utility (Exelon) couldn't finance one such project on its own balance sheet, the cost of such "options" doesn't complement but devours its rivals. It consumes money, time, and attention better devoted to the solutions that buy ~2–20 times more carbon reduction per dollar and ~20–40 times more carbon reduction per year. These—efficiency and micropower—are the solutions that the global marketplace is overwhelmingly choosing in preference to nuclear power, where allowed to.[81]

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[78] Within half a year, Socolow added eight more wedges: industrial process efficiency, lighting efficiency, solar concentrators (troughs and dishes), hydropower, geothermal, grid-charged batteries for transport, heat pumps for furnaces and boilers, and methane management (www.stabilisation2005.com/day3/Socolow.pdf). I could add still more efficiency wedges based on RMI's empirical results with superefficient buildings, factories, and vehicles.
[79] R.H. Socolow & A. Glaser, "Balancing risks: nuclear energy & climate change," *Daedalus*, Fall 2009, pp. 31–44.
[80] M. Meinshausen *et al*., "Greenhouse-gas emissions targets for limiting global warming to 2˚C," *Nature* **458**:1158–1163 (30 April 2009).
[81] Many durable trends, not counted in ref. 1–5's "snapshot" analyses of current and recent market costs, *all* favor efficiency and renewables. These include: side-benefits of efficiency often worth 1–2 orders of magnitude more than the saved energy; distributed benefits (*Small Is Profitable*, ref. 45) often worth about an order of magnitude in value;

The "role of government" myth

Brand's fourth and last reason for choosing nuclear power (p. 84) is "the role of government ….Energy policy is a matter of such scale, scope, speed, *and* patient follow-through that only a government can embrace it all. You can't get decent grid power without decent government power." That seemingly straightforward observation is far less clear in its implications.

Of course government policy sets the framework for the choices we all make as citizens and as market participants. I think governments should steer, not row, and should steer in the right direction, which includes carbon pricing. I am not a market fundamentalist who supposes that whatever markets choose (distorted as they often are by various heavy hands on the scales) is automatically right and wise: they chose lots of coal power when carbon emissions and land ruination were free, and they've often inhibited efficiency and renewables. But stronger, smarter, more coherent governance *does not automatically favor nuclear power*. It's the other way around: nuclear power *requires* governments to mandate that *it* be built at public expense and without effective public participation—excluding by fiat, or crowding out by political allocation of huge capital sums, the competitors that otherwise flourish in a free market and a free society.

This might sound like an overblown characterization until one reaches the chapter's last six pages. Brand favors "the French approach" to nuclear policy. As ref. 95 shows, and as I reconfirmed on a recent visit to Paris, French energy remains an island of hermetic policy in a sea of market reality: no meaningful public participation, no examination of open issues or new information, and a core strategy—unchanged, one is proudly told, under 14 Prime Ministers and five Presidents over 35 years—set and executed by an elite technocratic cadre unaccountable to anyone. That is what a large nuclear enterprise requires. Such authoritarian rules, says Brand, are also part of the "mobilization that is needed to deal with climate change," so the kind of governance he thinks climate change demands also neatly fits what his favored nuclear solution requires. He praises the new U.S. nuclear subsidies, which rival or exceed new nuclear plants' entire capital cost but vastly exceed competitors' subsidies. (That's the point: if all options were unsubsidized and their social costs internalized, the observed market prices suggest that nuclear would lose decisively against practically anything else.) In short, he would rig the market.

Brand's notion that governments will ignore nuclear power's economics and just buy it—rather as they fought World War II because they must, not because it was cost-effective—presupposes all the rest of the fallacious arguments that nuclear power is vital and desirable for climate protection. Recognize those fallacies, and the tautologous "role of government" argument collapses. However, if Brand were right about this, I would find the political implications disturbing. The world he considers necessary to protect the climate is not a world of market economics and democracy. His view is consistent with the observation that virtually all nuclear orders come from authoritarian governments (or at least ones that allow scant public influence on energy choices) whose power sectors are well insulated from market forces. My own belief, after

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technical and economic synergies of efficiency/renewables and renewables/renewables integration; generally decreasing cost and construction time for efficiency and micropower (but increasing for central plants); generally rising fuel-price volatility and supply risk; increasing climatic and environmental costs and consequences of central plants; financial risk aversion; greater competition in power generation; and more transparent decisionmaking.

observing energy policy in 50-odd countries, is that markets and democracy can produce equal or better climate and energy solutions if allowed to. I also prefer to live in that sort of society.

There's another serious problem with the government-will-just-buy-nuclear assertion. France is commonly cited by nuclear advocates as the model of having done everything right in organizing and managing its nuclear program. Yet its unique and impressive achievements have not saved the French program from serious operational and financial stress,[82] nor from major and continuing escalation in both real capital costs and construction times. Analyzing for the first time the long-secret official cost data on French nuclear construction recently revealed[83] that during 1970–2000, French reactor-builders suffered ~3.5× escalation in real capital cost per kilowatt, and in the 1990s, from major stretching of construction schedules. Thus the world's best-organized and most dirigiste nuclear power program has not been immunized from bad economics.[84]

Citing bad science

Brand's chapter illustrates a troublesome tendency in similar literature to select papers and conclusions that cannot withstand critical scrutiny, while ignoring well-established literature reaching contrary conclusions. For example:

- On p. 82, Brand cites an International Atomic Energy Agency claim that nuclear energy's indirect carbon footprint about equals windpower's and is about half solar's. However, the authoritative independent review article[85] found that nuclear power's carbon intensity, as the mean of many widely divergent findings, is about twice that of photovoltaics or seven times that of modern onshore windpower.
- On p. 87, Brand relies on a biologist who supports nuclear power "in places like China, Europe, and the United States that don't have Australia's renewable energy resources." They must both be unaware of those places' enormous renewable resources—far more diversified than Australia's, which are dominated by sun. For example, the Bush Administration reported in May 2008[86] that the U.S. has >8 TW of economically capturable onshore wind resources (eight times its total electric capacity), and showed how the U.S. could get 305 GW of windpower (making more annual electricity than all U.S. nuclear plants do now) for ~7¢/kWh busbar, including the cost of new transmission lines and the <0.5¢/kWh cost of grid integration. That's one-third higher than the actual price of

[82] See M. Schneider, ref. 95, "Nuclear Power in France: Beyond the Myth" (Dec. 2008, www.greens-efa.org/cms/topics/rubrik/6/6659.energy@en.htm), and "What France got wrong," *Nucl. .Eng. Intl.*, Aug. 2009, p. 42. Financial stress is evident from past bailouts of parts of the nuclear complex and from Areva's overextension today. The nuclear system is so overbuilt, and so reliant on very peaky electric space-heating loads, that by February 2009 the gap between minimum and maximum daily loads was 61 GW, requiring >40 reactors to load-follow.
[83] A. Grübler, "An assessment of the costs of the French nuclear PWR program 1970–2000," Interim Report IR-09-036, International Institute for Applied Systems Analysis (Laxenburg, Austria), 6 Oct. 2009, www.iiasa.ac.at/Admin/PUB/Documents/IR-09-036.pdf.
[84] Even on favorable assumptions, nuclear officially fell off its always-cheaper-than-gas-combined-cycle throne as early as 1997 (ref. 83, p. 14). It still lacks any honest official comparison with micropower and efficiency.
[85] B.K. Sovacool, *En. Pol.* **36**:2490–2953 (Aug 2008), surveyed 103 published studies of nuclear power's energy inputs and indirect carbon emissions; excluded the 84 studies that were older than 10 years, not in English, or not transparent; and found that the other 19 derived gCO_2e/busbar kWh figures ranging from 1.4 to 288; the mean is 66.
[86] USDOE, *20% Wind Energy by 2030*, May 2008, www1.eere.energy.gov/windandydro/pdfs/41869.pdf.

windpower sold from U.S. windfarms installed in 2007[87]—or about one-half to one-third of the industry-reported cost for power from a new U.S. nuclear plant.

- Another misleading and tendentious reference is offered on p. 103 to support the claim that nuclear power in the United States is under-subsidized and renewables are over-subsidized. The opposite is true, as shown in many analyses by the most knowledgeable independent student of this subject, Doug Koplow, at www.earthtrack.net.[88] Of course, on this as on many other controversial topics, one can easily shop for references to support a desired conclusion. Any scholar should know, and any author should ascertain, whether those references are far from the analytically defensible end of a large distribution of diverse findings.
- In perhaps the most egregious speculation, Brand avers on p. 96 that the standard "no-threshold" theory—the "linear hypothesis" that the biological harmfulness of ionizing radiation is proportional to dose, down to even the smallest doses—"is wrong, as most scientists suspect it is…." He even lends credence to the claim that a little ionizing radiation is good for you ("radiation hormesis"). He does not mention that neither theory is accepted by any radiation protection authority, including the International Commission on Radiological Protection and the [U.S.] National Council on Radiation Protection and Measurements, despite many years of strenuous lobbying by the nuclear industry, which would find acceptance of these notions economically helpful. As Brand says on p. 96, "At stake are hundreds of billions of dollars"—a tipoff that careful scholarship is especially important. The balanced "Controversy" discussion of this issue in the *Wikipedia*[89] correctly says their rejection of radiation hormesis is "partly for the sake of caution and partly for the lack of contrary evidence….The notion that hormesis is a widespread of important phenomenon in biological systems is not widely accepted." The claim that "most scientists suspect" the linear hypothesis to be wrong is unsupported and unsupportable.

Sloppy scholarship

Other poor scholarship is evident throughout the nuclear chapter. For example, p. 80 describes California and U.S. "energy use" when it means "electricity use per capita." It also says the abandonment of the Shoreham nuclear plant in or around 1980 "helped frighten the American nuclear industry to a standstill"; actually the plant was completed in 1984 and abandoned in 1988–89, but the industry's last order was in 1978 (the year *before* Three Mile Island), and all orders after 1973 were cancelled. Page 84 says the world and the U.S. "increased" their energy intensity; it means *de*creased. Pages 88–89 misrepresents as nuclear proponents several people whose views, they tell me, are the opposite. Pages 91 and elsewhere list nuclear power's 2008 share of world electricity production as 16%; it was actually 14% and still falling. Page 91 lists 443 civilian power reactors as operating in 2008; the IAEA listed 436, of which five have been in "long term shutdown" since the mid-1990s and at least 17 generated no power in 2008. (At 13 October 2009, the IAEA listed 436 operating reactors, eight fewer than in 2002.) Pages 92 and 95 misspell the name of John Gofman. Page 98 erroneously includes end-use efficiency as part

[87] Bolinger & Wiser, ref. 35: the average 2007- or 2008-installed windfarm sold power for respectively \$0.045/kWh and \$0.0515/kWh, both net of the Production Tax Credit whose levelized aftertax value is ~\$0.01/kWh.
[88] See ref. 95, pp. 73–91, for the best available summary of U.S. and U.K. nuclear subsidies.
[89] At en.wikipedia.org/wiki/Hormesis.

of micropower. Page 107 repeats all the standard fallacies—debunked by National Academy and many other independent studies—about reprocessing's alleged ability to make nuclear waste more compact, easy, and cheap to manage; in fact it does the opposite. The troubled La Hague plant is also said to have "an impeccable safety record." (Thankfully, Brand acknowledges reprocessing's bad economics—but then praises breeders, which require it.) Page 111 uses the nonsensical unit "2 gigawatts per year" as a rate of electricity flow. Page 116 assumes people without electricity can get it only from the grid; actually, when offered it from decentralized solar power (as in Kenya), most prefer and adopt that instead. Brand's external summaries of his nuclear thesis rely upon these and other obvious errors.[90]

Some topics are so thoroughly garbled that one must simply start over from scratch. For example, the discussion of proliferation (in most experts' view, including mine, nuclear power's biggest noneconomic issue) on pp. 108–111 misses all the basic points: *e.g.*, that the problem is not just fissionable materials but also equipment, technology, skills, knowledge, and cadres of nuclear experts, all wrapped in innocent civilian disguise; that nonproliferation requires unmasking proliferators by removing that ambiguity; that supposedly "safe" materials like low-enriched LWR fuel do have significant military potential; that recognizing nuclear power's economic failure offers a unique opportunity to disambiguate it; and that the civil and military sides of nuclear energy have always been and today remain closely intertwined.[91] I concur with Socolow and Glaser, who "judge the hazard of aggressively pursuing an expansion of nuclear power today to be worse than the hazard of slowing the attack on climate change by whatever increment such caution entails."[92] Of course, the simplest way to avoid this disagreeable choice is to take economics seriously and choose the best buys first, thus gaining the most climate protection per dollar and per year through inherently nonviolent technologies.

Brand also claims that nuclear power is a major method of reducing nuclear weaponry. He's referring to the downblending of Russian weapons' highly enriched uranium into reactor fuel at low or natural ^{235}U concentration. That's an excellent idea, but it doesn't require that the resulting low-enriched uranium be used; optionally fissioning it in reactors simply helps repay its

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[90] For example, in www.edge.org/3rd_culture/brand09/brand09_index.html#video he refers to the "vast amount of energy that global computation is consuming." However, J.G. Koomey ("Worldwide electricity used in data centers," *Environ. Res. Lett.* **3**:1–8 (2008)) shows that data centers used 1% of world electricity in 2005—half of it for the servers, half to power and cool them. Such old data-center designs won't be able to compete with efficient new designs. For example, RMI's latest data-center design, due online November 2009 in the U.K. for EDS (now part of HP), is expected to use ~1/16th the previous amount of electricity per unit of computing, and to cost ~10–15% less to build. Had EDS followed all our recommendations, this new data center would have ~1/80th the previous design's electric intensity and cost ~50% less to build. Perhaps Brand has believed the coal industry's extensively debunked disinformation campaign on this topic by Peter Huber and Mark Mills. For details, see J.G. Koomey *et al.*, "Sorry, wrong number: The use and misuse of numerical facts in analysis and media reporting of energy issues," *Ann. Rev. En. Envt.* 119–258 (2002)(also LBNL-50499), and "Network electricity use associated with wireless personal digital assistants," *ASCE J. Infrastr. Systs.* **10**(3):131–137 (Sept. 2008). Koomey's *Turning Numbers into Knowledge* (2d ed., Analytics Press, Oakland, www.analyticspress.com, 2008, Epilogue) is a useful antidote to scholarly lapses.

[91] See *e.g.* A.B. & L.H. Lovins & L. Ross, "Nuclear power and nuclear bombs," *Foreign Affairs* **58**(5):1137–1177 (Summer 1980), www.foreignaffairs.org/19800601faessay8147/amory-b-lovins-l-hunter-lovins-leonard-ross/nuclear-power-and-nuclear-bombs.html or www.rmi.org/images/other/Energy/E05-08_NukePwrEcon.pdf, and S. Cooke, *In Mortal Hands*, Bloomsbury USA, 2009.

[92] Ref. 79, at p. 41. Their paper did not consider relative cost, speed, or hence opportunity cost.

exorbitant sunk cost and is not a disarmament benefit of nuclear power. On the contrary, nuclear power creates demand and "cover" for ambiguous dual-purpose enrichment plants, as in Iran.

The safety and waste issues are similarly too complex to cover here. Suffice it to say that Brand oversimplifies both into engineering issues, then sweeps them away with breathtaking insouciance. These issues have vexed skilled nuclear engineers and scientists for decades because they're hard, not because they're easy; yet Brand mentions none of them specifically. Rather, he breezily proclaims at p. 91, "Reactor safety is a problem already solved": nuclear waste probably isn't so dangerous, major accidents weren't really so bad, operators (presumably better than those at Three Mile Island) will keep reactors safe to prevent huge financial losses, we need to let go of our irrational fears, the engineers assure him they've figured it all out, he's comfortable with their unmentioned solutions, and if anything goes wrong, our descendents can figure out better solutions later. (As Hugh Nash said, how can we better pay tribute to our descendents' boundless technological ingenuity than to make damned sure they'll need it?) Of course, these are not purely engineering issues either: they have a long and disturbing history of human fallibility,[93] institutional laxity, regulatory capture, and sometimes outright mendacity—which has apparently concealed from him, among other things, the geological unsuitability of Yucca Mountain and the many basic reactor safety problems still unsolved since the 1960s.

Nuclear vs. *competitors: market status and prospects*

Perhaps the clearest example of why we differ on nuclear power's status and prospects is his emphasis, on pp. 98–100, on my supposedly being flat wrong about nuclear power's failure in the marketplace. As contrary evidence, he adduces a long list of countries that he claims are planning or building nuclear power plants.[94] In fact, most of those are mere gleams in vendors' eyes, or have merely asked the IAEA for information about nuclear power, or have made a political announcement of intended nuclear plants but without the money, skills, political acceptance, or infrastructure to build and run them—and often without even a power grid big enough to put one into. (The IAEA says a nuclear plant can't be bigger than ~10% of the grid's total capacity, and the smallest power reactors on the market are at least 0.4–0.5 GW, yet Brand lists as "now building nukes for the first time" such nations as Albania with a mere 1.7 GW grid, Bangladesh with 4.7 GW, and Burma, which uses less electricity than one modern reactor makes. (He can only be referring to a 10-MWt *research* reactor now proposed by Myanmar's generals, probably for military use or threat; it's ~0.2% the size of a modern power reactor.) France hopes Vietnam and Thailand will buy reactors, but neither has adequate funds, infrastructure, or grid. In short, many countries' nuclear prospects, as thoroughly documented elsewhere,[95] are far dimmer

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[93] C. Perrow (Yale) argues in *Normal Accidents* (Princeton U. Press, 1984/99) that technologies as complex as nuclear power are inherently unsafe because they fail in more ways than can be foreseen or technologically averted. A terse lay summary by Prof. Robert Pool (*Searching for Safety*, Oxford U. Press, 1997) is at www.pbs.org/wgbh/pages/frontline/shows/reaction/readings/search.html, p. 16.

[94] At p. 98, Brand's unsourced quotation has me telling a TV interviewer in 1986 that no more nuclear plants will be built. I can't find such a quotation, but if I said it, I would certainly have been referring to the United States, although Brand wrongly embeds the quotation in a global context.

[95] M. Schneider *et al.*, *The World Nuclear Industry Status Report* 2009, German Federal Ministry of Environment, Nature Conservation and Reactor Safety, 27 Aug. 2009, www.bmu.de/english/nuclear_safety/downloads/doc/44832.php, See also the IAEA's 2008 "International Status and Prospects of Nuclear Power," which notes that of 43 countries newly requesting the Agency's technical cooperation

than a mere wish-list implies. The IAEA says it typically takes ~15 years for a country with "little developed technical base" to implement its first nuclear power plant.[96]

Some discrepancies are particularly glaring. For example, Brand says Ireland, Norway, and Poland were "planning their first reactors" in 2007;[97] yet according to the IAEA and the OECD Nuclear Energy Agency, Ireland and Norway were and are doing nothing of the sort. Ireland's supposed nuclear customer confirmed to me in May 2009 its intent to go all-renewable. Poland's state power company did announce a wish to build two reactors by 2020, but has no money to buy them, no site (selection is 3–5 years away), no political consensus, and no legal framework or institutional infrastructure.[98] And while it's true that more countries are valuing carbon, they all face fierce nuclear capital cost escalation from bottlenecked suppliers short of capacity and skills. Any countries that pay attention will see, too, that their options aren't just nuclear *vs.* coal.

To be sure, some centrally planned power systems do continue to order and build nuclear plants regardless, almost always drawing directly or indirectly on the public purse. Brand notes that in 2007, the IAEA listed 31 reactors as under construction. I'll spot him 21 more: as of 1 August 2009, there were 52—compared with 120 at the end of 1987 or with 233 at the ordering peak in 1979. To be sure, 52 is more than the 24 observed at the ordering nadir in 2004, but it's also below the annual ordering level of each year during 1967–93, and is just 22% of the peak thirty years ago. Viewed graphically, the past few years' small uptick of construction starts looks like what stockmarket watchers call a dead-cat bounce—especially when one looks more closely at those 52 plants "under construction":[99]

- 13 have been "under construction" for over 20 years
- 24 have no officially planned start date
- half are late, often substantially
- 36 (over two-thirds) are in just four countries—China, India, Russia, and South Korea—none of which use competitive markets to choose whether or which power plants are built, and none of which is very transparent about construction status or decision process.

In Europe, where Brand presents a distorted picture of supposed nuclear revival, there's just one nuclear project that might look at first glance like a private-sector purchase: a TVA-like nonprofit Finnish consortium of utilities, municipalities, and major industries bought the Olkiluoto-3 plant. As its manager recently explained during my site visit, the deal was backed by their balance sheets under a unique take-or-pay capital-charge contract of indefinite duration, with a fixed-price turnkey construction contract from the now-foundered Areva-Siemens joint venture.

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during 2006–08, 16 are "not planning to introduce nuclear power plants, but interested in considering the issues associated with a nuclear power program." Another 14 are "considering a nuclear program to meet identified energy needs with a strong indication of intention to proceed," but most of those lack basic elements to make a program feasible. Only one had prepared a bid to supply a nuclear plant, and just one, Iran, had a plant under construction—since 1975.

[96] "Considerations to Launch a Nuclear Power Programme," GOV/INF/2007/2 (April 2007).

[97] Apparently based on the World Nuclear Association's rosy and clearly exaggerated characterization of them as having nuclear power "under serious consideration": www.world-nuclear.org/info/inf102.html. *Cf.* ref. 95.

[98] An industry summary is at www.world-nuclear-news.org/NN_Nuclear_power_shapes_up_in_Poland_1208092.html.

[99] Ref. 95.

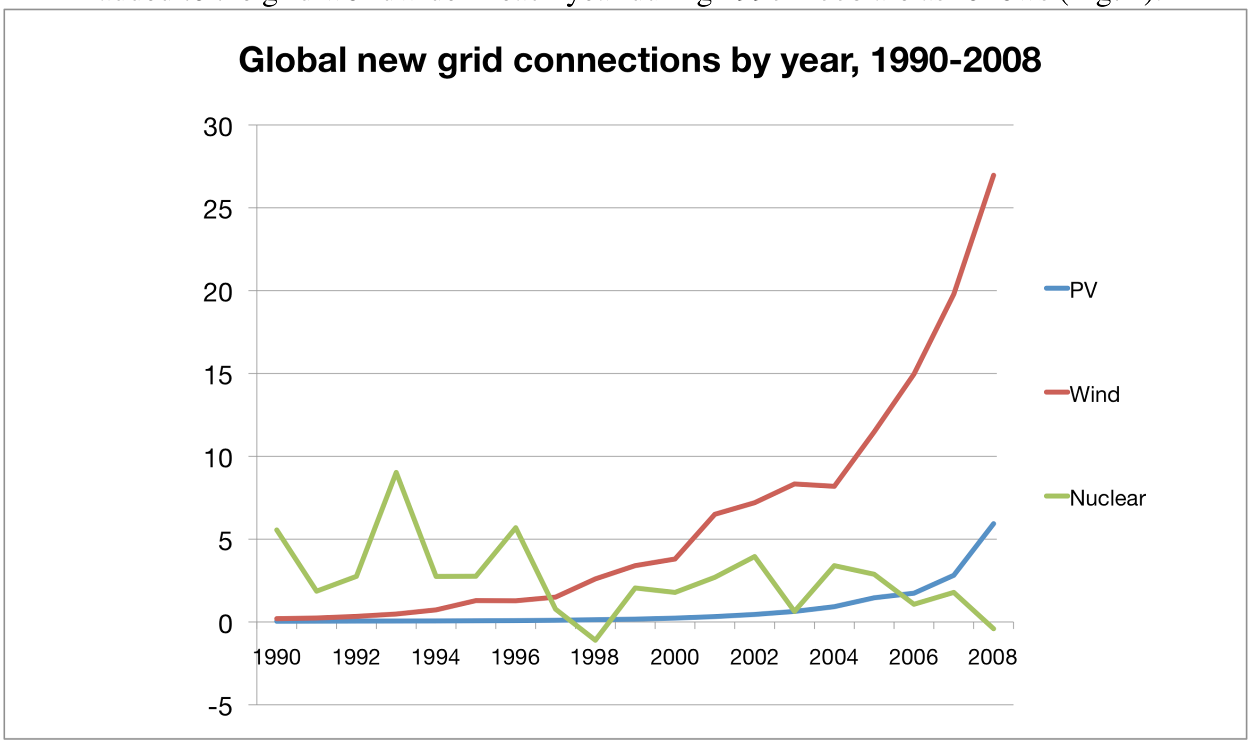
But the full story is more interesting. The plant was largely financed at far below market rates through regional parastatal banks in France and Germany—the builders' home countries. (That's still under legal challenge as an illegal subsidy.) After three and a half years' construction, the project is at least three years late and ~77%[100] over budget, with probably worse to come; the Finnish regulator is publicly very unhappy. In France, the 91%-state-owned vendor Areva has been given an order and an announcement of a second order by the 85%-state-owned national utility Électricité de France despite its manifest nuclear overcapacity. The ordered plant (Flamanville-3), bid 20% higher than the identical Finnish unit and not at a fixed price, has been under construction for a year and a half and is likely a year late and at least 20% over budget. All this may reflect an atrophy of world-leading vendor Areva's capabilities—not surprisingly, since its last order before the Finnish plant was in 1992. The only other European units under construction are mid-1980s projects in Bulgaria and Slovakia. Politically weak Prime Ministers in Italy and Britain declaim about building more reactors, but they lack financing, are barred by EU rules from offering subsidies, and will face serious domestic obstacles as they try to adopt French political structures and decisionmaking practices to support their proposed outsourcing of nuclear construction, financing, and to some degree regulation to organs of the French state.

My 2008 conclusion, which Brand correctly quotes but disputes, was: "Nuclear power is continuing its decades-long collapse in the global marketplace because it's grossly uncompetitive, unneeded, and obsolete." Since he acknowledged and discussed none of the evidence presented for this view in refs. 1–6, let me repeat here an illustrative summary of the past three years' nuclear *vs*. competing orders and installations worldwide. Observed global market behavior tells the story with striking clarity:

- By 2006, micropower was producing one-sixth of the world's total electricity (slightly more than nuclear power), one-third of the world's new electricity, and from one-sixth to more than half of all electricity in a dozen industrial countries—not including the badly lagging U.K. or U.S. (at ~7%), whose rules favor incumbents and their large plants.
- In 2006, nuclear power worldwide added 1.44 billion watts (about one big reactor's worth) of net capacity—more than all of it from uprating old units, since retirements exceeded additions. But photovoltaics added more capacity than that in 2006; windpower, ten times more; micropower, 30–41 times more (depending on whether you include standby and peaking units). Micropower plus negawatts probably provided over half the world's new electrical services. In China, the world's most ambitious nuclear program ended 2006 with one-seventh the installed capacity of China's distributed renewables, and was growing only one-seventh as fast.
- In 2007, the U.S., Spain, and China each added more wind capacity than the world added nuclear capacity, and the U.S. added more wind capacity than it added coal-fired capacity during 2003–07 inclusive. China beat its 2010 windpower target.

[100] According to the additional loss provisions reported in Areva's 30 June 2009 *Half Year Financial Report*, p. 11; a credible source reports, though I have not yet confirmed, €0.4b of additional provisions, implying the plant is 90% over budget (www.challenges.fr/magazine/1/0183-026747/areva_cherche_a_gagner_du_temps.html&ct=ga&cd=P-YGYrhSnwM&usg=AFQjCNGGQCaWUl-Fs2F-LfzmGTLCk3Yz0A). See also "Kernkraft: Die Atom-Schlamperei," *Der Spiegel*, 12 Oct. 2009, pp. 118–121.

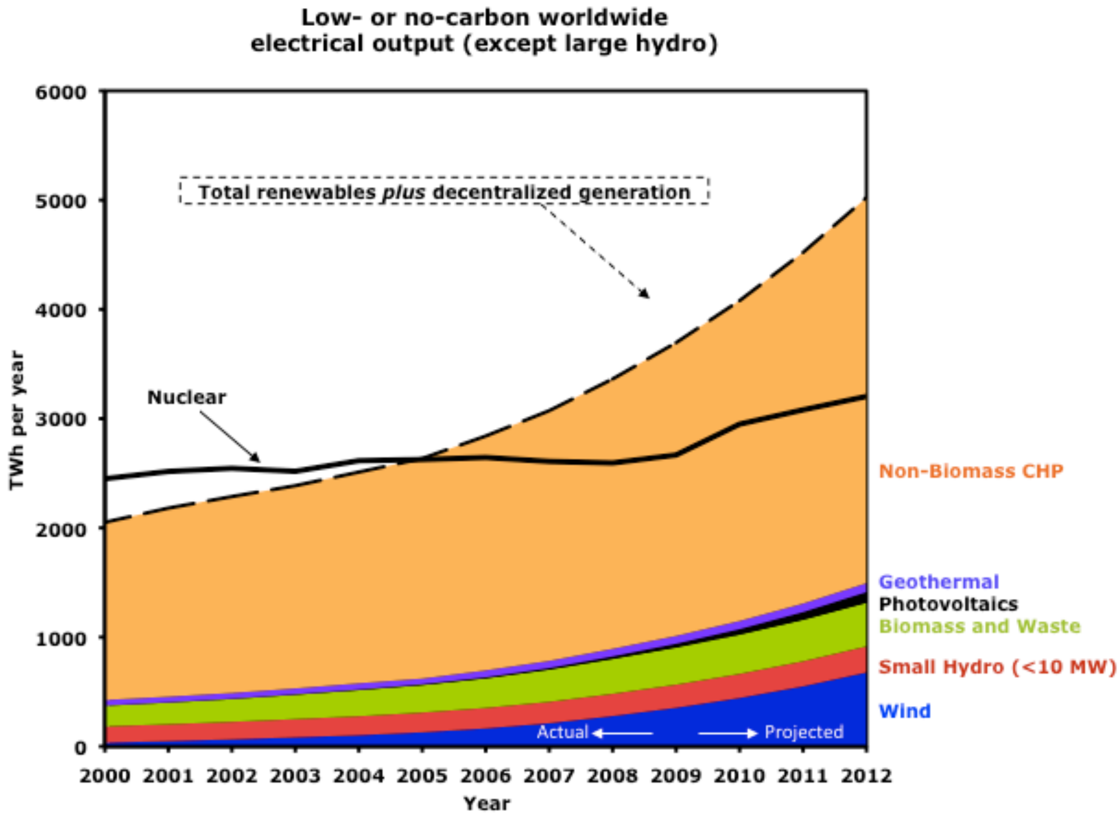
- In 2008, China doubled its windpower installations for the fourth year in a row and looked set to beat its 20*20* windpower target in 20*10*.[101] Windpower pulled ahead of gas-fired capacity additions for the first year in the U.S. and the second year in the EU. For the first time in the nuclear era, no new nuclear plants came online worldwide: nuclear net capacity and output fell. (At 12 October 2009, no new nuclear unit had reportedly come online since August 2007—in Romania, after 24 years' construction.) Nuclear orders trickled in from centrally planned systems but not from markets, garnering only a few percent market share and ~4.4% of all global capacity under construction. In the U.S. from August 2005 to August 2008, with the most robust capital markets and nuclear politics in history, and despite new nuclear subsidies (on top of the old ones) rivaling or exceeding new nuclear plants' total construction cost, not a penny of private equity was offered for any of the 9 "planned" or 24 "proposed" new units: their developers were happy to risk taxpayers' money but not their own. Meanwhile, distributed renewables worldwide in 2008 added 40 GW from $100 billion of investment. That plus ~$40 billion for big hydro dams brought renewable power production, for the first time in about a century, more investment than the ~$110 billion put into fossil-fueled power stations.
- The billions of watts (GW) of new wind, photovoltaic, and nuclear generating capacity added to the grid worldwide in each year during 1990–2008 are as follows (Fig. 2):



- The latest data on micropower's worldwide electricity production are as follows (renewables actual through 2008, cogeneration actual through 2006 and about to be updated to mid-2009, nuclear projections assuming that all announced completions occur

[101] K. Bradsher, www.nytimes.com/2009/07/03/business/energy-environment/03renew.html, "Green Power Takes Root in the Chinese Desert," *N.Y. Times*, 2 July 2009,. The Global Wind Energy Council's 2009 *Outlook* foresees 352–1,193 GW of global windpower in 2020 producing 864–2,600 TWh/y; the latter equals nuclear's output today.

on time and, very implausibly, that no retirements occur in 2010–12—hence the jump shown in apparent output in those years) (Fig. 3):[102]



This rout of nuclear power in the global marketplace, and its inability to persuade private investors anywhere to risk their money on its equity, marks the biggest collapse of any industrial enterprise in the history of the world. Brand can ignore it only by reading World Nuclear Association press releases instead of actual market order and installation data, and by pretending that the decentralized technologies that actually add tens of times more global capacity each year than nuclear power adds somehow cannot be important or effective competitors. He describes solar as "a bit player"—yet even PVs, the costliest renewable, have added more new-unit capacity and output than nuclear has in each of the past three years, and nuclear may never catch up with its explosive growth. As ref. 10 describes, "new" reactor types (pp. 113–114) aren't materially different. No wonder German Environment Minister Sigmar Gabriel, whose country Brand inaccurately says has reneged on its nuclear shutdown law, stated on 27 August 2009 in releasing his Ministry's publication, the *World Nuclear Industry Status Report 2009* (ref. 95):[103]

> The renaissance of nuclear energy, much trumpeted by its supporters, is not taking place. The only thing frequently revived is the announcement. The study shows: the number of old nuclear power plants which are decommissioned worldwide is greater than the number of new ones taking up

[102] RMI periodically updates its documented database of global micropower data from industrial and governmental sources at www.rmi.org/sitepages/pid256.php#E05-04. This graph is from the current update-in-progress. A comparable independent database of distributed renewables, not including cogeneration, is at www.ren21.net.
[103] As posted by his Ministry at www.bmu.de/english/current_press_releases/pm/44840.php; see also *Power in Europe* **558**:5–7 (7 Sep. 2009).

> operation. Available resources, engineering performance and funds are not even enough to stop the downward trend, let alone increase the number of reactors. All the facts are in favour of phasing out this technology while at the same time expanding the use of renewable energies and energy efficiency, as this is a promising option for the future.

Conspicuously absent from Brand's assessment of new nuclear plants is their offset by larger nuclear retirements, as ref. 95 trenchantly analyzes. The average nuclear plant in 2009 is 25 years old, *vs*. 22 for the 123 units already closed. To offset the plants reaching age 40 (their typical now-expected operating life), or 32 by law for the 17 German units, would require completion of all 52 units "under construction" at 1 August 2009; planning, construction, and startup of 42 more plants, one every six weeks, to 2015; plus 192 more, one every 19 days, over the following decade. The 2015 target is unachievable due to constraints on capacity to manufacture key components, so "the number of reactors operating will decline over the years to come—even if the installed capacity could be maintained—unless lifetime extension beyond 40 years becomes standard," raising difficult safety, maintenance-cost, and other issues.[104] U.S. regulators, uniquely, have approved 54 license extensions from 40 to 60 years; other countries have not, and the only two reactors in the world that have run for more than 40 years are slated for shutdown within two years, so operating experience to justify 60-year licenses is extremely sparse. The U.S. extensions only slightly postpone the inevitable global decline in operating nuclear units.

Perhaps Brand's disagreement with my assessment is not really about nuclear power's failure in, as I said, the global marketplace; rather, he's emphasizing its pursuit in countries that *don't* have a marketplace for power plants. A few countries that centrally plan their power systems and socialize their costs *do* buy nuclear plants, some still in substantial numbers. What's in dispute is whether that's the exception or the new rule for the future world. I think nuclear power can't get far without having a business case in market economies too, because I doubt that most of the world's economy will adopt a command-and-control energy economy. Brand apparently thinks they will and should, because (p. 105) "Market forces cannot limit greenhouse gases. Governments have to take the lead. What they deem the atmosphere requires will be the prime driver of the economics of energy." (Of course, carbon pricing, whether by carbon taxes or cap-and-trade, is a market mechanism instituted by governments to limit CO_2 by correcting the market failure of this unpriced major externality.) From there he leaps boldly to the supposition that the nuclear imperative he perceives should, must, and will override all economic, security, and other considerations and cause governments to mandate and finance nuclear construction.

Even if this logic held, the biggest centrally planned energy systems have their own fiscal and logistical limits that are coming into view. China has nearly one-third of all reactors under construction worldwide, with a 2020 nuclear target that was 30–40 GW in 2006 but was recently raised to 70 GW, Brand states, and then to ~80 GW. Clearly if anyone can build enough reactors quickly enough to matter, it's China. Yet if the extraordinarily ambitious target of 80 GW in 2020 were achieved, it would offset only about one-fifth of the expected global retirements of nuclear plants meanwhile. This looks unlikely:

- Many analysts doubt that even China can build or finance 80 GW so quickly. Even if construction time shrank to 5.0 years from the first ten units' 6.3 years, they'd all need to

[104] Schneider *et al*., ref. 95, analyzes the retirement profile with and without life extensions.

be under construction by 2015, *i.e.*, in the next five years. In 2008, China had 8.4 GW of nuclear plants installed, making about 2% of her electricity and 0.8% of her primary energy. Only ~16 units have started construction in the past four years, leaving another 57 to start in the next five years—one a month. Even for China, that's a big challenge.

- Precedent is no proof, but China's 1985 nuclear target of 20 GW in 2000 was missed by tenfold; the 2009 capacity is still under 10 GW (less than windpower, though characteristically, official press releases still describe nuclear's share numerically and all other non-big-hydro renewables' larger share as trivial or negligible).
- By autumn 2009, China's acceleration to 16 nuclear units (15 GW) officially under construction was raising questions about logistical and safety performance. Zhang Guobao, head of the National Energy Administration, warned of signs of "improper" and "too fast" nuclear development in some regions, and added, "We'd rather move slower and achieve less than incur potential safety concerns in terms of nuclear energy."[105]
- Meanwhile, China is moving toward more transparent decisionmaking and more competitive capital allocation. Global experience suggests that neither trend bodes well for prolonged nuclear expansion.
- China's electricity demand, dominated by energy-intensive and export-oriented basic-materials industries, dipped in 2008 and is still recovering to 2007 levels. Power-plant construction has slackened. Tough efficiency standards and policies are also gaining momentum throughout the economy. So are many competitors. A modern natural-gas sector is emerging, and China believes it has at least half as much gas as coal, while some foreign experts think it has far more; it doesn't matter, since the supergiant east Siberian fields will ultimately flow eastward. Chinese analysts are further starting to realize that new coal power is much costlier than meets the eye, especially due to its huge opportunity cost of bottlenecking the winter rail network.
- In striking contrast to central stations, China's aggressively entrepreneurial, largely private-sector vendors of distributed generation seem much better able to meet their newly raised 2020 targets (including 150 GW of windpower and 20 GW of PVs) than nuclear power can. China is #1 in 5–6 renewable technologies and aims to be in all; it became #1 in PV-making in 2008 and should become #1 in wind-installing in 2009. Though windpower's rapid scaling-up is subject to many mishaps—it's lately outpaced both grid expansion and quality control—such glitches can be fixed much more easily in modular renewables than in unforgiving, monolithic nuclear construction projects. All the fast-and-cheap skills that China brings to thermal power plants apply in spades to windpower too, because its tractable unit size, quick manufacturing, and modularity can rapidly capture volume economies and learning effects. And a new Harvard/Tsinghua analysis confirms that available, suitable, windy Chinese sites can meet *all* China's electrical needs—the total, not just the growth—cost-effectively through at least 2030.[106]

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[105] E. Chen & L. Hornby, "China official warns on 'too fast' nuclear plans," 27 Sep. 2009, www.reuters.com/article/GCA-GreenBusiness/idUSTRE58Q1GR20090927.

[106] M.B. McElroy, X. Lu, C.P. Nielsen, & Y. Wang, "Potential for Wind-Generated Electricity in China," *Science* **325**:1378–1380 (11 Sep. 2009), www.sciencemag.org/cgi/content/abstract/325/5946/1378. The turbines analyzed are smaller (1.5 MW), shorter (80 m), and less efficient and well sited (~20% average capacity factor) than modern Western ones, leaving considerable room for improvement without sacrificing China's speed and cost advantages.

Brand thinks renewables can't be important because wind and PVs "aren't baseload," and dismisses or ignores the equally large dispatchable renewables, cogeneration, fuel-switching, or efficiency, so he thinks the only relevant comparison is nuclear *vs.* coal. The nuclear industry shares and spreads this view that its most potent actual competitors aren't legitimate and scarcely matter. But the global power industry knows better. It is shifting massively, even in China, from coal to efficiency, cogeneration, and renewables. Its top officials tell me so.

Reforms like "decoupling and shared savings"—already adopted in 8 of the United States and pending in 11 for electricity, adopted in 18 and pending in 5 for natural gas—will greatly accelerate this shift by rewarding utilities for cutting your bill, not for selling you more energy. So will financial innovations like PACE bonds for retrofitting efficiency and renewables into buildings.[107] So will climate and national-security pressures. Brand believes (p. 105) these pressures can work only through national policy, so governments will set prices and subsidies that will reverse or bypass the market's trend toward micropower. But carbon pricing, though helpful (especially in the electricity sector because it will speed the shift away from coal[108]), seems to me likely to exert less leverage on big energy investments than the underlying competition between efficiency and supply, or between central stations and micropower. A ~\$20/tCO_2 carbon tax makes nuclear look ~2¢/kWh better *vs.* coal, or 1¢/kWh against gas, but it doesn't help any of those three prevail against the zero-carbon efficiency, wind, and solar competitors that are rapidly grabbing the power market from *all* kinds of central thermal stations.

The only key sense in which governments matter to the nuclear choice is whether market economies will force taxpayers to buy lots of the nuclear plants that private investors refuse to finance. The U.S. has tried this since 2005, but no equity has been offered, so now the industry is trying to eliminate the legal requirement for it. If this succeeded on an extremely large scale—hard to imagine for both budgetary and political reasons, even if competitive logic were utterly abandoned—this might perhaps raise nuclear power's market share from a few percent to nearer micropower's tens-of-times-larger level. But I think the expenditures needed are so large that they would quickly exhaust both fiscal capacity and political tolerance, and vendors' recent track record makes it doubtful that they could deliver. Therefore I keep returning to nuclear power's lack of a tenable business case—and its grave opportunity cost of reducing and retarding climate protection. These issues demand answers. Myths are not a responsible substitute.

Physicist Amory Lovins is cofounder, Chairman, and Chief Scientist of Rocky Mountain Institute (www.rmi.org) and Chairman Emeritus of one of its five for-profit spinoffs (www.fiberforge.com), and has written 29 books and hundreds of papers. His wide-ranging innovations in energy, security, environment, and development have been recognized by the Blue Planet, Volvo, Onassis, Nissan, Shingo, and Mitchell Prizes, MacArthur and Ashoka Fellowships, the Benjamin Franklin and Happold Medals, 11 honorary doctorates, honorary membership of the American Institute of Architects, Fellowship of the Royal Society of Arts, Foreign Membership of the Royal Swedish Academy of Engineering Sciences, and the Heinz, Lindbergh, Right Livelihood, National Design, and World Technology Awards. He has taught such topics as design, economics, and business in eight universities, most recently as a 2007 visiting professor in Stanford University's School of Engineering. He has briefed 20 heads of state, advised governments and major firms worldwide on advanced energy and resource efficiency, and led the technical redesign of more than \$30 billion worth of industrial facilities in 29 sectors (and in scores of buildings) to achieve very large energy savings at typically lower capital cost. He has been an independent student of nuclear power for over 40 years and has consulted for over 100 utilities, many of them nuclear operators. In 2009, Time *named him one of the 100 most influential people in the world.*

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[107] See www.pacenow.org.

[108] S.W. Hadley & W. Short, "Electricity sector analysis in the clean energy futures study," *En. Pol.* **29**(14):1285–1298 (Nov. 2001).