Renewable energy's "footprint" myth

Amory B. Lovins, Chairman and Chief Scientist
Rocky Mountain Institute (www.rmi.org)
6 April 2011

Preprint of an article of the same title accepted for publication in July 2011 in
The Electricity Journal **24**(6), June 2011, doi:10.1016/j.tej.2011.06.005

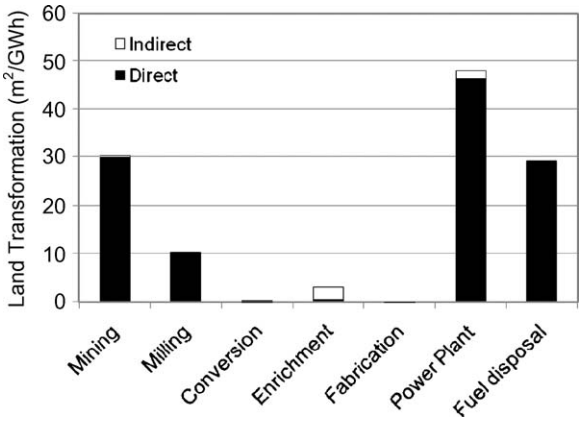
Land footprint seems an odd criterion for choosing energy systems: the amounts of land at issue are not large, because global renewable energy flows are so vast that only a tiny fraction of them need be captured. For example, economically exploitable wind resources, after excluding land with competing uses, are over nine times total national electricity use in the U.S.[i] and over twice in China[ii]; before land-use restrictions, the economic resource is over 6× total national electricity use in Britain and 35× worldwide—all at 80-meter hub height, where there's less energy than at the modern ≥100 m.[iii] Just the 300 GW of windpower now stuck in the U.S. interconnection queue could displace two-fifths 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,[iv] 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.[v] 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…."[vi]

Nonetheless, many nuclear advocates[vii] argue that renewable electricity has far too big a land "footprint" to be environmentally acceptable, while nuclear power is preferable because it uses orders of magnitude less land. If we assume that land-use *is* an important metric, a closer look reveals the opposite is true.[viii]

For example, Stewart Brand's 2010 book *Whole Earth Discipline* 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).[ix] 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[x] 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.[xi] Coal-mining to power the enrichment plant commits about another 22 mi^2-y of land disturbance for coal mining, transport, and combustion,[xii] 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 Brand) plus its exclusion zone adds[xiii] another 3 mi^2. Though this sum is incomplete,[xiv] clearly Brand's nuclear land-use figures are too low by more than 40-fold[xv]—or, according to an older calculation done by a leading nuclear advocate, by more than 120-fold.[xvi]

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[xvii] 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:



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[xviii] 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[xix]—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 15% 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."[xx] Further, as noted by Stanford's top renewables

expert, Professor Mark Jacobson,[xxi] 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 m^2*. That's just ~0.005 mi^2 of actual windpower footprint to produce 900 average MW:[xxii] 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.[xxiii] 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.[xxiv] PVs on the world's urban roofs alone could produce many times the world's electricity consumption.[xxv] The National Renewable Energy Laboratory found that:

> 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% [xxvi]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."*[xxvii] 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 are 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;[xxviii] PVs' energy payback ranges from months to a few years (chiefly for their aluminum and glass housings);[xxix] and adding indirect (via materials) to direct land-use increases PV systems' land-use by only a few percent,[xxx] 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. Only for that purpose is energy or power density a meaningful metric. For civilian energy production, it's merely an intriguing artifact. What matters is economics and practicality.

Physicist Amory Lovins, consultant to business and government leaders worldwide and active in the electricity industry for over 30 years, has written 31 books and over 450 papers. He's received the Blue Planet, Volvo, Onassis, Nissan, Shingo, Zayed, and Mitchell Prizes, MacArthur and Ashoka Fellowships, 11 honorary doctorates, and the Heinz, Lindbergh, Right Livelihood, National Design, and World Technology Awards. Formerly an Oxford don and a visiting teacher at nine universities (most recently Stanford's School of Engineering) he's an Hon. AIA and a Swedish engineering academician. In 2009, *Time* named him one of the 100 most influential people in the world, and *Foreign Policy*, one of the 100 top global thinkers. He's currently Chairman and Chief Scientist at Rocky Mountain Institute (www.rmi.org).

---

[i] National Renewable Energy Laboratory and AWS Truewind, "Estimates of Windy Land Area and Wind Energy Potential by State for Areas ≥30% Capacity Factor at 80 m," 4 Feb 2010.

[ii] M.B. McElroy, Xi Lu, C.P. Nielsen, & Yuxuan Wang, "Potential for Wind-Generated Electricity in China," *Science* **325**:1378 (11 Sep 2009), www.sciencemag.org/cgi/content/full/325/5946/1378, doi: 10.1126/science/1175706.

[iii] 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.

[iv] 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.

[v] 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. xxvii). For detailed U.S. solar resource data, see http://rredc.nrel.gov/solar/pubs/redbook/.

[vi] 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 M.Z. Jacobson & M.A. Delucchi, "A Path to Sustainable Energy by 2030," *Sci. Amer.*, Nov. 2009; on PVs, V. Fthenakis, J.E. Mason, & K. Sweibel, *En. Pol.* **37**:387–399 (2009).

[vii] 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.

[viii] 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 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.

[ix] Ref. vi, 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.

[x] J.G. Delene, K.A. Williams, & B.H. Shapiro, "Nuclear Energy Cost Data Base," DOE/NE-0095 (1988), cited in Spitzley & Keoleian, ref. xi. 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. xvii expands this analysis to include the full nuclear fuel cycle.

[xi] 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. xvii 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.

[xii] 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. xvii, is presented below.

[xiii] The Yucca Mountain high-level waste repository, according to D. Bodansky's data cited by Spitzley & Keoleian (ref. xi), 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. x) derive 29 m^2/GWh, or 3.5 mi^2 for our nominal 1-GW plant.

[xiv] 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.

[xv] 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. iv) 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. vii), 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.

[xvi] 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.

[xvii] 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.

[xviii] 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.

[xix] According to the European Wind Energy Association's 2009 treatise *The Economics of Wind Energy*, 2009 (www.ewea.org), 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. vi), 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.

[xx] 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. iv, 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. xix) 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.

[xxi] Ref. iv.

[xxii] 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 m^2, so 514 turbines directly occupy ~20 x 514 = 10,280 m^2 or ~0.004 mi^2. 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.

[xxiii] In an *average* U.S. site, PVs spreading across 15 mi^2, 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 ~2011–12). The math is simple. The U.S. receives annual-average, 24/7/365 sunlight of 1,800 kWh/m^2y (one-fifth of full equatorial sea-level noon irradiance), so a 19.3%-efficient module captures an average of 347 kWh/m^2y or 40 average WDC/m^2. 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/m^2. Now derate generously by another 25%, to 23.1 average WAC/m^2, 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 m^2 or 15 mi^2 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. xxvii) found that the most efficient packing of tilted 15%-efficient PV modules can spread across 10 km^2/GW_p, or 17.4 mi^2 to match the annual output of our nominal 1-GW nuclear plant; at our 19.3% efficiency that would be 13.5 mi^2. 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 mi^2 (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.

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

[xxv] 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 m^2. About one-fourth of that, or 0.38 million km^2, is 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. v, 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.

[xxvi] This old figure assumes 10% module efficiency. With the best 2011 modules in or entering production, the 7% figure would drop to roughly 3%.

[xxvii] 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.

[xxviii] 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.

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

[xxx] *E.g.*, Kim & Fthenakis, ref. x, Fig. 3. Ref. xvii 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. vi, 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.