NUCLEAR MONITOR

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MONITORED THIS ISSUE:

Don't Nuke the Climate!

Climate change and its impacts are now undeniable. Leaders from the whole world will have to reach a new climate agreement during the December 2009 Copenhagen Summit. Urgent measures must be taken to achieve a massive reduction in our greenhouse gas emissions: our future depends on it!

Under the current Kyoto Protocol, nuclear energy is rightly excluded from the possible solutions available to reduce greenhouse gas emissions. Yet the nuclear industry, in collaboration with certain countries, is pushing for this dangerous and polluting technology to be included in the next climate agreement as a "clean" technology.

This issue of the Nuclear Monitor will counter arguments used by nuclear advocates and -industry. The first article is based on 'Four Nuclear Myths. A commentary on Stewart Brand's Whole Earth Discipline and on similar writings' by Amory B. Lovins, *Chairman, and Chief Scientist of Rocky Mountain Institute*, but shortened and edited by WISE Amsterdam. The second article assesses different lifecycle studies of greenhouse gas equivalent emissions for nuclear and renewable power plants to identify a subset of the most current, original, and transparent studies.

NUCLEAR MYTHS

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.

These arguments are 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.

(699.5999) - This review relies chiefly on five papers. [1-5] They document 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 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 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, 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;[6] and
* windpower and photovoltaics, both rejected on the flawed bases described below.

Other than a mention of big hydro dams, the 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;[7]
* cogeneration (combined-heat-and-power), which is larger today than distributed renewables, has vast further potential[8], 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.[9]

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 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.

Energy efficiency
Nuclear advocates often praise energy efficiency and agree it can do much more, but then drop 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[10] 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 electricity would become unnecessary.[11] 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.[12]
* 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)[13]; or, according to the U.S. utilities' think-tank, could save ~40–60% at an average cost ~3¢/kWh[14] (cheaper than the delivered price of existing coal-fired electricity). The difference between these two findings was largely methodological, not substantive.[15]
* 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.[16]
* Developing countries tend to have greater efficiency *potential* than developed countries. [17] 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.[18] 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 nuclear advocates agree, energy needs a diverse portfolio, not a single "silver bullet." Yet having arbitrarily rejected efficiency as unable to meet *all* global needs for displacing coal and powering economic development, they fail to count any lesser achievement that could stretch other alternatives' contribution to the portfolio -unless it's nuclear.

The "baseload" myth
Many times the most important and successful renewable sources of electricity are rejected for one key reason; it is not

a baseload power. The definition of “baseload” power is often quoted 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.”[19] Thus it describes a pattern of aggregated [20] customer *demand*. Then asserting: “So far [baseload power] comes from only three sources: fossil fuels, hydro, and nuclear.” And explaining 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 is met by generating plants *collectively, not individually.* That is, *reliability is a statistical attribute of all the plants on the grid combined.*[21] 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%).[22] Worldwide through 2008, nuclear units were unexpectedly unable to produce 6.4% of their energy output.[23] 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.”

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.[24] But their inherent variability can be managed by proper resource choice, siting, and operation.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.[25] 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.[26]

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[27] 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 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.[28]

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.[29] 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.[30] 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.[31] Without exception, ~200 international studies have found the same thing.[32] Indeed, the 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.”[33]

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.[34] The Danish utility Dong plans in the next generation to switch from ~15% renewables (mainly wind) and ~85% fossil fuel (mainly coal and 5% nuclear) 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.[35] Similar allrenewable scenarios are emerging for the United States and the world, even without efficiency.[36]

Nonetheless often it is concluded 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 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.[37] The “fourth-fifths illusory” remark also appears to reflect confusing an imaginary 20% limit on windpower’s share of electrical 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.[38] Proven and costeffective bulk power storage is also available if needed.[39]

Even if it were right that variability limits windpower’s potential contribution, that would be irrelevant to windpower’s climate-protecting ability. Grid operators normally[40] 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 the 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 the dismissal of solar power:

* 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 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 ~2.5x a coal plant’s onpeak output, will have 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[41] -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 and when financed over the long term like power plants, *e.g.*, under the Power Purchase Agreements (see box) 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.

A **Power Purchase Agreement** (PPA) is a legal contract between an electricity generator and a power purchaser. The power purchaser purchases energy, and sometimes also capacity and/or ancillary services, from the electricity generator. Such agreements play a key role in the financing of independently owned (i.e. not owned by a utility) electricity generating assets.
The PPA is often regarded as the central document in the development of independent electricity generating assets (power plants), and is a key to obtaining project financing for the project. Under the PPA model, the PPA provider would secure funding for the project, maintain and monitor the energy production, and sell the electricity to the host at a contractual price for the term of the contract. The term of a PPA generally lasts between 5 and 25 years. In some renewable energy contracts, the host has the option to purchase the generating equipment from the PPA provider at the end of the term, may renew the contract with different terms, or can request that the equipment be removed.
From Wikipedia, the free encyclopedia

* 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 assumed, 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.[42]

* Solar power, is often asserted, 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).[43] 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 the other main objection -that these renewable resources take up too much land?

The "footprint" myth

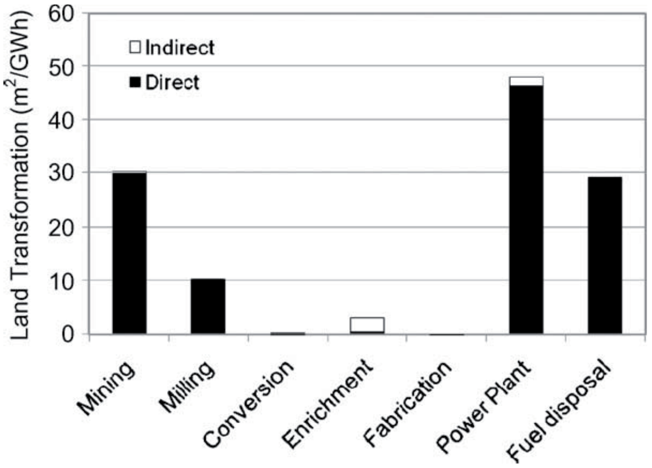
Land footprint seems an odd criterion for choosing energy systems: the amounts of land at issue are not large, because global renewable energy flows are so vast that only a tiny fraction of them need be captured. For example, economically exploitable wind resources, after excluding land with competing uses, are over twice total national electricity use in the U.S. and China; before land-use restrictions, the economic resource is over 6x total national electricity use in Britain, over 10x in the U.S., and 35x worldwide -all at 80-meter hub height, where there's less energy than at the modern ≥100 m.[44] 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.[45] 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.[46] 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…."[47]

Nonetheless, if we assume that land-use *is* an important metric, a closer look reveals that the land-use argument is backwards.[48]

Many quote novelist and author Gwyneth Cravens's claim (in 'Power to Save the World: The Truth About Nuclear Energy', 2007) 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 mi2). [49] 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[50] says the nominal site needs 7 mi2, or 21x Cravens's figure. She also omits the entire nuclear fuel cycle, whose first steps -mining, milling, and tailings disposal- disturb nearly 4 mi2 to produce that 1-GW plant's uranium for 40 years using typical U.S. ores.[51] Coal-mining to power the enrichment plant commits about another 22 mi2-y of land disturbance for coal mining, transport, and combustion,[52] or an average (assuming full restoration afterwards) of 0.55 mi2 throughout the reactor's 40-y operating life. Finally, the plant's share of the Yucca Mountain spent-fuel repository (abandoned by DOE) plus its exclusion zone adds[53] another 3 mi2. Though this sum is incomplete,[54] clearly the quoted nuclear land-use figures are too low by more than 40-fold[55] -or, according to an older calculation done by a leading nuclear advocate, by more than 120-fold.[56]

This is strongly confirmed by a new, thorough, and authoritative assessment 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[57] that U.S. nuclear-system land use totals 119 m2/GWh, or for our nominal 1-GW plant over 40 y, 14.5 mi2 -virtually identical to the estimate of at least 14.3 mi2. Here's their summary of "Land transformation during the nuclear-fuel cycle," **Fig. 1:**



The land-use errors for renewables, however, are in the opposite direction. "A wind farm 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." Conservation biologist and climate change researcher Jesse Ausubel of the Rockefeller University in New York claims [58] a land–use of 298 and 58 square miles respectively. Yet these windpower figures are ~100–1,000 x too high, because they include the undisturbed land *between* the turbines --~98–99+% of the site[59] -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 mi2, not “over 200” or “298.”[60] Further, as noted by Stanford’s top renewables expert, Professor Mark Jacobson,[61] 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[62]; not ~50–100 x but *22,000 – 34,000 x* 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.

The photovoltaic land-use figures are also at least 3.3–3.9 x too high (or ≥4.3 x *vs.* an optimized system), apparently due to analytic errors.[63] 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.[64] PVs on the world’s urban roofs alone could produce many times the world’s electricity consumption.[65] 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% 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 underused 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.”*[66] 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. Nuclear*’s “footprint” is thus the opposite of what is often claimed.

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 basicmaterials- 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;[67] PVs’ energy payback ranges from months to a few years (chiefly for their aluminum and glass housings);[68] and adding indirect (via materials) to direct land-use increases PV systems’ land-use by only a few percent,[69] 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 nuclear proponents claim, 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

“…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. 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 the assumption that *all* energy options are necessary, nor is 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.

Nuclear expansion 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 US$10 billion, perhaps US$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.[70]

The "role of government" myth

A fourth 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. Governments should steer, not row, and should steer in the right direction, which includes carbon pricing. One doesn't have to be 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 looks at "the French approach" to nuclear policy. As ref. 71 shows, 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, as often heard, are also part of the "mobilization that is needed to deal with climate change."

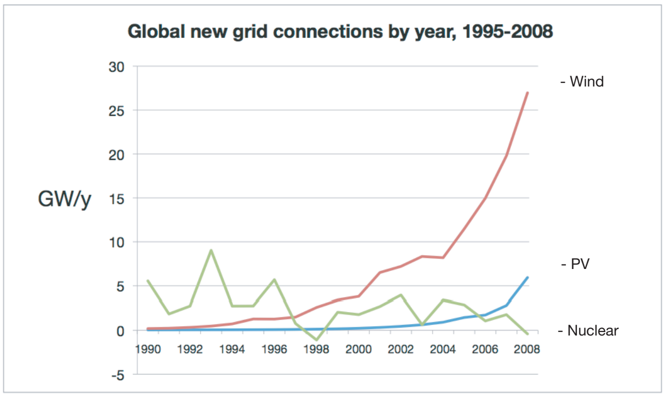
The notion that governments will ignore nuclear power's economics and just buy it -rather as they fought World War II because they must, not because it was cost-effective- presupposes all the rest of the fallacious arguments that nuclear power is vital and desirable for climate protection. Recognize those fallacies, and the tautologous "role of government" argument collapses. However, if the argument was right, the political implications would be disturbing. The world then considered necessary to protect the climate is not a world of market economics and democracy. This 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)[71] whose power sectors are well insulated from market forces. Markets and democracy can produce equal or better climate and energy solutions if allowed to. It is also preferable 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,[72] 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[73] that during 1970–2000, French reactor-builders suffered ~3.5 x 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.[74]

Nuclear* vs. *competitors: market status and prospects

Lovin's 2008 conclusion was: "Nuclear power is continuing its decades-long collapse in the global marketplace because it's grossly incompetitive, unneeded, and obsolete." Let's 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.
* 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*.[75] Windpower pulled ahead of gasfired 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 US$100 billion of investment. That plus ~US$40 billion for big hydro dams brought renewable power production, for the first time in about a century, more investment than the ~US$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 1996–2008 are as follows **(Fig. 2):**



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. Nuclear power can't get far without having a business case in market economies too, because it is doubtful that most of the world's economy will adopt a command-and-control energy economy. But some argue "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 CO2 by correct the market failure of this unpriced major externality.) They leap boldly to the supposition that the nuclear imperative they perceive 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 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 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."[77]
* 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 basicmaterials 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.

> ***"A gram of silicon in amorphous solar cells, produces more lifetime electricity than a gram of uranium does in a light-water reactor."***

* 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.[78]

The nuclear industry spreads the view renewables can't be important because wind and PVs "aren't baseload," and dismiss or ignore the equally large dispatchable renewables, cogeneration, fuel-switching, or efficiency, so we think the only relevant comparison is nuclear *vs.* coal, and that nuclear power's 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.

Some believe climate and national-security 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[79]), 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 ~US$20/tCO2 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 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 it is important to 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.

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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] idem, "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] 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.

[7] 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.

[8] 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.

[9] 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 onethird of all U.S. coal-fired electricity, lowering CO2 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).

[10] 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.

[11] S. Doig *et al.*, "Assessing the Electric Productivity Gap and the U.S. Efficiency Opportunity," RMI, 2009, ert.rmi.org/research/cgu.html.

[12] 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.

[13] 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.

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

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

[16] 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.

[17] 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 Euro per ton of CO2: www.mckinsey.com/clientservice/ccsi/. (That analysis, however, doesn't yet include integrative design (ref. 16).)

[18] 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.

[19] 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.

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

[21] Jim Harding, who led strategic planning for Seattle City Light, says it has no "baseload" resources in the quoted definition'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 the 'demand' definition was right, this would be impossible.

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

[23] IAEA, "Lifetime Unplanned Capability Loss Factor," www.iaea.org/programmes/a2/index.html, accessed 7 Sept. 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%.

[24] 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?
[25] 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).
[26] 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.
[27] 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.
[28] Author's analysis from U.S. Nuclear Regulatory Commission data posted at www.nrc.gov/reading-rm/doccollections/event-status/reactor-status/2003/index.html and www.nrc.gov/info-finder/reactor/.
[29] 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.
[30] *More Fight, Less Fuel*, Feb. 2008, www.acq.osd.mil/dsb/reports/2008-02-ESTF.pdf.
[31] 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.
[32] 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. 31. See also *Small Is Profitable*, ref. 41, and citations in ref. 5.
[33] "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.
[34] Summarized and referenced at www.claverton-energy.com/wind-energy-variability-new-reports.html.
[35] 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.unikassel.de/abt/w3-w/projekte/Risoe200305.pdf.
[36] *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. Fthankis, J.E. Mason, & K. Zweibel, *En. Pol.* 37: 387–399 (2009).
[37] 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).
[38] Bolinger & Wiser, ref. 31, pp. 37–39.
[39] 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.
[40] 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.
[41] 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.
[42] T. Dinwoodie (SunPower), personal communication, 1 Oct. 2009. Two-axis trackers produce more but cost more.
[43] See *e.g.* www.solarbuzz.com/Marketbuzz2009-intro.htm.
[44] 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.
[45] 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.
[46] 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/.
[47] 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. 36.
[48] A cautionary note: land-use analyses assess land transformation (m2) -land altered from a reference state- or land occupation (m2-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.
[49] Ref. 47, p. 161. By international norms, the minimum buffer zone is 200 ha or 0.77 mi2: 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 no public activities are permitted.

[50] 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 m2/GWh or, for our nominal 1-GW plant, 6.3 mi2: “The Fuel Cycles of Electricity Generation: A Comparison of Land Use,” *Mater. Res. Soc. Symp. Proc. Vol. 1041*, 1041-R05-03 (2008). Their ref. 57 expands this analysis to include the full nuclear fuel cycle.

[51] 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/tU3O8 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% U3O8 (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% U3O8 (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/tU3O8 should therefore be adjusted to a modern U.S. value ~4.5x higher, or ~0.112 ha/tU3O8. 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 tU3O8/y on standard assumptions, or 8,769 tU3O8/40 y -hence a lifetime total of 986 ha, or 3.8 mi2, 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. 57 is in excellent agreement at 3.66 mi2. 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 short ton tailings per acre (24 ft thick), committing 193 acres or 0.30 mi2 for the 1-GW plant’s tailings; at the modern 0.1% ore grade this would be ~1.35 mi2. 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.

[52] 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 mi2-y to power the enrichment -less with centrifugal enrichment or with less landintensive electricity sources. Such a reduced modern estimate, from ref. 57, is presented below.

[53] The Yucca Mountain high-level waste repository, according to D. Bodansky’s data cited by Spitzley & Keoleian (ref. 51), commits 6.2 km2 x (40 y x 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 km2 (232 mi2, 150,000 acres; see Final EIS, pp. 4-5 and 2-79), thus understating its land-use by 97 x as ~0.08 rather than the correct ~7.7 km2 for the nominal 1-GW plant. (That plant’s lifetime spentfuel 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. 50) derive 29 m2/GWh, or 3.5 mi2 for our nominal 1-GW plant.

[54] 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.

[55] That is, (7 + 3.8 + 0.55 + 3) / 0.33 = 14.35, which is 43 x Cravens’s 0.33. As a cross-check, using slightly different global-average nuclear data, Jacobson (ref. 45) uses the Spitzley & Keoleian data to calculate a land commitment of ~20.5 km2/847 MW reactor at 85.9% capacity factor, or 25.4 km2 using our assumptions here but excluding enrichment fuel and the Yucca Mountain exclusion zone. That’s 9.8 mi2 (29 x Cravens’s number), or, adjusted to 0.1%U ore, 16.1 mi2 or 48 x 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), expresses its nuclear land-use as 1.9–2.8 km2/TWh/y, or 5.8–8.5 mi2 for our nominal 1-GW plant, but shows no derivation, and I have not been able to reproduce its results from its stated sources.

[56] 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 mi2 for fixed facilities, plus ~0.5 mi2/y for the fuel cycle using 0.203%U ore, which would be ~1 mi2/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 mi2 for the 1-GW nuclear plant over its 40-y lifetime, which is 2.9 times my conservative estimate or 123 x Cravens’s claim.

[57] 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.

[58] 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.

[59] 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%20utilityscale%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 x 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 Sept. 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. 47), 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.

[60] Wind turbines on flat ground are typically spaced 5–10 diameters apart (*e.g.*, in an array designed at 4 x 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 mi2 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 km2 (ref. 45, 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. 59) of the area they spread across, which is 1,715/6 = 286 km2 or 110 mi2. That 1–2% occupied area is thus 2.9–5.7 km2 or 1–2 mi2. 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 km2 of land, or 1.3–3.2 mi2/installed GW, or at 35% capacity factor, 3.3–8.1 mi2/1-GW-reactor-equivalent -still 37–90 times lower than Ausubel’s claim of 298 mi2.

[61] Ref. 45.

[62] 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.

[63] 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. 66) found that the most efficient packing of tilted 15%-efficient PV modules can spread across 10 km2/GWp, 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 x100-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.

[64] Ref. 45, which conservatively projects that 30% of long-term PV capacity will be roof-mounted.

[65] 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 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 x global 2005 electricity use. (This assumes the same 75% module derating factor as before, and global-average horizontal surface irradiance of 170 W/m2 (WEC, ref. 46, but most big cities are at relatively low latitudes with more sun.) Large land areas now occupied by old landfills, or overwater, could also be covered with PVs without displacing any useful activity.

[66] 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.

[67] 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-cycleassessment-(lca).aspx.

[68] See *e.g.*, Ref. 57's citations 27, 34, and 35.

[69] *E.g.*, Kim & Fthenakis, ref. 50, Fig. 3. Ref. 63 states that using U.S. average solar irradiance (1800 kWh/m2y) and a 30-y assumed life, the indirect land-use for PV balance-of-system is 7.5 m2/GWh, plus for the installed PV array itself, 18.4, 18, and 15 m2/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 mi2. For comparison, that paper calculates 30–60-y direct land-use as 164–463 m2/GWh with optimal tilt but ~10% efficiency. These direct land-uses correspond to 20–56 mi2/900 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. 47, 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. coalfired power plants do.

[70] 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; 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.

[71] As of 1 August 2009, there were 52 reactors under construction -compared with 120 at the end of 1987 or with 233 at the ordering peak in 1979. But, from those 52:
* 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. (see 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

[72] See M. Schneider, "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.

[73] A. Grubler, "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.

[74] Even on favorable assumptions, nuclear officially fell off its always-cheaper-than-gas-combined-cycle throne as early as 1997 (ref. 73, p. 14). It still lacks any honest official comparison with micropower and efficiency.

[75] 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.

[76] 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.

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

[78] 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.

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

NUCLEAR ENERGY AND RENEWABLE POWER: WHICH IS THE BEST CLIMATE CHANGE MITIGATION OPTION?

This article assesses different lifecycle studies of greenhouse gas equivalent emissions for nuclear and renewable power plants to identify a subset of the most current, original, and transparent studies. It calculates that mean value for greenhouse gas emissions for nuclear energy over the lifetime of a plant are quite high at about 66 carbon dioxide equivalent per kWh (gCO2e/kWh). Offshore wind power has less than one-seventh the carbon equivalent emissions of nuclear plants; large-scale hydropower, onshore wind, and biogas, about one-sixth the emissions; small-scale hydroelectric and solar thermal one-fifth. This makes these renewable energy technologies seven-, six-, and five-times more effective on a per kWh basis at fighting climate change. Policymakers would be wise to embrace these more environmentally friendly technologies if they are serious about producing electricity and mitigating climate change.

(699.6000) Benjamin K. Sovacool - Advocates of nuclear power have recently framed it as an important part of any solution aimed at fighting climate change and reducing greenhouse gas emissions. Opponents of nuclear power have responded in kind. Which side is right?

I. Introduction

To find out which side is right, this paper screened 103 lifecycle studies of greenhouse gas equivalent emissions for nuclear power plants to identify a subset of the most current, original, and transparent studies. It begins by briefly detailing the separate components of the nuclear fuel cycle before explaining the methodology of the survey and exploring the variance of lifecycle estimates. It calculates that while the range of emissions for nuclear energy over the lifetime of a plant reported from qualified studies examined is from 1.4 grams of carbon dioxide equivalent per kWh (gCO2e/kWh) to 288 gCO2e/kWh, the mean value is 66 gCO2e/kWh.

The article then explains some of the factors responsible for the disparity in lifecycle estimates, in particular identifying errors in both the lowest estimates (not comprehensive) and the highest estimates (failure to consider co-products). It should be noted that nuclear power is not directly emitting greenhouse gases, but rather that life-cycle emissions account for fossil fuel emissions occurring elsewhere and indirectly attributable to nuclear plant construction, operation, uranium mining and milling, and plant decommissioning.

II. Nuclear Lyfecycle

Engineers generally classify the nuclear fuel cycle into two types: “once-through” and “closed.” Conventional reactors operate on a “once-through” mode that discharges spent fuel directly into disposal. Reactors with reprocessing in a “closed” fuel cycle separate waste products from unused fissionable material so that it can be recycled as fuel. Reactors operating on closed cycles extend fuel supplies and have clear advantages in terms of storage of waste disposal, but have disadvantages in terms of cost, short-term reprocessing issues, proliferation risk, and fuel cycle safety. Despite these differences, both once-through and closed nuclear fuel cycles involve at least five interconnected stages that constitute a nuclear lifecycle: the “frontend” of the cycle where uranium fuel is mined, milled, converted, enriched, and fabricated; the construction of the plant itself; the operation and maintenance of the facility; the “backend” of the cycle where spent fuel is conditioned, (re)processed, and stored; and a final stage where plants are decommissioned and abandoned mines returned to their original state.

III. Review of lifecycle studies

To assess the total carbon dioxide-equivalent emissions over the course of the nuclear fuel cycle, this study began by reviewing 103 lifecycle studies estimating greenhouse gas emissions for nuclear plants. These 103 studies were narrowed according to a three-phase selection process.

* First, given that the availability of high quality uranium ore changes with time, and that mining, milling, enrichment, construction, and reactor technologies change over the decades, the study excluded surveys more than ten years old (i.e., published before 1997). Admittedly, excluding studies more than a decade old is no guarantee that the data utilized by newer studies is in fact new. One analysis, for instance, relies on references from the 1980s for the modeling of uranium mining; data from 1983 for modeling uranium tailing ponds; 1996 data for uranium conversion; and 2000 data for uranium enrichment. Still, excluding studies more than ten years old is an attempt to hedge against the use of outdated data, and to ensure that recent changes in technology and policy are included in lifecycle estimates. Still, 40 studies analyzed are excluded by their date.

* Second, this study excluded analyses that were not in the public domain, cost money to access, or were not published in English. Nine studies excluded for lack of accessibility.

* Third, 35 studies were excluded based on their methodology. These studies were most frequently discounted because they either relied on “unpublished data” or utilized “secondary sources.” Those relying on “unpublished data” contained proprietary information, referenced data not published along with the study, did not explain their methodology, were not transparent about their data sources, or did not detail greenhouse gas emission estimates for separate parts of the nuclear fuel cycle in gCO2e/kWh. Those utilizing “secondary sources” merely quoted other previously published reports and did not provide any new calculations or synthetic analysis on their own.

Excluding detailed studies that rely on unpublished or non-transparent data does run the risk of including less detailed (and less rigorous) studies relying on published and open data. Simply placing a study in the public domain does not necessarily make it "good." However, the author believes that this risk is more than offset by the positives benefits of transparency and accountability. Transparency enhances validity and accuracy; public knowledge is less prone to errors, and more subject the process of debate and dialogue that improves the quality of information, tested against other propositions in the marketplace of ideas. Furthermore, transparency is essential to promoting social accountability. Society simply cannot make informed decisions about nuclear power without public information; since the legitimacy of nuclear power is a public issue, the author believes that only results in the public domain should be included.

The survey conducted here found 19 studies that met all criteria: they were published in the past 10 years, accessible to the public, transparent about their methodology, and provided clear estimates of equivalent greenhouse gas emissions according to the separate parts of the nuclear fuel cycle. These studies were "weighed" equally; that is, they were not adjusted in particular for their methodology, time of release within the past ten years, or how rigorously they were peer reviewed or cited in the literature.
A somewhat rudimentary statistical analysis of these 19 studies reveals a range of greenhouse gas emissions over the course of the nuclear fuel cycle at the extremely low end of 1.4 gCO2e/kWh and the extremely high end of 288 gCO2e/kWh. Accounting for the mean values of emissions associated with each part of the nuclear fuel cycle, the mean value reported for the average nuclear power plant is 66 gCO2e/kWh. The frontend component of the nuclear cycle is responsible for 38 percent of equivalent emissions; decommissioning 18 percent; operation 17 percent; backend 15 percent; and construction 12 percent.

IV. Assessing the disparity in estimates

What accounts for such a wide disparity among lifecycle estimates of greenhouse gas emissions associated with the nuclear fuel cycle? Studies primarily differ in terms of their scope; assumptions regarding the quality of uranium ore; assumptions regarding type of mining; assumptions concerning method of enrichment; whether they assessed emissions for a single reactor or for a fleet of reactors; whether they measured historical or marginal/future emissions; assumptions regarding reactor type, site selection, and operational lifetime; and type of lifecycle analysis.

4.1 Scope

Some studies included just one or two parts of the nuclear fuel cycle, whereas others provided explicit details for even subcomponents of the fuel cycle. One study, for example, analyzed just the emissions associated with construction and decommissioning for reactors across the world, where another assessed the carbon equivalent for the construction of the *Sizewell B* nuclear reactor in the United Kingdom. Their estimates are near the low end of the spectrum, at between 3 and 11.5 gCO2e/kWh. In contrast, another study looked at every single subcomponent of the fuel cycle, and produced estimates near the high end of the spectrum at 112 to 166 gCO2/kWh.

4.2 Quality of Uranium Ore

Studies varied in their assumptions regarding the quality of uranium ore used in the nuclear fuel cycle. Low-grade uranium ores contain less than 0.01% yellowcake, and is at least ten times less concentrated than high-grade ores, meaning it takes ten tons of ore to produce 1 kg of yellowcake. Put another way, if uranium ore grade declines by a factor of ten, then energy inputs to mining and milling must increase by at least a factor of ten . This can greatly skew estimates, as uranium of 10% U3O8 has emissions for mining and milling at just 0.04 gCO2/kWh, whereas uranium at 0.013% grade has associated emissions more than 1,500 times *greater* at 67 gCO2/kWh. The same trend is true for the emissions associated with uranium mine land reclamation. With uranium of 10 percent grade, emissions for reclamation are just 0.07 gCO2e/kWh, but at 0.013%, they are 122 gCO2/kWh.

4.3 Open Pit or Underground Mining

The type of uranium mining will also reflect different CO2e emissions. Open pit mining often produces more gaseous radon and methane emissions than underground mines, and mining techniques will release varying amounts of CO2 based on the explosives and solvents they use to purify concentrate. They also point out that the carbon content associated with acid leeching used to extract uranium can vary, as well as the emissions associated with the use of lime to neutralize the resulting leached tailings. The emissions associated with uranium mining depend greatly on the local energy source for the mines. In Canada, uranium extracted from mines closer to industrial centers rely on more efficient, centrally generated power. In contrast, remote mines there have relied on less efficient diesel generators that consumed 45,000 tons of fossil fuel per year/mine, releasing up to 138,000 tons of carbon dioxide every year.

4.4 Gaseous Diffusion or Centrifuge Enrichment

Another significant variation concerns the type of uranium enrichment. Gaseous diffusion is much more energy-intense, and therefore has higher associated carbon dioxide emissions. Gaseous diffusion requires 2,400 to 2,600 kWh per seperative work unit (a function measuring the amount of uranium processed proportioned to energy expended for enrichment), compared to just 40 kWh per SWU for centrifuge techniques. The energy requirements for these two processes are so vastly different because gaseous diffusion is a much older technology, necessitating extensive electrical and cooling systems that are not found in centrifuge facilities. Emissions will further vary on the local power sources at the enrichment facilities. One study calculated 9 gCO2e/kWh for Chinese centrifuge enrichment relaying on a mix of renewable and centralized power sources, but up to 80 gCO2e/kWh if gaseous diffusion is powered completely by fossil fuels.

4.5 Individual or Aggregate Estimates

Some studies look at just specific reactors, while others assess emissions based on industry, national, and global averages. These obviously produce divergent estimates.

One study, for instance, looked at just two actual reactors in Switzerland, the *Gosgen* Pressurized Water Reactor and *Liebstadt* Boiling Water Reactor and calculate emissions at 5 to 12 gCO2e/kWh, whereas other studies look at global reactor performance and reach estimates more than 10 times greater.

4.6 Historical or Marginal/Future Emissions

Yet another difference concerns whether researchers assessed historic, future, or prototypical emissions. Studies assessing historic emissions looked only at emissions related to real plants operating in the past; studies looking at future average emissions looked at how existing plants would perform in the years to come; studies analyzing prototypical emissions looked at how advanced plants yet to be built would perform in the future. One study, for example, found historical emissions for light water reactors in Japan from 1960 to 2000 to be rather high at between 10 and 200 gCO2e/kWh. Others looked at future emissions for the next 100 years using more advanced Pressurized Water Reactors and Boiling Water Reactors. Still other studies made different assumptions about future reactors, namely fast-breeder reactors using plutonium and thorium, and other Generation IV nuclear technology expected to be much more efficient if they ever reach commercial production.

4.7 Reactor Type

Studies varied extensively in the types of reactors they analyzed. More than 30 commercial reactor designs exist today, and each differs in its fuel cycle, output, and cooling system. The most common are the world's 263 Pressurized Water Reactors, used in France, Japan, Russia and the U.S., which rely on enriched uranium oxide as a fuel with water as coolant. Boiling Water Reactors are second most common, with 92 in operation throughout the U.S, Japan, and Sweden, which also rely on enriched uranium oxide with water as a coolant. Then come Pressurized Heavy Water Reactors, of which there are 38 in Canada, that use natural uranium oxide with heavy water as a coolant. Next comes 26 gas-cooled reactors, used predominately in the United Kingdom, which rely on natural uranium and carbon dioxide as a coolant. Russia also operates 17 Light Water Graphite Reactors that use enriched uranium oxide with water as a coolant but graphite as a moderator. A handful of experimental reactors, including fast breeder reactors (cooled by liquid sodium) and pebble bed modular reactors (which can operate at fuel load while being refueled), still in the prototype stages, make up the rest of the world total.

To give an idea about how much reactor design can influence lifecycle emissions, CANDU reactors are the most neutron efficient commercial reactors, achieving their efficiency through the use of heavy water for both coolant and moderator, and reliance on low-neutron absorbing materials in the reactor core. CANDU reactors thus have the ability to utilize low-grade nuclear fuels and refuel while still producing power, minimizing equivalent carbon dioxide emissions. This could be why CANDU reactors have relatively low emissions (~15 gCO2e/kWh) compared to the average emissions from qualified studies as described by this work (~66 gCO2e/kWh).

4.8 Site Selection

Estimates vary significantly based on the specific reactor site analyzed. Location influences reactor performance (and consequential carbon equivalent emissions). Some of the ways that location may influence lifetime emissions include differences in:
 * Construction techniques, including available materials, component manufacturing, and skilled labor;
 * Local energy mix at that point of construction;
 * Travel distance for materials and fuel cycle components;
 * Associated carbon footprint with the transmission and distribution (T&D) network needed to connect to the facility;
 * Cooling fuel cycle based on availability of water and local hydrology;
 * Environmental controls based on local permitting and siting requirements.
Each of these can substantially affect the energy intensity and efficiency of the nuclear fuel cycle.

Consider two extremes. In Canada, the greenhouse gas-equivalent emissions associated with the CANDU lifecycle are estimated at about 15 gCO2e/kWh. CANDU reactors tend to be built with skilled labor and advanced construction techniques, and they utilize uranium that is produced domestically and relatively close to reactor sites, enriched with cleaner technologies in a regulatory environment with rigorous environmental controls. By contrast, the greenhouse-gas equivalent emissions associated with the Chinese nuclear lifecycle can be as high as 80 gCO2e/kWh. This could be because Chinese reactors tend to be built using more labor-intensive construction techniques, must import uranium thousands of miles from Australia, and enrich fuel primarily with coal-fired power plants that have comparatively less stringent environmental and air-quality controls.

4.9 Operational Lifetime

How long the plants at those sites are operated and their capacity factor influences the estimates of their carbon-dioxide equivalent intensity. A 30-year operating lifetime of a nuclear plant with a load factor of 82 percent tends to produce 23.2 gCO2/kWh for construction. Switch the load factor to 85 percent and the lifetime to 40 years, and the emissions drop about 25 percent to 16.8 gCO2/kWh. The same is true for decommissioning. A plant operating for 30 years at 82 percent capacity factor produces 34.8 gCO2/kWh for decommissioning, but drop 28 percent to 25.2 gCO2/kWh if the capacity factor improves to 85 percent and the plant is operated for 40 years.
Most of the qualified studies referenced above assume lifetime nuclear capacity factors that do not seem to match actual performance. Almost all of the qualified studies reported capacity factors of 85 to 98 percent, where actual operating performance has been less. While the nuclear industry in the U.S. has boasted recent capacity factors in the 90-percent range, average load factors over the *entire* life of the plants is very different: 66.3 percent for plants in the UK and 81 percent for the world average.

4.10 Type of Lifecycle Analysis

The type of lifecycle analysis can also skew estimates.

Projections can be "top-down," meaning they start with overall estimates of a pollutant, assign percentages to a certain activity (such as "cement manufacturing" or "coal transportation"), and derive estimates of pollution from particular plants and industries. Or they can be "bottom-up," meaning that they start with a particular component of the nuclear fuel cycle, calculate emissions for it, and move along the cycle, aggregating them. Similarly, lifecycle studies can be "process-based" or rely on economic "input-output analysis." "Process-based" studies focus on the amount of pollutant released—in this case, carbon dioxide or its equivalent—per product unit. For example, if the amount of hypothesized carbon dioxide associated with every kWh of electricity generation for a region was 10 grams, and the cement needed for a nuclear reactor took 10 kWh to manufacture, a process analysis would conclude that the cement was responsible for 100 grams of CO2. "Input-output" analysis looks at industry relations within the economy to depict how the output of one industry goes to another, where it serves as an input, and attempts to model carbon dioxide emissions as a matrix of interactions representing economic activity.

V. Conclusion

The first conclusion is that the mean value of emissions over the course of the lifetime of a nuclear reactor (reported from qualified studies) is 66 gCO2e/kWh, due to reliance on existing fossil-fuel infrastructure for plant construction, decommissioning, and fuel processing along with the energy-intensity of uranium mining and enrichment. Thus, nuclear energy is in no way "carbon free" or "emissions free," even though it is much better (from purely a carbon equivalent emissions standpoint) than coal, oil, and natural gas electricity generators, but worse than renewable and small scale distributed generators (See Table 1).

Source: This article is based on B.K. Sovacool, "Valuing the Greenhouse Gas Emissions from Nuclear Power: A Critical Survey," Benjamin K. Sovacool. *Energy Policy* 36 (8) (August, 2008), pp. 2940-2953.

Contact: B.K. Sovacool is with the Lee Kuan Yew School of Public Policy at the National University of Singapore, 469C Bukit Timah Rd., Singapore, 259772.
Tel: +65 6516 501;
Email: bsovacool@nus.edu.sg.

Table 1: Lifecycle greenhouse gas emission estimates for various electricity generators

Technology	Capacity/Configuration/Fuel	Estimate (gCO2e/kWh)
Wind	2.5 MW, Offshore	9
Hydroelectric	3.1 MW, Reservoir	10
Wind	1.5 MW, Onshore	10
Biogas	Anaerobic Digestion	11
Hydroelectric	300 kW, Run-of-River	13
Solar Thermal	80 MW, Parabolic Trough	13
Biomass	Forest Wood Co-combustion with hard coal	14
Biomass	Forest Wood Steam Turbine	22
Biomass	Short Rotation Forestry Co-combustion with hard coal	23
Biomass	Forest Wood Reciprocating Engine	27
Biomass	Waste Wood Steam Turbine	31
Solar Photovoltaic	Polycrystalline silicone	32
Biomass	Short Rotation Forestry Steam Turbine	35
Geothermal	80 MW, Hot Dry Rock	38
Biomass	Short Rotation Forestry Reciprocating Engine	41
Nuclear	Various reactor types	66
Natural Gas	Various combined cycle turbines	443
Fuel Cell	Hydrogen from gas reforming	664
Diesel	Various generator and turbine types	778
Heavy Oil	Various generator and turbine types	778
Coal	Various generator types with scrubbing	960
Coal	Various generator types without scrubbing	1,050

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WISE/NIRS offices and relays

WISE Amsterdam
P.O. Box 59636
1040 LC Amsterdam
The Netherlands
Tel: +31 20 612 6368
Fax: +31 20 689 2179
Email: wiseamster@antenna.nl
Web: www.antenna.nl/wise

NIRS
6930 Carroll Avenue, Suite 340
Takoma Park, MD 20912
Tel: +1 301-270-NIRS
(+1 301-270-6477)
Fax: +1 301-270-4291
Email: nirsnet@nirs.org
Web: www.nirs.org

NIRS Southeast
P.O. Box 7586
Asheville, NC 28802
USA
Tel: +1 828 675 1792
Email: nirs@main.nc.us

WISE Argentina
c/o Taller Ecologista
CC 441
2000 Rosario
Argentina
Email: wiseros@ciudad.com.ar
Web: www.taller.org.ar

WISE Austria
c/o Plattform gegen Atomgefahr
Roland Egger
Landstrasse 31
4020 Linz

Austria
Tel: +43 732 774275; +43 664 2416806
Fax: +43 732 785602
Email: post@atomstopp.at
Web: www.atomstopp.com

WISE Czech Republic
c/o Jan Beranek
Chytalky 24
594 55 Dolni Loucky
Czech Republic
Tel: +420 604 207305
Email: wisebrno@ecn.cz
Web: www.wisebrno.cz

WISE India
42/27 Esankai Mani Veethy
Prakkai Road Jn.
Nagercoil 629 002, Tamil Nadu
India
Email: drspudayakumar@yahoo.com;

WISE Japan
P.O. Box 1, Konan Post Office
Hiroshima City 739-1491
Japan

WISE Russia
P.O. Box 1477
236000 Kaliningrad
Russia
Tel/fax: +7 95 2784642
Email: ecodefense@online.ru
Web: www.antiatom.ru

WISE Slovakia
c/o SZOPK Sirius
Katarina Bartovicova
Godrova 3/b
811 06 Bratislava
Slovak Republic
Tel: +421 905 935353
Email: wise@wise.sk
Web: www.wise.sk

WISE South Africa
c/o Earthlife Africa Cape Town
Maya Aberman
po Box 176
Observatory 7935
Cape Town
South Africa
Tel: + 27 21 447 4912
Fax: + 27 21 447 4912
Email: coordinator@earthlife-ct.org.za
Web: www.earthlife-ct.org.za

WISE Sweden
c/o FMKK
Tegelviksgatan 40
116 41 Stockholm
Sweden
Tel: +46 8 84 1490
Fax: +46 8 84 5181
Email: info@folkkampanjen.se
Web: www.folkkampanjen.se

WISE Ukraine
P.O. Box 73
Rivne-33023
Ukraine
Tel/fax: +380 362 237024
Email: ecoclub@ukrwest.net
Web: www.atominfo.org.ua

WISE Uranium
Peter Diehl
Am Schwedenteich 4
01477 Arnsdorf
Germany
Tel: +49 35200 20737
Email: uranium@t-online.de
Web: www.wise-uranium.org

WISE/NIRS NUCLEAR MONITOR
c/o WISE Amsterdam
PO Box 59636
1040 LC Amsterdam
Netherlands

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