Supporting Information (28 pages, published online)

for Diesendorf M (2016) Subjective Judgments in the Nuclear Energy Debate.
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Appendix S1: Text of supporting information

Debate over energy policy choices

For the debates over energy policy choices, especially 'hard' versus 'soft' energy paths, and nuclear versus renewable energy (RE), see Teller & Latter (1958); Lovins (1977); Smil (2010); and Sovacool (2011).

Subjective judgments by scientists

Brook and Bradshaw (2015) exhibit biased subjective judgments by stating that theirs is a 'scientific appraisal' and 'objective', while opponents are guided by 'preconceived notions and ideals'. They ignore the existence of many scientist opponents of nuclear energy and fail to recognise that science alone cannot determine a stance or a policy on an issue; value (subjective) judgments and other considerations are unavoidable. The subjective judgments inherent in scientific research are particularly visible when that research is applied to the real world. They include selection of data, method, definitions, terminology, context, assumptions about unknown variables and onus of proof. These subjective judgments are inevitably biased, since scientists are people and so their values and attitudes are influenced by their experiences, readings, peer groups, friends, funding sources, vested interests and the media. (Mitroff 1974; Diesendorf 1983; Chalmers 2013; Martin 2014, Chapter 2).

The solution is not to claim objectivity, but to state openly one's background, assumptions and motivations. Both the article by Brook & Bradshaw (2015) and my critique inevitably contain value judgments. Therefore it is relevant to mention the backgrounds of the parties to this debate. I am a physical scientist who has researched RE, sustainable development and energy policy for about 35 years. I have come to a public position opposed to nuclear energy on the grounds that it is too dangerous, too expensive, too high in life-cycle CO_2 emissions in the long run, too inflexible in operation and too slow a technology to construct in order to make a significant contribution to cutting greenhouse gas emissions. Brook and Bradshaw are biologists who have more recently entered the energy debate in support of nuclear energy. Brook runs a website, Brave New Climate http://bravenewclimate.com that promotes nuclear energy and criticises RE. Brook and Bradshaw have organised a letter http://bravenewclimate.com/2014/12/15/an-open-letter-to-environmentalists-on-nuclear-energy and media release entitled 'Nuclear should be in the energy mix for biodiversity' (15 December 2014) signed by more than 60 conservation scientists and citing Brook and Bradshaw's *Conservation Biology* paper as the basis of the statement. Therefore, both Brook and Bradshaw's paper and my Comment on it are socio-political documents as well as scientific papers. The reader must judge which has the better science and logic.

Multicriteria analysis is no exception to subjectivity (Keeney 2009; Department for Communities and Local Government 2009). Indeed leading practitioners of this science and art recognize the presence of value judgments as a strength, provided that the value-laden assumptions and judgments made in such analysis are stated openly and not hidden behind false claims of objectivity (Keeney 2009).

System reliability

As pointed out in the paper, in comparing energy scenarios rather than individual technologies, the important concept is the reliability of the whole generating system, not the dispatchability of individual power stations making up that system. There are three principal measures of power system reliability: Loss-of-Load Probability (LOLP), which is the expectation value of the probability that supply fails to meet demand; the energy shortfall (usually over one year) and the frequency and duration of forced outages (Čepin M 2011). The USA generally uses Loss-of-Load Probability (e.g. Mai et al. 2012, Box 1-1), the Australian National Electricity Market uses energy shortfall (Australian Energy Regulator 2011) and all three measures are used in Europe.

Appendix S2 lists a recent sample from the dozens of hourly computer simulations of the operation of large-scale electricity supply systems with 80–100% renewable electricity. These simulations demonstrate that RE systems can be just as reliable as conventional systems. A more extensive list, including older papers, is given by Diesendorf (2014, Table 3.1). Sørensen (2015) gives a comprehensive review and analysis of RE variability and several ways of managing it. Brook and Bradshaw ignore the extensive scholarly literature in this field.

In the modelling of the Australian National Electricity Market (Elliston et al. 2013, 2014), biofuelled gas turbines are used to fill potential shortfalls in supply on winter evenings following those overcast days when wind speeds were low. These events are infrequent and mostly of short duration (1–2 hours) and so, in the studies published so far, gas turbines supply only 6% of annual electricity generated. This could easily be provided from agricultural and/or plantation forestry residues in Australia, even during drought years (Diesendorf 2007, pp.138–141). Recent simulations have increased the geographic distribution of wind farms, resulting in a reduction of the bioenergy contribution to about 2% of annual electricity generation (Elliston, private communication, to be published).

Gas turbines have low capital cost (since they are essentially jet engines) and in the model have low annual operating cost (since they are operated infrequently and for short periods in these scenarios). Therefore they play the role of reliability insurance with a low premium.

Some nuclear proponents claim that nuclear power stations can also be operated flexibly to follow the ups and downs in daily demand or variable renewables when required, pointing to France's experience. Because France has such a high nuclear capacity, supplying about 75% of annual electricity generation, it has no choice but to break the general rule and operate some nuclear stations in load-following mode. However, since the current generation of nuclear power stations is not designed for load-following, it can only do this with some of its reactors some of the time – at the beginning of their operating cycle, with fresh fuel and high reserve reactivity – but cannot continue to load-follow in the late part of their cycle (World Nuclear Organisation website). Load-following has two economic penalties for nuclear power stations:

- Substantially increased maintenance costs due to loss of efficiency.
- Reduced earnings during off-peak periods. Yet, to pay off of their high capital cost, they must be operated as much as possible at rated power.

An additional reason why a nuclear station is a poor partner for a large variable RE contribution in an electricity supply system is that, when it breaks down, it is usually down for weeks or months. For comparison, gas turbines are down for hours or days. They are also much smaller in capacity and are usually installed in groups. When one gas turbine in a group breaks down, the others can continue to balance the fluctuations in variable RE.

Proliferation of nuclear weapons

Nuclear expertise resulting from a civilian nuclear energy program provides most of the expert knowledge required for a nuclear weapons program. The remaining requirement, the nuclear explosive, can be obtained from civil nuclear energy in several alternative ways:

- further enriching uranium beyond the level required for most conventional reactors to obtain a high concentration of fissile isotope uranium-235;
- reprocessing the spent fuel from a conventional reactor to extract fissile plutonium-239;
- or, if the thorium reactor becomes commercially available, extracting fissile uranium-233 that the thorium reactor makes by bombarding non-fissile thorium with neutrons;
- or, if the fast breeder reactor ever becomes commercially available, breeding plutonium-239 from the non-fissile uranium-238;
- or, if the integral fast reactor (IFR) ever becomes commercially available, applying conventional reprocessing to the actinides, which were previously separated from the highly radioactive fission products in the IFR, to extract fissile plutonium-239.

Nuclear energy supporters attempt to obscure these basic facts of nuclear physics with incorrect, misleading and/or irrelevant statements. For instance, they create the false impression that it's impossible to make nuclear bombs from the plutonium-239 extracted from a civil nuclear reactor, or from the uranium-233 extracted from a thorium reactor (in both cases because of the presence of impurities), but the fact is that expert government nuclear bomb-makers and regulators have stated that the USA has done so (U.S. Congress OTA 1994; Diesendorf 2014, pp.156–162).

Brook and Bradshaw are particularly supportive of the Integral Fast Reactor (IFR), a concept that has only operated as a prototype in the USA. The project was cancelled by Congress in 1994 for reasons including funding, doubts about whether it was needed, and concerns about its potential for proliferation (Kerry 1994). The IFR is a type of fast neutron reactor; it is called 'integral' because it would have an on-site reprocessing plant. The latter would perform a new, experimental kind of reprocessing called pyroprocessing, which would separate the long-lived radioactive elements (transuranics) as a group from the medium-lived radioactive elements (fission products) as a group. Then, in theory, the group of transuranics could be fed back into the reactor as a fuel, converting them to fission products. Thus the only wastes left would comprise the medium-lived fission products, which decay to the background level of radioactivity after several centuries. Plutonium would not be separated from the other transuranics and the combination of transuranics could not be *directly* used as a nuclear explosive. This appears to be the basis for Brook and Bradshaw's support for the IFR. However, they create the incorrect impression that the IFR is proliferation-proof as follows:

> The IFR technology in particular counters one of the principal concerns regarding nuclear expansion–the proliferation of nuclear weapons–because its electrorefined-based fuel-recycling system cannot separate weapons-grade fissile material.

The flaw in the argument is that, once most of the highly radioactive fission products have been separated from the less radioactive transuranics, it would become easier to extract the Pu-239 from the transuranics by means of conventional chemical reprocessing and use it to produce nuclear weapons. As a bonus, the concentration of plutonium in the spent fuel from an IFR is much higher than in the waste from a conventional light water reactor. An alternative proliferation pathway would be to modify an IFR to enable it to be used as a breeder reactor to produce weapons grade plutonium from uranium-238. (Wymer et al. 1992; US Congress OTA 1994).

The countries whose governments have used civil nuclear energy to assist them in developing or starting to develop nuclear weapons in secret are listed in Appendix S4. Some of these governments terminated their weapons production process before their goal was reached. Nevertheless, nuclear energy is increasing the probability of nuclear war. Even if the probability of nuclear war is small (and this has not be established), the potential impacts are huge (Robock & Toon 2010. Therefore it is inappropriate to ignore the risk, which is probability multiplied by impact (ISO 2009).

Some of the limitations of the Nuclear Non-Proliferation Treaty (NPT) are that several of the countries listed in Appendix S4 delayed becoming parties to the NPT until after they had developed, or attempted to develop, nuclear weapons, while others (e.g. India and Pakistan) never became parties. North Korea withdrew and Iran, although a party, was found to be non-compliant (Charnysh undated). Some parties to the NPT (USA, Australia and China) are risking proliferation by transferring uranium and other nuclear materials to non-parties, India and Pakistan (BBC News 2006; Joshi 2011; Prusty 2014). Furthermore, under the NPT, it is legal for a non-nuclear state to operate a fully closed nuclear fuel cycle, including the right to run a number of facilities with a high potential for proliferation, such as uranium enrichment and nuclear waste reprocessing plants (Nassauer 2005).

A supplementary argument by Brook and Bradshaw, that some countries with nuclear energy have not (so far) used it to proliferate, does not logically contradict the conclusion that nuclear energy is increasing the probability of nuclear war. More generally, the argument that the risk of nuclear war also depends on other variables, such as research reactors and trade in nuclear explosives, is irrelevant to the point that nuclear power is increasing the risk of nuclear war and that transitioning away from nuclear energy would reduce that risk. Research reactors, in particular, have helped with education and training in nuclear science and engineering, but most of these are too small to produce sufficient nuclear explosive for a national weapons program. In most cases the nuclear explosive was produced, or intended to be produced, in civil nuclear energy facilities.

Land use

Land use by wind

Brook and Bradshaw stated in their Appendix S1 that ‘For Figure 2 we took the amount of land area displaced for energy produced (facility footprint, roads, construction materials, fuel, etc).’ That this is incorrect in the case of wind farms is shown by their Appendix S5 where they used power density in watts per metre squared (W/m^2) of land area as the basis for their calculation. In other words they took land area spanned by the wind farms instead of the much smaller area of land actually occupied by the turbines and access roads. The latter is estimated at typically 1–2% of land spanned (Denholm et al. 2009) or 1–3% (McGowan & Connor 2000). Using power density (or energy density for that matter) does not give any information on the land actually occupied. In many parts of the world wind farms are placed on agricultural land where the land between turbines continues to be used for grazing and crops and environmental impacts are very low. While best practice guidelines (e.g. Clean Energy Council 2013; Irish Wind Energy Association 2012) do not usually specify that wind farms must be sited on either agricultural or marginal land, in practice the extensive guidelines, applied in countries or states with strong environmental legislation and planning constraints such as Australia, strongly encourage that outcome: for example, "wind farms and ancillary development (including wind monitoring masts) are envisaged in sparsely populated zones such as general farming, primary production and rural zones" (Rau 2012).

An approximate calculation for the Australian case study of land area occupied by wind technology per unit of annual energy generation follows:

Give each wind turbine a typical rated power of 3 MW and capacity factor (average power divided by rated power) of 0.3.

Then its annual energy generation (MWh) = rated power (MW) x capacity factor x no. of hours (h) per year (y) = 3 x 0.3 x 8760 = 7884 MWh = 7.884 GWh.

Assuming turbines are spaced at 1 km separation (10 blade diameters) in square arrays that are sufficiently large that we can neglect edge effects, gives one turbine per km^2 and its annual energy generation per km^2 = 7.884 GWh.
Therefore the land area (km^2) *spanned* per GWh per year = 1/7.884 km^2/GWh/y = 0.127 km^2/GWh/y = 127 km^2/TWh/y.

The land actually *occupied* by the wind turbines, access roads and substations is typically 1-2% of land spanned (Denholm et al. 2009).
Therefore the land occupied = 1.27-2.52 km^2/TWh/y, which can be rounded off to 1.3-2.5 km^2/TWh/y, the result given in Table 1.

The number of turbines required is calculated as follows. Using the economic optimal mix derived by Elliston et al. (2013) for Australia, the annual electricity generation = 0.464 x 250 TWh/y = 116 TWh/y. Then the total wind generating capacity in the case study is: 116,000/(0.3 x 8760) = 44.14 GW, which can be provided by 14,713 turbines rated at 3 MW each.

Although Brook and Bradshaw's paper is nominally about the impacts of energy technologies on biodiversity, they did not discuss bird fatalities. However, there is little or no difference in this impact between nuclear and wind. A study by Sovacool (2013) found that wind and nuclear power are each responsible for 0.3–0.4 bird fatalities per gigawatt-hour (GWh) of electricity, while fossil fuelled power stations are responsible for about 5.2 deaths per GWh. Appropriate siting of wind farms (e.g. avoiding wetlands and bird migration routes) can reduce their bird impacts to much lower levels. For comparison, on two consecutive foggy nights about 5000 birds in total were killed when they collided with the chimneys of a thermal power station in Florida, USA (Maehr et al. 1983). The authors of this report do not identify whether the thermal power station was fossil or nuclear, however the impacts would have been the same.

Land use by bioenergy

Brook and Bradshaw stated that 'Biofuels and wind energy in particular require land area per unit energy produced similar to hydro electric dams'. Not only is this statement is incorrect for wind everywhere, but it is also incorrect for bioenergy in the case of the global scenarios for 100% RE (Jacobson & Delucchi 2011; Delucchi & Jacobson 2010), which have no bioenergy, and the Australian simulation models (Elliston et al. 2013, 2014) where the tiny bioenergy contribution comes from agricultural and/or plantation forestry residues and so has no additional land use.

Land use by hydro-electric dams

While several countries – e.g. Brazil, Iceland, New Zealand, Sweden, Bhutan and China – have large percentage contributions to electricity supply from hydro, this is not typical of the majority of countries and so the land-use attributed by Brook and Bradshaw to hydro appears to be an over-estimate on a global scale.

Land use by solar energy

Brook and Bradshaw's calculation of the land use by solar energy doesn't state whether it takes into account that a large fraction of solar photovoltaic (PV) modules can be installed on the rooftops of residential and commercial buildings in many parts of the world. Currently rooftop solar is dominant over on-ground solar power stations in Europe, Australia and Japan. Brook and Bradshaw also ignore the fact that most large solar PV power stations can be installed on land that is either marginal or low-value agricultural land and so is low in impact on biodiversity. If we assume that 25% of the solar contribution is rooftop, then Brook and Bradshaw's numerical result of 5.7 km^2/TWh for solar is an order of magnitude too *small*, as shown by the following calculation based on the Australian case study (Table 1).

Annual energy generation = 0.215 x 250 TWh/y = 53.75 TWh/y.
Assuming a capacity factor of 0.2, total generating capacity becomes 53,750 / (0.2 x 8760) = 30.6 GW.

To obtain the approximate land use, I use the 20 MW Gemasolar power station in Spain, which occupies 195 ha. Therefore, 1 GW occupies 50 x 195 ha = 9750 ha = 97.5 km^2 and 30.6 GW occupies 2983 km^2. Since the on-ground solar collectors are closely spaced, unlike wind turbines, the land between them cannot be used productively and its biodiversity is limited. Hence I assume for simplicity that the land spanned by a solar power station is approximately equal to the land occupied. Therefore the land use per unit of annual energy generation becomes 2983/53.75 = 55.5 TWh/km^2/y, which is the result given in Table 1.

The calculation of land use by solar power is the only error or assumption in Brook and Bradshaw's paper that (inadvertently) favours RE. Incidentally, if Brook and Bradshaw assumed that all solar power was generated from ground-mounted power stations, their error would even larger.

Land use by nuclear energy

The basis for Brook and Bradshaw's estimate of land use by nuclear energy is opaque. Does it include tiny buffer zones around nuclear facilities? The choice of buffer zone size around a nuclear power station is of course a subjective judgment depending upon how much risk is acceptable and who makes the decision. The larger the buffer zone, the smaller the impact of a nuclear accident or terrorism at a nuclear facility. The effect of the choice of buffer radius on the land use by nuclear energy is demonstrated by the following back-of-the-envelope calculation based on a hypothetical 20 km radius exclusion zone for a 2 GW nuclear power station with lifetime average capacity factor 75%:

Annual electrical energy generation (TWh) = 2 GW x 8760 h/y x 0.75 /1000
=13.14 TWh
Land area = π x 20 x 20 = 1257 km^2
Therefore land use per annual energy generation = 1257/13.14 = 96
or approximately 100 km^2/TWh/y.

This should be compared with Brook and Bradshaw's estimated total nuclear land use of 0.1 km^2/TWh/year, which is three orders of magnitude smaller. In view of the debate about the adequacy of the exclusion zone around the Fukushima Daiichi power station and the devastation within this radius of Chernobyl, there could be a case for making the radius at least as large as 20 km for all nuclear power stations, reprocessing plants, etc.

Safety/fatalities

Brook and Bradshaw claim to have done a 'hard-nosed assessment' of fatalities. However, they don't have a credible reference for nuclear fatalities and they don't explain the assumptions underlying their claimed fatality score of 0.04/TWh for nuclear. Their sole reference (located in their Appendix S3) for nuclear fatalities is a blog called NextBigFuture.com, whose author is 'Brian L. Wang, M.B.A. a long time futurist. A lecturer at the Singularity University and Nextbigfuture.com author' (quoted from the homepage). After a search, the blog item on fatalities was eventually found at http://nextbigfuture.com/2008/03/deaths-per-twh-for-all-energy-sources.html . It claims to cite the ExternE study, but its dead Weblink targets a Polish conference. The ExternE assumptions and result are discussed below.

Whatever their source, Brook and Bradshaw appear to believe that their fatality score for nuclear omits cancers induced by nuclear accidents. Note (f) to Table 1 of their paper states that their result covers 'deaths from accidents, excluding chronic health problems', which appears to include prompt deaths from acute radiation syndrome while excluding cancers. The view that Brook and Bradshaw omitted all or most cancer fatalities is further supported by other writings by Brook, the lead author of Brook and Bradshaw (2015), that reject estimated cancer deaths from Chernobyl, apart from a few thyroid cancers, and attempt to critique the science-based linear no-threshold (LNT) relationship between dose and response at low doses. For example, in his pro-nuclear blog http://bravenewclimate.com/2010/03/05/open-thread-3/#comment-61051 , Brook stated that 'the 4000- & 5000-death numbers, based as they are on the discredited LNT model, have no relevance to the real world'. An article by Brook & Heard (2011), in a magazine produced by the South Australian Chamber of Mines and Energy, states that at Chernobyl 28 emergency workers were killed and, out of the 6000 thyroid cancers observed, 15 were fatal. It then goes on to quote out of context an unreferenced report of the UN Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) to imply that there will be no additional cancers, omitting to inform the reader that expert scientific opinion supports the LNT model (e.g. BEIR VII Committee 2006 and ICRP 2005): 'The LNT hypothesis, combined with an uncertain DDREF for extrapolation from high doses, remains a prudent basis for radiation protection at low doses and low dose rates.' (ICRP 2005).

For Chernobyl, the lowest estimate of future cancer deaths was ‘up to 4000’ by the Chernobyl Forum (2006), a group of United Nations agencies led by the International Atomic Energy Agency (IAEA). It only considered the impact on the 600,000 emergency and recovery workers. Because the IAEA has a mission of promoting nuclear energy, its estimate is given less weight in this paper than studies by authors with no obvious conflict of interest who made less limiting assumptions. Estimates from such authors range from 16,000 from the International Agency for Research on Cancer (Cardis et al. 2006) to 93,000 from a team of international medical researchers from Ukraine, Russia and elsewhere (Yablokov et al. 2006). The prediction of about 16,000 fatalities by Cardis et al (2006) covers the period up to 2065. It is made up of 14,100 (95% UI 6200-32,100) for all cancers excluding leukaemia, thyroid cancer and nonmelanoma skin cancer (Cardis’ Table I) plus about 1700 from leukaemia (Cardis et al. 2006, p.1230). A very small fraction of thyroid cancers are also fatal but are not counted explicitly by Cardis et al.

Now let’s return to the ExternE study, which Brook and Bradshaw could have cited instead of NextBigFuture.com. The ExternE nuclear study was written by CEPN, a committee of French radiological protection and nuclear industry groups (CEPN 1995). It was a thorough study for its time, choosing a detailed risk-based method, where risk = probability x impact, summed over different scenarios. It considered cancer fatalities not limited to rare thyroid cancer fatalities and used the LNT relationship. Its principal limitations were:

- It did not recognise the risk of nuclear war resulting from the proliferation of nuclear weapons assisted by nuclear energy. Although this is not at present quantifiable, it should be recognised as a real risk with potentially billions of fatalities.
- It was published in 1995, after Chernobyl, but before Fukushima, so its assumed probability of a major accident is likely to be much too low.
- It considered only four hypothetical accident scenarios (which is understandable in a project with limited scope). However, care must be taken by others to avoid assuming incorrectly that the CEPN results are an upper limit.

The results depend on whether one includes global as well as local and regional impacts and whether one considers periods up to 100,000 years. In the latter case for global emissions, normal operations dominate fatalities/TWh, even though fatalities/year are very small, and the CEPN result is about 0.1 fatalities/TWh. (This is based on adding up the various ‘normal’ fatalities calculated in Chapter 8. However, the report’s summary in its Chapter 14 gives 0.65 fatalities/TWh.)

For its most severe reactor accident scenario (ST2), with radiation release of 0.6 times Chernobyl’s, with probability of core meltdown assumed to be 5 x 10^{-5} per reactor per year and conditional probability of a major release from meltdown to be 0.19, its estimate of total cancer fatalities over a radius of 3000 km was about 14,500, consistent with Cardis’ (2006) estimate of 16,000 for Chernobyl. However, because of the large number of years over which the deaths were spread and because of the tiny assumed probability of core meltdown, the resulting impact was only 0.018 per TWh.

Thus CEPN’s estimate of total cancer fatalities from nuclear energy of 0.12/TWh is at least three times Brook and Bradshaw’s score of 0.04/TWh and could be much higher if more scenarios had been included and the probability of core meltdown were revised to take account of Fukushima.

Life cycle CO_2 emissions

Unfortunately IPCC (2014, chapter 7, p.540) is unhelpful in pinning down the life-cycle emissions from nuclear energy, giving uncritically the huge range of 1–220 gCO_2/kWh. The bottom-of-range score of 1 gCO_2/kWh is so low that it could not possibly apply to any commercially available (generation 2, 3 or 3+) nuclear power reactor. It is even doubtful as to whether it could apply to a future fast breeder reactor. Lenzen (2008) and Sovacool (2008) performed independent detailed meta-analysis of hundreds studies on conventional nuclear fuel life-cycles. Lenzen is a leading life-cycle analyst, a nuclear physicist and a supporter of nuclear energy, so he cannot be credibly accused of anti-nuclear bias. Both authors obtain *mean* emissions across the studies they analysed of about 65 gCO_2/kWh (65,000 tCO_2/TWh), much greater than values chosen by Brook and Bradshaw. The latter authors do not cite either of these major meta-analyses directly, although the source they cite for their incorrect score of 20 tCO_2/TWh actually gives Lenzen's average correctly and not the score that Brook and Bradshaw claim it does (see the section on Other Errors, below).

An average can hide a wide range of variation resulting from different factors. Lenzen (2008) is one of the few pro-nuclear authors who recognise in print that life-cycle emissions will increase greatly as uranium ore-grade declines over the next few decades (Mudd & Diesendorf 2010). This is a particular case of the general situation in mining that high-grade ores are tapped first and, as they are used up and lower-grade ores have to be utilised, with the result that the energy inputs and environmental impacts increase (Norgate & Jahanshahi 2010). Lenzen (2008) calculated that, for low-grade uranium ore (0.01% U_3O_8), life-cycle emissions of conventional nuclear energy would amount to about 130 g CO_2/kWh, which is much higher than emissions from most RE sources. However, in his calculations Lenzen (2008) made a key assumption favourable to nuclear energy, namely that uranium mines are not rehabilitated by covering the waste mountains (Mudd and Diesendorf 2010, p.334). This assumption greatly reduces the calculated energy input (and hence CO_2 emissions) to uranium mining while imposing a substantial hazard to future generations when integrated over 100,000 years of low-level radiation emissions from the waste mountains blowing in the wind. Rehabilitating the mines and covering the waste mountains could lift the life-cycle CO_2 emissions of the nuclear life-cycle using low-grade uranium to 220–437 g CO_2/kWh (Mudd and Diesendorf 2010, p.334), making emissions from conventional (generations 2 & 3) nuclear energy comparable with those of natural gas. This makes it very difficult to justify new conventional nuclear power stations on the basis of combating climate change.

Like nuclear energy, RE technologies have life-cycle emissions that must be taken into account in calculating carbon budgets (Hertwich et al. 2015). The difference is that the key RE technologies, wind and solar, have short construction/installation times (typically 1–3 years for large-scale systems) compared with the US average for nuclear power stations of 9 years plus planning years (Koomey & Hultman 2007). Therefore the transition to using RE to build RE systems, with zero life-cycle emissions, can occur much faster than by using nuclear energy to make and build nuclear facilities. Furthermore, wind and solar have no emissions from fuel production, while emissions from mining and milling uranium for generations 2 & 3 nuclear energy are significant and will increase over time, as discussed above, until, in the distant future, mining and milling can possibly be done with low-carbon energy.

Nuclear economics

In their Table 1, Brook and Bradshaw's price of nuclear energy, \$108/TWh, should be corrected, along with the other energy prices they quote, by multiplying by one million. The corrected price of \$108/MWh agrees approximately with the median private costs given by IPCC (2014). The higher cost estimates of \$124–132/MWh by Lazard (2014) include quantifiable direct government subsidies, which are not counted in private costs. Even ignoring subsidies, it should be noted that the vast majority of IPCC (2014) data are based on papers and reports that were published on or before 2012 and these papers in turn use data from 2011 or earlier. Since 2000 the capital costs of nuclear power stations have escalated steadily. From 2002 to 2009, estimated capital costs of nuclear energy in the USA increased from \$2000/kW + interest during construction to \$7400/kW (Diesendorf 2014, Table 6.3). More recent escalations are indicated by actual costs of nuclear power stations under construction (see below) and recent quotes for new nuclear power stations. One cause of the escalations has been the new requirement by some potential buyers that vendors carry all or part of the risk of cost increases beyond the quoted price (Schneider et al. 2013, p.35). Another likely cause is 'severe manufacturing bottlenecks and scarcities of critical engineering, construction and management skills that have decayed during the industry's long order lull' (Lovins & Sheikh 2008).

The validity of these escalating factors is supported by recent empirical data from nuclear power stations under construction in western countries. Two generation 3+ reactors are under construction in Europe (these are European Pressurised Water Reactors or EPR) and two in the USA (these are AP1000 reactors). In Finland, Olkiluoto-3 is nearly a decade behind schedule and nearly three times budgeted cost (World Nuclear Association 2015). In France, Flamanville-3 is five years behind schedule and triple budgeted cost (McPartland 2015; Matlack 2015). In Georgia USA, the Vogtle reactors are three years behind schedule and \$1.4 billion over budget (Power Engineering 2015).

The proposed two new generation 3+ reactors, Hinkley C, in the UK, each 1600 MW in capacity, will cost (in theory) £8 billion each, or £5 million/MW (about \$7.7 million/MW). To this must be added interest during construction, which could amount to 25–35% of the raw capital cost. They will receive a guaranteed inflation-linked price for electricity over 35 years, commencing at £92.5/MWh (\$144/MWh), double the wholesale price of electricity in the UK. At an inflation rate of 2.5%, this guaranteed payment would rise to £222/MWh (\$337/MWh) (2015 currency) in its 35th year of operation. This price is based on a Contract for Difference (CfD), meaning that the subsidy is the difference between the CfD price (known as the 'strike price') and the time-varying wholesale price (UK Government 2014). Hinkley C will also receive a loan guarantee of £10 billion (\$15.3 billion). Its capped liability for accidents and inadequate insurance will be backed by the British taxpayer. For comparison, on-shore wind in the UK will receive much less over its lifetime, initially a CfD of 95 £/MWh, then *reducing* over time until 2020 and thereafter possibly zero (Schneider & Froggatt 2014, pp.48–54; Parkinson 2015). That was the situation until June 2015, when the new UK government announced that it would terminate subsidies to new on-shore wind farms from 1 April 2016 (Wintour & Vaughan 2015).

It is difficult to determine the true costs of nuclear power reactors (both EPRs and AP1000s) under construction in China. However, construction delays are also occurring there (Schneider et al. 2013, p.47). Even if these reactors turn out to be cheaper than in Europe and the USA, many potential buyers would have concerns about their quality and safety.

Only four generation 3 reactors, all Advanced Boiling Water Reactors (ABWRs), were operating in the world just before the Fukushima disaster. All are located in Japan; none was operating in early 2015. They were constructed in rapid time, about four years (Goldberg & Rosner 2011). The nuclear industry reports that their capital costs were low, but others report that this is offset by their poor performance as measured by capacity factor, which has been less than 50% (NCE 2012). On the basis of the limited operating experience so far, it is difficult to reach a firm conclusion on the economics of ABWR. A recent desktop study for the first ABWR proposed to be installed in the UK gives a levelised cost of energy of £90/MWh (about $140/MWh) (DECC 2013, Table 2).

Subsidies to nuclear energy include investment tax credits, loan guarantees, research and development, uranium enrichment, nuclear waste management, decommissioning of nuclear power stations, caps on liability for reactor accidents and stranded assets paid for by electricity consumers and taxpayers (WISE 2005; Koplow 2007, 2011; Schneider et al. 2009, pp.70–88; Meyer et al. 2009). Some specific examples are:

- On nuclear waste management in the USA, Schneider et al. (2009) comment that 'The waste fee [$1/MWh] is an arbitrary price set more than two decades ago. While it is periodically reviewed for "adequacy", the value is not based on actual experience – no fuel disposal facilities exist in the USA or anywhere else – and all the US spent fuel remains in temporary store pending the construction of a spent fuel repository.'
- In the UK, the discounted cost of decommissioning of the current UK nuclear power station fleet, including Sellafield reprocessing plant, is £62 billion (Nuclear Decommissioning Authority 2015), which will have to be paid by British taxpayers, not the industry (Schneider et al. 2009).
- TEPCO's estimate of the partial costs of cleaning up the Fukushima Daiichi nuclear disaster are $137 billion (Inajima & Song 2012). However, a Japanese government panel estimated that the clean-up plus compensation could cost 20 trillion yen (then $257 billion) (Reuters 2011). The nuclear power station was insured for $1.5 billion.

Meanwhile, subsidies to RE, for example, in the form of feed-in tariffs and certificate schemes, are being rapidly reduced in Europe, Australia, and North America; they are rare in South America.

As mentioned above, the levelised cost of energy results by Lazard (2014) are supposed to be the 'unsubsidized' costs. However, it appears that, apart from US federal funding for R&D and US federal tax benefits, they did not include most of the above subsidies to nuclear. This is not surprising, because it is difficult to quantify most of them.

Renewable energy economics

In the years since data were inputted to IPCC (2014), costs of solar PV have dropped dramatically and costs of wind and CST have also decreased as their markets continue to grow.

Wind economics

Lazard (2014) estimated unsubsidized costs of $37–81/MWh for on-shore wind averaged across the USA. An independent empirical study by US Department of Energy reported in 2013 levelised power purchase agreement (PPA) prices for wind power in different regions of the USA: for the interior (the region with the highest wind speeds generally) were about

$25/MWh, and in the west (the region with the lowest wind speeds generally) about $60/MW (US DoE 2014, Fig.46). The US government subsidises wind with a Production Tax Credit of $23/MWh over 10 years, so the actual cost average in the interior was about $47/MWh plus any state subsidies, and in the west about $87/MWh plus any state subsidies. These are approximately consistent with the ranges estimated by Lazard (2014), which include federal subsidies. The price quoted by Brook and Bradshaw, $87/MWh (correcting their error of one million), is roughly comparable with the upper end of Lazard's (2014) range and the highest price region reported by US DoE (2014).

Wind energy prices are even lower in Brazil: in 2014 contracts were awarded at a reverse auction for an average unsubsidised clearing price of 129.3 real/MWh (US $41/MWh) (GWEC 2014, p.32).

Solar PV economics

Lazard (2014) estimated unsubsidized costs of $72–86/MWh for large-scale solar PV in the USA. In New Mexico, USA, a Power Purchase Agreement for $57.9/MWh has been signed for electricity from the Macho Springs 50 MW solar PV power station; federal and state subsidies bring the actual cost to around $80–90/MWh depending on location (Kroh 2014). In Chile a contract for electricity from a large-scale solar PV power station to be built in 2016 has been signed for US$89/MWh without subsidy; in addition, for generation in 2017, a contract has been signed for US$85/MWh (Roselund 2014). In Brazil in 2014 contracts for solar power were awarded at a reverse auction for an unsubsidised clearing price of US$87/MWh and previously in Uruguay for an unsubsidised price of US$91/MWh (Bloomberg New Energy Finance 2014). While not all contracts will be fulfilled, the global trend of declining prices is clear. The above recent solar PV prices are far below that quoted by Brook and Bradshaw of $144/MWh.

CST economics

Concentrated solar thermal (CST) power with thermal storage is a young technology with 4.8 GW installed worldwide by the end of 2014. It is currently the most expensive of the commercially available RE technologies, with weighted average levelised costs of energy (LCOEs) until recently in the range $200–250/MWh. However, costs continue to fall and at present projects are being built with LCOEs of $170/MWh, and power purchase agreements are being signed at even lower values where low-cost financing is available (IRENA 2015). With market growth over the next decade the installed cost of CST will inevitably fall much further. Brook and Bradshaw did not quote a price for CST.

Status and implementation of energy technologies

In Appendix S1 of their Supporting Information, Brook and Bradshaw claim incorrectly that 'historically, no country has achieved a penetration of solar or wind beyond about 20% of [electricity] supply'. To the contrary, the highest percentage non-hydro RE supply for a country is Denmark with wind 39% of electricity consumption in 2014 (Ministry of Foreign Affairs website). Denmark is on track to its next target of 50% wind by 2020 and beyond that to 100% renewable electricity and heat by 2035. Two German states, Schleswig-Holstein (Morris 2014) and Mecklenburg-Vorpommern (Richardson 2014) already have around 100% net RE, almost all wind (Appendix S3). 'Net' takes into account that they trade electricity with each other and other neighbours.

Also in Appendix S1 of their Supporting Information, Brook and Bradshaw claim incorrectly that ‘even the Danes still rely on domestic coal, imported nuclear and hydro to meet their reliable baseload power needs, resulting in high domestic electricity prices’. One of the reviewers of my paper stated the following variant of this incorrect claim:

> the majority of it [Danish wind energy] is dumped into other countries, often at a negative price. In other words, the Danes are paying Sweden and others to take their excess wind-generated electricity, while also paying the owners of the turbines subsidies to keep producing.

Both misrepresentations of the Danish electricity system are well-known myths that are based on a lack of understanding of how international electricity markets work. Although they were busted several years ago in a detailed study by Danish scientists and engineers (Lund et al. 2010), the myths are still being disseminated widely by RE deniers and those who have uncritically accepted them. In electricity markets with large contributions of renewable energy, the spot price of wholesale electricity occasionally becomes negative at times when supply is high and demand is low, but this is not dumping. Denmark still has coal-fired power stations, but because their operating costs (including fuel) are greater than that of wind, the coal stations are rarely operated as base-load supply nowadays. Thus wind is displacing coal. However, when the spot price of electricity in the Nordic market rises to a sufficiently high level, then the coal stations are fired up to export electricity. Based on data from 2004–2008, only 1% of wind energy production is exported (Lund et al. 2010). Since then Danish wind energy capacity has doubled, so it’s possible that nowadays about 2% is exported.

The myth that Denmark has high domestic electricity prices because of its large wind energy production is also wrong. Denmark has high electricity prices because it has high taxes on electricity, which go into consolidated revenue. When tax-free electricity prices across Europe are compared, Denmark is far below average. This is not surprising, because wind energy actually reduces the wholesale price of Danish electricity (Lund et al. 2010). This is one result of the Merit Order Effect (Agora Energiewende 2013).

Brook and Bradshaw’s Appendix S1 incorrectly places concentrated solar thermal (CST) power with thermal storage in the category of a ‘next generation’ source. Nowadays CST with molten salt storage is commercially available at a specified price and time to commissioning, unlike generation 3+ nuclear. Commercial CST power stations with capacity greater than 5 MW electrical are operational in the USA, Spain, South Africa, Algeria, Morocco, UAE, Egypt and Thailand (NREL website).

Brook and Bradshaw express enthusiasm for generation 4 reactors such as fast breeders (see their Fig.3), which ‘breed’ more nuclear fuel than they consume. (The ‘fast’ refers to the speed of the neutrons produced.) The closest these reactors came to commercial availability was a full-size demonstration reactor, the French Superphénix, 1200 MW. It was launched in 1974, connected to the grid in 1986 and was closed in 1998 after many technical problems. It cost €12 billion (2010 currency) excluding decommissioning and operated for only 10 months (Cours des Comptes 2012). In Russia the 800 megawatt (MW) BN-800 demonstration fast neutron reactor commenced operation in 2014 after nearly 30 years of on-off construction. Russia appears to be the only country currently developing fast breeders. The pro-nuclear MIT study of 2003 did not expect that the breeder cycle would come into commercial operation during the following three decades and the 2010 report did not change that (MIT 2003, 2010).

More generally, the technology roadmap of the GenIV International Forum 2014) places the first early commercial deployments of generation 4 in the period 2030-2040. Apart from fast breeders, other types of generation 4 reactor under development include the thorium reactor, the small modular reactors and the integral fast reactor.

- The thorium reactor, is more complex than the uranium reactor, because it needs at least one additional step: the conversion of non-fissile thorium to fissile uranium-233 by bombarding the former with neutrons.
- Small modular reactors that could be mass-produced have been the dream of the nuclear industry for decades, but have the disadvantages of losing the economies of scale of existing large reactors and of not at present having a market.
- The integral fast reactor has only limited research development to the pilot stage.

Other proposed 'advanced' reactors need much R&D too.

Solid waste

Brook and Bradshaw divided wastes into solid wastes and radiotoxic wastes and then assumed that the nuclear fuel cycle produces no solid waste (see their Table 1). They ignored the vast quantity of rock mined to produce uranium and the additional waste produced from uranium milling and enrichment. For instance, the waste mountain at Olympic Dam uranium-copper mine in Australia has about 150 million tones of solid waste (which is slightly radioactive). An ore-grade of 0.1% means that 99.9% of the ore is left as solid waste, known as tailings. In the future, as low-grade ore replaces high-grade, the waste mountains will increase in size by an order of magnitude. Then to obtain 1 kg of uranium oxide from low-grade ore (0.01% uranium oxide U_3O_8), one will have to mine 10 tonnes of rock. Based on figures provided by the World Nuclear Association website and assuming a capacity factor of 75%, 1 MWh of nuclear electricity could require as much as 60 kg of uranium ore at a current ore-grade. For future use of low-grade uranium ore, this would increase to several hundred kg, comparable in magnitude to the mass of black coal required to generate 1 MWh (about 500 kg). Although this rough calculation does not take into account coal mine waste or waste from milling and enriching uranium, it shows that the total mass of solid waste from a future nuclear fuel life-cycle based on low-grade uranium is the same order of magnitude of that of coal power, a very different result from that of Brook and Bradshaw. (This is not intended as an argument for keeping coal power!)

Other errors and inconsistencies

1. The main text of Brook and Bradshaw's paper states that 'We ignored the difficult-to-quantify embodied greenhouse-gas emissions from the full life cycle of an energy-production facility', but the notes to their Table 1 say that the values of CO_2 emissions 'include production-related and embodied life-cycle emissions', an internal contradiction.

2. CO_2 emissions of nuclear energy are given as 20 tonnes/TWh in the text of the paper (5th page) and 16,000 tonnes/TWh in Brook and Bradshaw's Table 1, another internal contradiction.

3. The error of a factor of 1000 in the former CO_2 emission score, which occurred for both nuclear and coal, can be explained by a careless systematic error in converting 65 tonnes/GWh in Karecha & Hansen (2013) to tonnes/TWh in Brook and Bradshaw. But

the second error, changing 65 to 20, is difficult to explain by carelessness, since this change was made for nuclear alone.

4. With reference to the integral fast reactor, Brook and Bradshaw state incorrectly that 'the large-scale deployment of fast technology would result in *all* [my emphasis] of the nuclear-waste and depleted-uranium stockpiles generated over the last 50 years being consumed as fuel'. In reality, the highly radioactive fission products would still have to be managed for several centuries, as acknowledged in Brook and Bradshaw's Figure 3. This is another internal contradiction.

5. In the notes to their Appendix S4, Brook and Bradshaw state that 'reported CO_2e emissions [from nuclear energy] are direct power station output, not life-cycle/embodied emissions'. If that were correct, it would be useless information. However, it is incorrect, because the nuclear emissions given in their Appendix are non-zero. Nuclear power stations themselves do not combust any fuel and so the operational component of their life-cycle emissions is zero, but the other steps in the life-cycle produce emissions. This is another internal contradiction.

6. Brook and Bradshaw's Fig.1 and the supporting data in their Appendix S3 express the land use in km^2/TWh, but Fig.2 and the right-hand graph in their Appendix S2 express land use in km^2/TWh/y, another internal contradiction. Based on their statement that 'we used an annual estimate herein' in their Appendix S1, it appears that Brook and Bradshaw intended land use in their Fig.1 and Appendix S3 to be expressed per year. This is appropriate for wind and solar power, since their sites can be used far into the future.

7. The levelised costs of electrical energy in Brook and Bradshaw's Table 1 are stated to be in \$/TWh, but are actually in \$/MWh, an error by a factor of one million.

8. Brook and Bradshaw's treatment of energy storage is absurd. They claim that the average developed-nation human using renewable electricity would require 'an 86,000 t [tonne] elevator-shaft-battery over 13 km high'. However, some households in developed countries are already supplying all or most of their electricity requirements from rooftop solar PV and a Lithium-ion battery bank similar in volume to a large refrigerator (e.g. Bosch website; Zen Energy Website). For large-scale electricity generation, the Elliston et al. (2013) scenario for 100% renewable electricity in the Australian National Electricity Market has no battery storage, only modest amounts of hydro storage from existing dams, and thermal storage associated with concentrated solar thermal power.

9. In Appendix S1 of their Supporting Information, Brook and Bradshaw also claim that a penetration of 50% non-hydro renewables requires 'as-yet-unrealized advancements in large-scale energy storage', which is refuted by the computer simulations for the USA, Europe and Australia cited above. The alleged 50% limit has already been far exceeded by the German states listed in Appendix S3 and by 2020 will probably be exceeded by Denmark and Scotland.

10. Brook and Bradshaw's Appendix S1 also claims, without any reference, that 'The life-cycle greenhouse-gas emissions of photovoltaics are higher than nuclear power'. That was only true several decades ago in the days before mass production of solar PV

modules, but nowadays PV's life-cycle emissions are typically an order of magnitude less than those of nuclear—energy payback periods of PV (in energy units, not dollars) are, depending on location, 0.5–1.8 years (e.g. Raugei et al. 2012).

11. Brook and Bradshaw ignore the huge continuing subsidies to nuclear energy (cited in the previous section), but state that 'ideally all low-carbon energy options should be free to compete on a fair and level playing field', an inconsistent position.

12. Despite the fact that a nuclear power station is one of the slowest electricity generation technologies to build, taking on average 9 years plus several years for planning and infrastructure in the USA (Koomey & Hultman 2007), Brook and Bradshaw create the opposite impression by stating that 'France, which built 59 large reactors in 22 years (1978 to 1999)…is a real-world illustration of what can be achieved quickly with nuclear deployment under favorable sociopolitical circumstances.' They omit to mention that many of these reactors were built almost simultaneously, creating a huge debt carried by the government-owned utility EDF (Cours des Comptes 2012, pp.30–33), which continues today (Amiel et al. 2015).

13. While several of Brook and Bradshaw's key points are unreferenced, some others are referenced to pro-nuclear secondary or tertiary authors who have apparently published no original research on the points in question. For example, Blees, whom Brook and Bradshaw cited to dismiss nuclear weapons proliferation, has apparently no peer-reviewed journal publication devoted to that topic; Trainer, whom Brook and Bradshaw cited on the materials use by energy technologies has apparently no publication demonstrating any original research on that topic; Karecha & Hansen, whom Brook and Bradshaw cited (misrepresenting their score) for life-cycle CO_2 emissions from energy technologies, do not claim expertise on that topic and anyway they cited correctly Lenzen (2008) who is one of the experts I cite.

Discussion

To conclude, Brook and Bradshaw have claimed to have done the impossible, an 'objective' comparison of nuclear and renewable energy technologies. However, the choice of criteria and scores for criteria in multicriteria analysis are all subjective and Brook and Bradshaw's choices are biased to nuclear energy. Furthermore, Brook and Bradshaw have claimed to have used methods that they didn't actually use and have omitted to reveal their assumptions underlying several results. Their paper and supporting information contain many internal inconsistencies, factual and arithmetical errors, poor referencing, inappropriate comparisons, unsupported claims, much rhetoric and absurdities. Almost all their assumptions and data on renewable energy, and many on nuclear energy, are incorrect.

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Appendix S2. Selected recent simulations of high penetration renewable energy in electricity grids

Region, country or state	**References**
USA	Mai et al. (2012); Budischak et al. (2013)
California	Solomon et al. (2014)
Europe	Heide et al. (2010, 2011); Rasmussen et al. (2012); Rodriguez et al. 2014
Germany	Henning & Palzer (2014); Palzer & Henning (2014)
Australia	Elliston et al (2013, 2014); AEMO (2013)

Appendix S3. Leading countries and states with high contributions of non-hydro[a] renewable energy (RE) to the electricity grid and ambitious RE targets

Country or state		**RE penetration[b] in 2014**	**Target**
Country	Denmark	Wind 39% of domestic consumption + bioenergy 7%	Wind 50% by 2020; 100% renewable electricity and heat by 2035.
	Scotland	RE 44%, of which wind is 29%	100% net[c] renewable electricity by 2020
	Germany	Total RE 30% of domestic consumption from biomass, wind solar & hydro in order from largest	≥80% of consumption by 2050
	Portugal	Wind 23%	
	Spain	Wind 21% + solar 4%	
State	Mecklenburg-Vorpommern, Germany	RE about 100% net[c], almost entirely wind	
	Schleswig-Holstein, Germany	RE 100% net[c], almost entirely wind	N/A
	South Australia[d]	Wind 33%; rooftop solar 6%	
	Iowa, USA	Wind 27%	
	South Dakota, USA	Wind 26%	
	California, USA	RE 24%, including 5% from utility scale solar	RE 33% by 2020; 50% by 2030 proposed

Sources: References include AEMO (2014), Ministry of Foreign Affairs (Denmark) (2015); Morris (2014); REE (2013); Richardson (2014); Scottish Government (2014). Some of the reports don't distinguish between % of generation and % of consumption – however the difference is generally small.

Notes: a. Countries such as Iceland and New Zealand, that have 90–100% RE with major contributions from hydro, have been excluded from the table.

b. Percentage of annual electricity generation or consumption.

c. 'Net' takes account of electricity trading by transmission line.

d. AEMO (2014) gives the wind energy penetration in South Australia in 2013–14 as 31%, however additional wind capacity since then has lifted it to about 33%.

Appendix S4. Nuclear weapons programs assisted by non-military nuclear technology

Programs that produced nuclear weapons	**Programs discontinued before producing weapons**
France	Algeria?
India	Argentina
North Korea	Australia
Pakistan	Brazil
South Africa	Iran
UK	Libya
	South Korea
	Taiwan (twice)

Sources: Research papers for several countries published on websites of the Nuclear Weapon Archive http://nuclearweaponarchive.org and Institute for Science and National Security http://isis-online.org.

Specific references are:

Algeria: Albright & Hinderstein (2001)

Argentina: Federation of American Scientists http://www.fas.org/nuke/guide/argentina/nuke/index.html;

Australia: Reynolds (2000); Broinowski (2003);

Brazil: Global Security.org: http://www.globalsecurity.org/wmd/world/brazil/nuke.htm;

France: Nuclear Weapon Archive http://nuclearweaponarchive.org/Nwfaq/Nfaq7-2.html#france;

India: http://nuclearweaponarchive.org/India/index.html;

Iran: ISIS http://isis-online.org/countries/category/iran ;

Libya: Albright & Hinderstein (2004);

North Korea: Papers by Hayes & Cavazos at http://nautilus.org/about/staff/peter-hayes/#axzz2YE94gjQ5;

Pakistan: Albright & Hibbs (1992); Corera (2006)

South Africa: Albright (1994); Nuclear Weapon Archive http://nuclearweaponarchive.org/Safrica/index.html;

South Korea: Kang et al. (2004);

Taiwan: ISIS http://isis-online.org/countries/category/taiwan;

UK: Barnham et al. (2000); Nuclear Weapon Archive UK http://nuclearweaponarchive.org/Uk/UKFacility.html .

Note: All websites accessed July 2015. Although France and the UK produce the vast majority of their nuclear weapons from military facilities, there is evidence from plutonium accounting that the UK supplemented its military program with plutonium from its Generation 1 nuclear power stations (see above references). France doesn't separate military and civil nuclear programs (see above Nuclear Weapon Archive website under *Marcoule* and *Other Reactor Sites*). South Africa successfully produced nuclear weapons with the assistance of nuclear power and then terminated its program and destroyed the weapons.