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# A WinACC view of the future of nuclear power in the UK

## Background

Can the UK provide for its future energy needs without recourse to nuclear power?

In 2015 the UK relied on 16 nuclear reactors on 9 sites to supply 22% of its electricity demand.[1] By June 2016 the UK had seven twin advanced gas-cooled reactor power stations and Sizewell B, a single pressurised water reactor power station. All but one of the existing nuclear reactors were due to be shut down by 2023[2] and the last one was due to be shut down by 2035[3] but in early 2016 the French company EDF, who manage all of the UK's existing reactors,[4] announced it would extend the life of four of its eight power plants. Heysham 1 and Hartlepool will have their life extended by five years until 2024, while Heysham 2 and Torness will see their closure dates pushed back by seven years to 2030.[5]

The government is keen to encourage private companies, and even other countries, to build new nuclear power stations to help fill the potential looming energy gap when demand will exceed supply.[6] For example, it was announced in early 2016 that a new nuclear power plant, part funded by France and China, would be built by 2025 at Hinkley Point C providing 7% of the UK's base-load electricity requirements. It is however already too late for any others to be planned and built by the coal "shut-off" target date of 2025.[1]

However, several scenarios of the UK's future energy supply suggest that nuclear energy is not a necessary part of the supply.[7,8,9,10] So can the UK provide for its future needs without nuclear energy and, if so, should it do so?

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[1] Anon (IMechE). "ENGINEERING THE UK ELECTRICITY GAP." London: Institution of Mechanical Engineers, 2016.
[2] http://www.world-nuclear.org/info/inf84.html
[3] Barnaby, F. (2012). Current UK nuclear issues, talk in Winchester 1 March 2012.
[4] http://www.gridwatch.templar.co.uk/links.html
[5] http://www.bbc.co.uk/news/business-35583740
[6] It has been said (Barnaby, F. (2012). Current UK nuclear issues, talk in Winchester 1 March 2012) that civil nuclear technology and military nuclear technology are identical. In that case the desire of UK government to continue to possess nuclear weapons, and be part of the prestigious nuclear club, might be seen as a reason, even the primary reason, why it wants to continue with the development of a civilian programme of power generation.
[7] MacKay, D. J. C. (2008). Sustainable energy - without the hot air. Cambridge, UIT although in the last days of his life (he died in April 2016) he remained convinced that nuclear power would continue to be essential; http://www.theguardian.com/environment/2016/may/03/idea-of-renewables-powering-uk-is-an-appalling-delusion-david-mackay

**Questions to be answered**

To assess the UK's future need for nuclear power the following questions need to be answered:

1. How practical is it to rely on a new generation of nuclear power stations to meet an electricity demand which has steadily decreased over the last decade[11] and to reduce both carbon dioxide emissions and the UK's increasing reliance on imported coal and gas for generating electricity?
2. How much would nuclear power contribute to the UK's greenhouse gas emissions?
3. What are the risks of continuing to depend on nuclear power?
4. Are there adequate, alternative, non-greenhouse gas emitting, sources of electricity?

**How practical is it in the long-term to rely on nuclear power stations?**

A conventional one-gigawatt nuclear power station consumes approximately 200 tonnes of uranium a year which must be extracted from ores which range between about 20% down to around 0.03% uranium, for the best of the low-grade ores.[12,13] Thus nuclear power normally depends on access to a significant supply of sufficiently rich uranium ores; it is therefore not renewable because the Earth's resources are finite. Although low-grade ores, in the form of granite for example, are widespread they are not rich enough to be exploited economically in today's world.

At current prices and rates of consumption the high-grade ores have been estimated by the World Nuclear Association to run out in about 60-80 years.[14] These estimates are based on current demand. If demand increases then supplies will run out sooner. These figures also take no account of the likely slowing down of production as reserves run out and available ores become less rich and harder and more expensive to exploit. 40% of global production occurs in politically and economically unstable countries, making availability (and hence prices) highly unpredictable.[15]

It seems clear that, even optimistically, reserves of high-grade uranium ore will run out before 2100. Some realistic estimates suggest that supplies will start to run out in 35 years' time or even sooner.[14] Indeed it has been predicted, on the basis of known national depletion rates, that globally uranium mining will peak around 2015 and will then decline with the result that there will not be sufficient ore to fuel the existing and planned nuclear power plants during the next 10-20 years.[16] This view is that, unless nuclear power is phased

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[8] Kemp, M. and J. Wexler (2010). ZERO CARBON BRITAIN 2030 A NEW ENERGY STRATEGY: The second report of the Zero Carbon Britain project. Machynlleth, CAT: pp.384.

[9] Helweg-Larsen, T. and J. Bull (2007). Zero carbon Britain. Machynlleth, Public Interest Research Centre, Centre for Alternative Energy: 105 pp.

[10] Anon. (2012). Electricity System: Assessment of Future Challenges - Summary. London, DECC: pp.12.

[11] http://www.carbonbrief.org/five-ways-the-uks-electricity-grid-is-changing

[12] http://www.after-oil.co.uk/nuclear.htm

[13] http://www.world-nuclear.org/information-library/nuclear-fuel-cycle/uranium-resources/supply-of-uranium.aspx

[14] and Nuclear Energy Agency (2006) quoted on p.11 in Fleming, D. (2007). The lean guide to nuclear energy: A life-cycle in trouble. London, The Lean Economy Connection. Also p.12-13.

[15] Burke, T., T. Juniper, et al. (2012). Climate Change and Energy Security: Why Nuclear Power is Not the Answer to the problems of Climate Change and Energy Security (A briefing for the government): pp.11.

out “some countries will simply be unable to afford sufficient uranium fuel at that point, which implies involuntary and perhaps chaotic nuclear phase-outs in those countries involving brownouts, blackouts, and worse.”[16]

A much more optimistic scenario has been painted by MacKay, possibly because he confused uranium resources and uranium reserves and neglected the implications of a falling off of ore-grade with time.[18]

Some argue that technology will find a way to use low-grade ores, almost irrespective of the cost involved, because of the huge capital investment already made in nuclear power stations. However, such arguments do not recognise the implications of the associated greenhouse gas emissions. Today 38% of the greenhouse gases emitted by a nuclear plant are from the extraction, processing and transport of uranium.[15] Some researchers have found that, using poor ores containing less than 0.02% uranium oxide ($U_3O_8$) to produce fuel for nuclear reactors could lead to the emission of more greenhouse gases per unit of electricity generated than natural gas-fired plants! This is the so-called $CO_2$ trap.[17] How soon this will happen will depend on future global demand and on future discoveries and grades of uranium ores but estimates suggest it will happen sometime in the second half of the 21st century.

Much more uranium exists in solution in the oceans (about 4,500 million tonnes).[18] However no commercial technology currently exists to extract uranium from this source and it has been claimed that more energy is required to extract the uranium than can be generated by the fuel produced.[19] Descriptions of the most recent advances in developing an ocean extraction method can be accessed here.[20] Here we consider only technologies that are mature and ready to be used.

Nuclear reactors currently have lifetimes of 30-40 years although the lifetimes of some reactors have apparently been extended to 60 years. Building one more generation of nuclear power stations appears to be the limit with current estimates of ore supply and will help to provide no more than a temporary solution to fill the energy gap until renewable technologies, smart grids,[21] energy storage and adequate interconnectivity are available on a large-scale.[10]

However the time required, including delays, to actually build and commission a nuclear power station also needs to be considered. In Europe there are two examples of building the third generation European Pressurised Water Reactor (EPR). The Olkiluoto 3 reactor in Finland, now under-construction, should have taken 4 years to build. It was started in 2005 and is now expected to commence operating in 2018.[22] The construction of a second EPR

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[16] Dittmar, M. 2011 “The end of cheap uranium” *Physics and Society* arXiv:1106.3617v2 . http://xxx.lanl.gov/PS_cache/arxiv/pdf/1106/1106.3617v1.pdf

[17] Fig. G.18 in http://www.stormsmith.nl/

[18] MacKay, D. J. C. (2008). Sustainable energy - without the hot air. Cambridge, UIT.

[19] Fleming, D. (2007). The lean guide to nuclear energy: A life-cycle in trouble. London, The Lean Economy Connection, p.27.

[20] http://phys.org/news/2016-04-advances-uranium-seawater-special-issue.html

[21] ‘A smart grid is an electrical grid that uses computers and other technology to gather and act on information, such as information about the behaviours of suppliers and consumers, in an automated fashion to improve the efficiency, reliability, economics, and sustainability of the production and distribution of electricity.’ From http://en.wikipedia.org/wiki/Smart_grid.

[22] http://www.theecologist.org/News/news_analysis/2859924/finland_cancels_olkiluoto_4_nuclear_reactor_is_the_epr_finished.html

reactor on that site was cancelled in 2015. Similarly, construction of the Flamanville reactor in France was started in December 2007 and is now predicted to be completed in 2018 after running into problems with steel quality in its reactor vessel.[23]

If planning consent delays are included, then any decision taken today to build a nuclear power station in the UK is in danger of ending up with a reactor that is running out of fuel before the end of its life.

Fast breeder reactors use uranium sixty times more efficiently than pressurised water reactors (PWRs).[7] They consume some of the waste plutonium and partly burnt uranium fuel from PWRs and produce yet more plutonium-239. The Russian BN-600 fast breeder reactor has operated since 1981 and a new version, the BN-800, is being built in Russia to replace it. Globally there have been 300 reactor.years of largely successful operation of fast neutron reactors since the 1950s.[24] [25]

On the other hand, although both Japan and France have their own prototype fast-breeder reactors, it was announced in 2012 that Japan's Atomic Energy Commission has decided that its almost 30-year old, fast breeder development programme 'cannot be considered as a realistic option for the next two to three decades due to technological considerations.' Similarly it has been said that '… the whole fast breeder cycle, consisting of three processes none of which [has] ever worked as intended, has itself never worked'.[26]

Finally, an international review of fast breeder reactors in 2010 concluded 'After six decades and the expenditure of the equivalent of tens of billions of dollars, the promise of breeder reactors remains largely unfulfilled and efforts to commercialize them have been steadily cut back in most countries' and 'The breeder reactor dream is not dead but it has receded far into the future.'[27] Therefore, it is concluded that fast breeder reactors are an immature technology not ready for immediate use.

An important factor that needs to be considered in the rational planning of any energy source, including nuclear power, is the *energy return on energy invested* (EROI). This can be defined as the delivered energy divided by the total energy that has been invested to produce that energy. Thus an energy source with an EROI less than 1 produces less energy than it consumes. It is probable that a nation's principal power source must have an EROI in excess of 10 to maintain anything approaching the complexity of our present society.[28]

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[23] http://www.world-nuclear-news.org/RS-Flamanville-EPR-vessel-tests-extended-1404165.html

[24] Blees, T. (2009). Prescription for the planet: The Painless Remedy for our Energy & Environmental Crises, p.137.

[25] General Electric – Hitachi have recently proposed that their PRISM-design of fast breeder reactor is used to consume the UK's reactor-grade plutonium stocks stored at Sellafield with the generation of electricity as a by-product for as long as 60 years. The PRISM design is also one of those proposed for demonstration at the US Department of Energy's Savannah River site in South Carolina. PRISM is the successor to the US fast breeder research at the Argonne national laboratory which culminated in the Integral Fast Reactor (IFR). The IFR combined a fast neutron reactor design with a form of reprocessing called pyrometallurgical reprocessing or pyroprocessing to allow a closed cycle system on a single site and virtually eliminate the danger of proliferation. However, the IFR was cancelled in 1994 for political reasons.

[26] Fleming, D. (2007). The lean guide to nuclear energy: A life-cycle in trouble. London, The Lean Economy Connection, p.23.

[27] Cochran, T. B., H. A. Feiveson, et al. (2010). Fast Breeder Reactor Programs: History and Status, International Panel on Fissile Materials**:** pp.128.

[28] Charles A. S. Hall and Kent A. Klitgaard (2012) Energy and the Wealth of Nations: Understanding the Biophysical Economy , Springer

It appears that the EROI of nuclear power depends on numerous factors and is hard to calculate. It has been suggested that it is unlikely to exceed 10 or 11.[29]

For any energy source it is also necessary to consider the *energy break even time*, which is the time taken to 'pay back' the energy invested in developing a source with the cumulative energy supplied by that source. Energy break-even time is important for two reasons.

First, although rapid growth of low carbon energy is dictated by concerns about both climate change and peak oil, the time over which the installed capacity of an energy source doubles cannot be less than the break-even time if the net available energy from that source is to increase rather than decrease.

Second, without massive subsidies, investors are unlikely to be interested in financing schemes in which the energy (and capital) payback time exceeds 5 years. According to a detailed life-cycle analysis, pressurised water reactors (PWRs) have an energy payback-time of 6.5 years.[30] As PWRs have a projected life-time of no more than 40 years the maximum estimated EROI over this period can be estimated as (40-6.5)/6.5 = 5. However, it can be argued that this estimate is conservative in that it relies on results from an earlier generation of less efficient PWRs and takes no account of potential lifetime extensions.[31]

Against this it has been argued that the EROI for future nuclear power sources does not take into consideration the decline in net energy caused by a switch to progressively lower grades of uranium ore driven by the depletion of the best ores[32]. Further, it could be argued that even if the EROI could be doubled to 10, this would not, as we have observed above, be enough for a principal energy source to support our society.[33]

Finally, a thorium nuclear fuel cycle is also possible. This cycle is being tested in India but is no longer being investigated elsewhere. Thorium is about three times as abundant in the Earth's crust as uranium but occurs in low concentrations in the ocean because thorium oxide is insoluble.[18] The thorium cycle has advantages, not least that in theory the fuel can be almost completely converted into heat, and therefore generates less waste. In addition the radioactive decay of the waste is much faster than for spent uranium fuel. But the thorium cycle needs other fissile material to initiate the chain reaction and one of the intermediary products - Pa-233 (protactinium-233) - is a strong neutron absorber which slows the reaction. Interest in this fuel cycle has largely waned since the late 1980s except in India. This appears to be a relatively immature technology not yet ready for deployment to mitigate climate change.

**How will nuclear power contribute to the UK's greenhouse gas emissions?**

Nuclear energy is called 'clean' or 'low carbon' in the sense that the marginal greenhouse gas emissions from generating an additional kilowatt.hour of energy are close to zero.

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[29] http://georgewashington2.blogspot.co.uk/2011/04/us-wastes-more-energy-than-it-uses.html and Hall, Charles and Bobby Powers."The Energy Return of Nuclear Power." State University of New York. April 22, 2008.

[30] Lenzen, M. (2008). "Life cycle energy and greenhouse gas emissions of nuclear energy: A review." Energy Conversion and Management **49**: 2178-2199.

[31] Pers. Comm. Alexandre Poisson, McGill University, April, 2012.

[32] http://www.stormsmith.nl/publications/secureenergy.pdf

[33] For comparison, in 2006 onshore US wind turbines had an EROI of around 20 (www.eoearth.org/article/Energy_return_on_investment_(EROI)_for_wind_energy) and in 2009 PV systems had an EROI of about 6.6 (www.eoearth.org/article/Energy_return_on_investment_(EROI)_for_photovoltaic_energy).

However, such statements take no account of the emissions generated by building a nuclear power station, mining, processing and transporting ores and enriching the uranium-235 content, manufacturing fuel rods and, eventually, decommissioning the power station and safely disposing of the waste, particularly the high-level waste.

Detailed life-cycle analyses of the production of energy by nuclear power stations have led to a range of estimates from 60 to 134 g $CO_2$ per kWh.[34,35] For the UK's reactors it has been estimated that emissions are at least 32 g $CO_2$ /kWh without including emissions from waste disposal.[36]

Nuclear power is not the lowest carbon technology available today to meet the 80% reduction in greenhouse gas emissions to which the UK government is legally committed by 2050. Although less than coal or gas-fired power stations, even when such stations are fitted with carbon capture and storage (CCS), such emissions are not insubstantial and exceed, for example, the highest estimate for onshore wind by at least a factor of three.

However nuclear power stations have much lower emissions than coal-burning or gas-burning power stations, even when fitted with carbon capture and storage, so a new generation of nuclear power stations could provide a temporary solution in supplying baseload electricity at least until renewable technologies and the necessary accompanying grid solutions are sufficiently well established.

**What are the risks of nuclear power?**

Nuclear power poses risks around accidents, terrorism and waste disposal. These risks are compounded as more nuclear power stations are built in more countries.[37] Here only qualitative risks are considered because there is so much uncertainty in estimating the risks quantitatively.

First, there is potential for lethal, widespread, extremely costly and long-lasting damage from any nuclear accident. In spite of a relatively safe record over the years, nuclear power stations will always be susceptible to human error and unexpected events even with modern technology (Three Mile Island 1975, Chernobyl 1986, Thorp 2005 and Fukushima 2011 are examples of accidents).

Second, terrorists could acquire material from nuclear programmes to build a nuclear weapon or a 'dirty' bomb (one that contaminates a wide area around the site of a conventional explosion with radioactive material). Either scenario could lead to the death, immediate or delayed, and injury of a very large numbers of people. Terrorists may also directly attack a nuclear facility with unpredictable but probably dire consequences.

The third risk centres on high-level waste (HLW) produced from waste fuel and the decommissioning of power stations. What right do we have to leave this hazard for thousands of future generations? The UK already has about 1,500 $m^3$ of high-level liquid waste at Sellafield. A 1 GW reactor produces about 0.5 $m^3$ (5 tonnes) of solid HLW per year so the annual increase in volume of HLW from a new generation of reactors is likely to be

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[34] Fleming, D. (2007). The lean guide to nuclear energy: A life-cycle in trouble. London, The Lean Economy Connection.

[35] Lenzen, M. (2008). "Life cycle energy and greenhouse gas emissions of nuclear energy: A review." Energy Conversion and Management 49: 2178-2199.

[36] As reported in Table 4 of Mez, L. (2012). "Nuclear energy–Any solution for sustainability and climate protection?" Energy Policy 48: 56-63.

[37] http://www.pppl.gov/pub_report/2011/PPPL-4617.pdf

relatively small.[38] However, in spite of extensive research over at least the last 30 years no acceptable underground site in the UK has been identified where high level waste can either be safely stored or disposed of. Plutonium-239, found in irradiated fuel, has a half-life of 24,400 years and consequently will remain hazardous for around 250,000 years. It decays into uranium-235 with a half-life of 710,000 years.[39] Although the hazard remains for millions of years it is generated, in theory, by a relatively small volume (less than a 22 metre cube of high-level and spent fuel waste for the UK so far[7]) yet it has to be broken up into safe, smaller volumes which have to be isolated from the biosphere for many thousands of years.

In sum, it is hard to fully and quantitatively assess the risks posed by nuclear power particularly in comparison with other sources of energy. Many people, including voters, feel deeply uneasy at the prospect of an expanding nuclear power industry. Fear of radioactivity and distrust of the nuclear industry among the general population are just as likely to play a significant role in any political decision about nuclear power as the arguments presented here.[40]

**Are there adequate, alternative, non-greenhouse gas emitting sources of electricity?**

The answer to this question is undoubtedly a qualified 'yes' depending on how energy demand can be reduced, how energy can be used more efficiently in future and on whether renewable sources can be installed fast enough and to a great enough extent to avoid dangerous climate change. The UK is investing strongly in renewables. In 2015 renewables, mainly wind and bioenergy, delivered 24.7% of the UK's electricity generation.[41]

Renewable energy means that the energy source is infinite on a human timescale, free and largely derived from the Sun or the Moon's rotation about the Earth. Renewable and well-tested technologies in the form of onshore and offshore wind turbines, hydroelectricity, tidal barrages, air-source and ground-source heat pumps and photovoltaic panels already exist. Some have operated for decades; some continue to be improved. New technologies in the form of wave and tidal current generators are being developed.

Although some embodied greenhouse gas emissions will be involved in the manufacture and construction of renewable energy equipment, the life-time emissions from such technologies per unit of energy produced are estimated to be lower than for fossil-fuel derived energy. Renewable energy also has the huge advantage that the 'fuel' is free and not susceptible to price fluctuations.

However, nuclear power stations have one big advantage over renewable sources in that in principle they can deliver baseload electricity i.e. the supply that is required to satisfy a demand that exists around the clock. In the 12 months to mid-June 2016 the UK baseload was about 25 GW which is around 55% of the peak demand in the same period.[42]

But in 2015, as already mentioned, nuclear supplied only 22% of the demand for electricity and the installed nuclear capacity is subject to planned power station closures. A national

[38] http://openlearn.open.ac.uk/mod/oucontent/view.php?id=398840&section=4.4
[39] http://www.nirs.org/factsheets/hlwfcst.htm
[40] Attention is drawn to government decisions in Belgium, Germany, Japan, Scotland and Switzerland to close or phase out nuclear power plants after the Fukushima accident in 2011.
[41] https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/524695/Energy_Trends_March_2016.pdf
[42] http://www.gridwatch.templar.co.uk/index.php

energy supply based predominantly on renewables might struggle, even with a smart grid, to supply the required baseload unless backed up by an efficient form of energy (electricity) storage and strong interconnectivity with other countries.

Finally, some advocate the use of nuclear fusion to generate electricity. Nuclear fusion aims to reproduce the fusion reactions that take place in the Sun. The International Thermonuclear Experimental Reactor (ITER) is being built over 10 years at Cadarache, France where 35 nations are collaborating to create a fusion reactor. ITER plans to create the project's First Plasma by 2025 and to reach full fusion power several years after that.[43] ITER is seen as the bridge toward a first plant that will demonstrate the large-scale production of electrical power. This might be a feasible way to generate electricity in the second half of the 21st century but today unfortunately it remains a technology that is unproven.

**Conclusions**

The UK faces a looming energy gap, when demand will exceed 'home grown' supply, which presently is filled by imported energy. The government would like to partly fill the gap by building a new generation of nuclear power stations (existing nuclear reactors will mostly be phased out by 2030). However, nuclear power is neither renewable nor free of significant greenhouse gas emissions.

Two possible conclusions can be reached from the above discussion which are at opposite ends of a spectrum of views.

1) A nuclear energy proponent will argue that one more generation of new nuclear power stations will help to temporarily fill the energy gap until renewable energy is sufficiently developed to take over entirely. It will be maintained, in spite of some current estimates, that new uranium reserves will be found, or fuels can be created using the fast breeder fuel cycle. The risks will be considered as worth taking and the argument will emphasise the increasing reliability, safety and security of nuclear power stations while downplaying the high-level waste disposal problem.

2) A nuclear energy sceptic will argue that, although a new generation of nuclear power stations may help to temporarily fill the energy gap, such power stations are likely to come on stream in the UK only as global supplies of uranium fuel start to dry up and/or their exploitation generates more greenhouse gas than gas-fired power stations (the carbon dioxide trap). The argument will be that it seems inescapable that efforts and financial resources would be better spent on expanding existing, well tried, renewable energy technologies the lifetimes of which will not be constrained by any depletion of their 'fuel'. Lastly, nuclear power carries the risk of serious accidents, will potentially bequeath hazardous waste to thousands of future generations and is open to terrorist attack.

In the final analysis it could be argued that the continued exploitation of nuclear energy in the form of a new generation of power stations is likely to face such serious practical problems that the construction and commissioning of any new nuclear power stations will probably be limited anyway.[44]

*Bob Whitmarsh, 1 July 2016*

[43] http://www.nature.com/news/us-advised-to-stick-with-troubled-fusion-reactor-iter-1.19994
[44] Mez, L. (2012). "Nuclear energy–Any solution for sustainability and climate protection?" Energy Policy **48**: 56-63.