

Subjective judgments in the nuclear energy debate

Mark Diesendorf

UNSW Australia, Sydney, New South Wales 2052, Australia

email m.diesendorf@unsw.edu.au

Keywords: scenarios, renewable energy, multi-criteria analysis, proliferation, land-use, safety, economics, CO2 emissions

Introduction

For decades scholars have debated energy policy choices, especially hard versus soft energy paths and nuclear versus renewable energy (Supporting Information). Brook and Bradshaw (2015) compare impacts and costs of future energy mixes for electricity generation. They describe their analysis as “objective.” However, all scientific research, including theirs, inevitably contains subjective judgments (e.g., selection of data, method, terminology, assumptions about unknown variables, and onus of proof) (Supporting Information).

Using multicriteria analysis, which is designed to address explicitly subjective judgments (Keeney 2009), Brook and Bradshaw analyzed 3 electricity scenarios: business as usual; renewable energy (RE); and nuclear energy. Their results gave top ranking to nuclear energy.

I examined Brook and Bradshaw’s use of “dispatchability” as a relevant criterion for reliability of electricity supply, their omission of the proliferation of nuclear weapons from the civil nuclear industry and the validity of the subjective values they assigned to the other criteria they considered: land use, life-cycle CO₂ emissions, safety, solid waste, and cost of electricity.

Choice of criteria

Electric power engineers measure the reliability of the electricity supply system by whole system indicators such as loss-of-load-probability and annual energy shortfall (Supporting Information). However, Brook and Bradshaw used dispatchability, the ability of an individual power station to deliver energy upon demand, to compare energy scenarios. This choice is inappropriate and biases their result against wind and photovoltaic (PV) solar power.

Over the past decade, dozens of computer simulations of the operation of large-scale electricity supply systems with 80–100% RE have found that these systems can satisfy standard reliability criteria (Supporting Information). Most of these simulation models use scaled-up commercially available technologies and hourly wind, solar and demand data spanning 1-8 years. They show that generating systems are reliable if they have a geographically dispersed RE supply mix that balances variable, non-dispatchable technologies, such as wind and solar, with flexible, dispatchable technologies, such as hydroelectric dams, biofueled gas turbines, concentrated solar thermal with thermal storage, and demand reduction at critical moments in a ‘smart’ grid. Contrary to Brook and Bradshaw’s contention, these simulation studies show no need for base-load power stations, such as coal or nuclear (e.g. Mai et al. 2012; Elliston et al. 2013). The poor operational flexibility of base-load power stations in general (Supporting Information), especially nuclear, makes them unsuitable partners for large contributions from variable RE. Flexible peak-load power stations are more appropriate partners.

The simulation results are confirmed by observations of reliable electricity systems that have large contributions from renewable energy sources. For example, about 100% of annual electricity consumed in the German states of Mecklenburg-Vorpommern and Schleswig-Holstein, and 39% in Denmark, is from RE, mostly wind (Supporting Information).

Brook and Bradshaw dismiss the possibility of proliferation of nuclear weapons from civil nuclear energy with the statement that it is “a complex political issue, with or without commercial nuclear power plants, and is under strong international oversight.” The Nuclear Non-Proliferation Treaty came too late and had too few signatories to prevent India, Pakistan, North Korea, and South Africa from using civil nuclear energy in varying degrees to build in

secret their nuclear weapons programs (Supporting Information). Furthermore, Australia, Argentina, Brazil, Iran, Libya, South Korea, and Taiwan used civil nuclear energy to commence nuclear weapons programs but discontinued them (Supporting Information).

Nuclear expertise and materials resulting from a civil nuclear energy program provide a civilian-military connection, creating opportunities for nuclear arms proliferation. Thus, nuclear energy increases the number of countries with nuclear weapons or the capacity to build them and hence increases the probability of nuclear war. The omission of proliferation biases the multicriteria analysis toward nuclear energy. Even if the probability of nuclear war arising from proliferation assisted by civil nuclear energy is low, the impact would be so great that it is inappropriate to disregard the risk. Specifically, Brook and Bradshaw claim incorrectly that their reactor of choice, the integral fast reactor, “counters...the proliferation of nuclear weapons”. This claim is only correct if the reactor is operated according to guidelines (Supporting Information).

Values assigned to criteria

Land use

Brook and Bradshaw claim they used “the amount of land area displaced for energy production (facility footprint, roads, construction materials, fuel acquisition, etc.)”. But their extraordinarily high figure for wind (Table 1) is actually the land spanned by wind farms (Supporting Information), which is typically 50–100 times the area displaced (Denholm et al. 2009). Wind farms are highly compatible with almost all forms of agriculture. Provided they are located on agricultural or marginal land, their impacts on biodiversity are likely to be small.

Brook and Bradshaw overestimate land-use by biomass, and hydropower, since several recent RE scenarios make little or no use of biomass and additional global hydro potential is limited (Supporting Information). . Apparently as a result of an arithmetic error, they underestimated the land area for solar energy by an order of magnitude (Table 1; Supporting Information).

As a case study, Elliston et al. (2013) determined the economically optimal mix of 100% renewable electricity in the Australian National Electricity Market (NEM) (Table 1). A simple calculation (Supporting Information) yielded the land area occupied in square kilometers per terawatt-hour per year ($\text{km}^2/\text{TWh/y}$) (Table 1). Brook and Bradshaw's estimate of total land area occupied by renewable electricity is nearly four times that of my estimate. In the case study, the area of land actually occupied by the 100% renewable electricity system is negligible (0.056–0.086%) compared with the land area of the Australian states belonging to the NEM (3.81 million km^2). Therefore, RE systems based primarily on wind and solar, sited appropriately, have tiny negative impact on biodiversity resulting from land use.

The basis for Brook and Bradshaw's calculation of nuclear land area is unclear. However, allowing a hypothetical exclusion zone of radius 20 km around a nuclear power station (as belatedly set for Fukushima) gives a land area in $\text{km}^2/\text{TWh/y}$ that is 1000 times that chosen by Brook and Bradshaw (Table 1; Supporting Information).

Safety

Brook and Bradshaw's treatment of nuclear accidents is not based on a credible reference

(Supporting Information), and they do not explain their assumptions clearly. Footnote f in their Table 1 implies that they considered only short-term deaths from acute radiation syndrome and ignored the major contribution, namely cancer deaths, that appear over several decades. Comprehensive scientific estimates of cancer fatalities from Chernobyl range from “up to 4000” to 93,000 (Supporting Information).

Life-cycle CO₂ emissions

Two independent meta-analyses of over 100 studies of life-cycle CO₂ emissions from nuclear energy obtained means of about 65,000 t CO₂/TWh (Lenzen 2008; Sovacool 2008). The value Brook and Bradshaw give, 20 t CO₂/TWh, was transferred incorrectly from their reference and is a factor of 3,000 below the mean value quoted above, while the value in their Table 1 of 16,000 t CO₂/TWh came from a different source and is a factor of four below the mean (Supporting Information).

Brook and Bradshaw ignore the reality that when high-grade uranium ore becomes scarce in several decades, the emissions from mining and milling low-grade ore (0.01% U₃O₈) will increase total life-cycle emissions substantially to 130,000 t CO₂/TWh (Lenzen 2008) or even 220,000–437,000 t CO₂/TWh (Mudd & Diesendorf 2010). For comparison, Lenzen (2008) found that life-cycle emissions from wind are 10,000–20,000 t CO₂/TWh and 491,000–577,000 t CO₂/TWh for natural gas-fired power stations, making emissions from conventional (generations 2 and 3) nuclear energy with low-grade ore comparable to those of natural gas.

While fast breeder reactors, favored by Brook and Bradshaw, would in theory have much

lower CO₂ emissions, they are not commercially available and may never be. Because they are more complex than generation 2 and 3 reactors, they are likely to be more expensive.

Economics

There are no credible cost estimates for the generation 4 reactors, which are not commercially available.. Brook and Bradshaw cited a projection to 2018 of US nuclear energy costs of \$108.4/MWh for ‘advanced’ reactors, presumably generation 3+, none of which is operating yet. The multinational financial analyst organization Lazard (2014) estimated nuclear costs of \$124–132/MWh in 2017. Lazard’s (2014) estimates are higher because they include direct federal government subsidies, but do not include many other substantial subsidies that would further increase the nuclear cost estimate (Supporting Information).

Brook and Bradshaw ignore that generation 3+ reactors under construction in countries where data are available, both EPR and AP1000, are over construction schedule and greatly over budget. The initial guaranteed price offered by the U.K. government for the proposed Hinkley C reactors is £92.5/MWh or \$140/MWh (greater than Lazard’s highest estimate) increasing with inflation for 35 years. Up-to-date data are unavailable from China, where construction delays are also occurring (Supporting Information). It is too early to assess the economics of generation 3 reactors, for which there is limited operating experience.

Lazard (2014) estimated \$37–81/MWh for onshore wind, and \$72–86/MWh for large-scale solar PV, which are much less than those quoted by Brook and Bradshaw. Lazard’s (2014) results for solar and wind are supported by an independent study and recent contract prices (Supporting Information).

Solid waste

Brook and Bradshaw assume incorrectly that nuclear energy does not produce solid waste (Supporting Information).

Discussion

In Brook and Bradshaw's application of multicriteria analysis to energy futures, their assumptions and choices on proliferation, land use, life-cycle CO₂ emissions, safety, reliability, and cost of electricity supply include inherent value judgments, all of which seem to favor nuclear energy. Furthermore, while they allude to "a sound discussion of risk," they dismiss the contribution of nuclear energy to the low-probability, high-impact risk of nuclear war. In risk analysis in general, low probability, high-risk events are a central concern for risk managers, and it seems unreasonable to ignore them in this discussion. They also appear to ignore an important aspect of nuclear accidents, namely cancer deaths, although their assumptions are not entirely clear.

Brook and Bradshaw do not cite a relevant earlier study on the same topic as their paper by Jacobson (2009), who took a similar approach but obtained quite different results. They also omit several key sources and assumptions, and their analyses appear to contain many factual and numerical errors, citation errors, internal contradictions, and biased statements (Supporting Information). I conclude that their paper is severely flawed and does not present a credible case for nuclear energy, either for biodiversity conservation or a better human society.

Supporting Information

Details supporting particular points made in the paper (Appendix S1), references for RE simulations (Appendix S2), leading RE regions (Appendix S3), and nuclear weapons proliferation countries (Appendix S4) are available online. The author is solely responsible for the content and functionality of this material. Queries (other than absence of the material) should be directed to the corresponding author.

Literature cited

Brook BW, Bradshaw CJA 2015. Key role for nuclear energy in global biodiversity conservation. *Conservation Biology* DOI:10.1111/cobi.12433.

Denholm P, Hand M, Jackson M, Ong S 2009. Land-use requirements of modern wind power plants in the United States. Technical report NREL/TP-6A2-45834. National Renewable Energy Laboratory, Golden CO.

Elliston B, MacGill I, Diesendorf M 2013. Least cost 100% renewable electricity scenarios in the Australian National Electricity Market. *Energy Policy* **59**:270-282.

Jacobson MZ 2009. Review of solutions to global warming, air pollution, and energy security. *Energy and Environmental Science* **2**:148–173.

Keeney RL 2009. Value-focused thinking: a path to creative decision-making. Harvard University Press, Cambridge MA.

Lazard. 2014. Levelized cost of energy analysis – version 8. Lazard, New York. Available from http://www.lazard.com/media/1777/levelized_cost_of_energy_-_version_80.pdf (accessed September 2015).

Lenzen M 2008. Life-cycle energy and greenhouse gas emissions of nuclear energy: A review. *Energy Conversion & Management* **49**:2178–2199.

Mai T, Wiser R, Sandor D et al. 2012. *Renewable electricity futures study*. Vol.1. Technical report TP-6A20-A52409-1. National Renewable Energy Laboratory, Golden, CO. Available from <http://www.osti.gov/bridge> (accessed March 2015).

Mudd GM, Diesendorf M 2010. Uranium mining, nuclear power and sustainability: rhetoric versus reality. Sustainable mining conference 2010. Minerals Institute, Carlton South, Victoria. Available from http://www.ies.unsw.edu.au/sites/all/files/Mudd_045_Uconfpaper-v2.pdf (accessed September 2015).

Sovacool BK 2008. Valuing the greenhouse gas emissions from nuclear power: a critical survey. *Energy Policy* **36**:2950–2963.

Table 1. Land area occupied by 100% renewable energy in the Australian National Electricity Market.^a

Technology	Contribution to electricity supply: Australia (%)	Land area occupied (km ²)	Land area occupied (km ² /TWh/y)	B&B's estimate land area occupied (km ² /TWh/y) ^h
Wind onshore ^b	46.4	147–294	1.3–2.5	46
Solar PV rooftop ^c	20.1	0	0	5.7 (total solar)
Solar on ground, including concentrated solar ^d	21.5	2983	55.5	
Bioenergy ^e	6.2	0	0	95
Existing hydro ^f	5.6	N/A	N/A	N/A
Additional hydro	0	0	0	50
Total for renewable energy	99.8	3130–3277	56.8–58.0	196.7
Nuclear in B&B's global scenario			100 ^g	0.1

- a. Annual electricity demand assumed to be 250 terawatt-hours (TWh), which equals Australia's total electricity generation in 2012-2013. Demand for grid electricity has been falling each year since 2010. Optimal mix of 100% renewable energy technologies, low-cost scenario, as calculated by Elliston et al. (2013, Table 5). While the optimal mix has been calculated for an Australian model, the land uses by wind and solar technologies are based on typical international observations (e.g. Denholm et al. 2009 for wind).
- b. Assumptions for columns 2-4: wind capacity factor 30%; 3 MW turbines spaced at 1 km in large square arrays.
- c. In Europe, Australia, and Japan most photovoltaic solar (PV) is on rooftops. Most PV in the United States is on the ground. There are sufficient rooftops in Australia to supply at least 25% of 250 TWh per year. Brook and Bradshaw treat solar as a single category and do not state the proportions of rooftop and on-ground solar they assume.
- d. Assumptions for columns 2-4: solar capacity factor 20%; based on Gemasolar solar power station 1 GW occupies 97.5 km².
- e. Bioenergy occupies zero land in the present scenario because it is obtained from residues of existing agriculture. Brook and Bradshaw assume dedicated energy crops that occupy additional land.
- f. Existing hydro contributes 5.6% of annual electricity supply; however, there is no additional hydro, so there is no additional land area for hydro in the table. The land occupied by existing hydro could be offset by the land gained by covering open-cut coal mines.
- g. My calculation based on placing a hypothetical buffer of radius 20 km around a 2 GW nuclear power station (Supporting Information).
- h. Brook and Bradshaw sometimes use km²/TWh and sometimes km²/TWh/y. I consider that the latter is the relevant measure for wind, solar and most other renewable energy sources, because the lifetime of the technology is irrelevant. When a wind turbine or solar collector reaches the end of its operating life, it can be replaced or renovated on the same site. However, this may not be the case for a nuclear power station, which leaves a contaminated site.