centre for sustainable energy

Common concerns about wind power (2nd edn)

Chapter 7
Wind power and nuclear power

This is one of a series of chapters of evidence-based analysis drawing on peer-reviewed academic research and publicly funded studies.

For other chapters, see
www.cse.org.uk/concerns-wind-power-2017

Centre for Sustainable Energy, June 2017

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The first edition of Common Concerns about Wind Power was published in 2011 to provide factual information about wind energy, in part to counter the many myths and misconceptions surrounding this technology.

Since 2011, much has changed in the legal and economic sphere, and a second edition became necessary. Research has been carried out for this edition since 2014. Therefore, this edition is formatted as a series of individual chapters available for download at www.cse.org.uk/concerns-wind-power-2017

All chapters written and researched by Iain Cox.

Centre for Sustainable Energy, June 2017
Written and researched: 2017

The Centre for Sustainable Energy is a national charity committed to ending the misery of cold homes and fighting climate change.

We share our knowledge and practical experience to empower people to change the way they think and act about energy.

We are based in Bristol although most of our work has relevance and impact across the UK. Our clients and funders include national, regional and local government agencies, energy companies and charitable sources.

Chapter 7
Wind power and nuclear power

Summary

The UK is invested with some of the best wind resources in Europe, and wind power forms the cornerstone of the government's aim of decarbonising the energy sector and improving energy security. Indeed, without the rapid expansion of installed wind capacity that is projected over the next 20 years it is difficult to see how the UK can meet these objectives. Nuclear power, however, remains under consideration as a form of low-carbon electricity, and it is argued that nuclear avoids the intermittency issues associated with wind by producing steady 'base-load' electricity at a cost at least comparable with onshore wind power. With growing awareness of climate change caused by excessive fossil fuel consumption, combined with the large increase in global electricity use driven by emerging economies, there has been a resurgence of interest in nuclear power in the 21st century, dubbed the 'nuclear renaissance'. Some opponents of wind and other renewables point out that nuclear can potentially supply much of the UK's (and the world's) low-carbon electricity needs, but is this true? With a great deal of support through policy and public financing, nuclear established itself over 50 years ago with promises to produce power 'too cheap to meter'. Since then the industry has been beset with economic woes and several high-profile accidents which threw its shortcomings into stark relief. Despite the industry's recent revitalisation, the latest generation of commercial reactors are proving to be costly and slow to build, and a post-Fukushima world sees safety concerns once more at the forefront.

With already lengthy start-up times, the additional delays that are seemingly inevitable for any new build means nuclear is likely to be irrelevant to any UK plans to cut carbon emissions before 2030. There are also questions being asked about nuclear's environmental credentials, which, while much superior to that of coal from the perspective of carbon emissions, are doubtful when taking into account the logistical chain necessary for extracting and processing uranium, and the construction and eventual decommissioning of the power plant. The latter stage in particular highlights the huge uncertainties surrounding the impact of nuclear power, both financial and environmental. Since private investors have repeatedly shown themselves unwilling to bear these potential costs, nuclear continues to receive substantial public underwriting in the form of subsidies and other financial assistance. The UK's existing nuclear fleet will continue to place a burden on the public purse for most of this century, and even after its first 50 years the industry is still struggling to resolve the unique problem of storage and disposal of hazardous radioactive waste, with the cost and potential health implications to be borne by future generations for many years to come.

What is this based on?

Nuclear power has been used to generate electricity since the 1950s, and purports to be a tried and tested method of power generation. From its heyday in the 1960s and 1970s, the nuclear industry underwent a slump that lasted several decades, precipitated by the high-profile incidents at Three Mile Island and Chernobyl (and other lesser-known incidents). To a large extent this slump came about due to the erosion of public trust as people began to realise that nuclear power carries significant risk despite its ability to provide abundant clean electricity, but by the 1970s growing awareness about radiation hazards had also prompted increasing regulatory standards that were already pushing up the operating costs of existing plants, in addition to making the construction of any new plant a complex and costly business.[1,2] At the start of the 21st century, however, several decades without a repeat of a Chernobyl-like accident had improved public opinion again, and the notable rise in fossil fuel prices coupled with international concern over the inexorable climb of greenhouse gas emissions prompted a resurgence of interest in nuclear power.[1]

The use of nuclear power stations has been hailed in recent years as the most efficient way to produce electricity without relying on traditional fossil fuels, thus creating a relatively 'carbon-free' grid. Whilst not strictly renewable, the potential stockpile of nuclear fuel available for extraction means its supporters describe nuclear power as a viable means to meet the world's energy needs for hundreds of years at least, based on the fraction of physical fuel required by a nuclear plant in comparison by bulk with coal or gas. A typical nuclear reactor will generate the same energy as a coal-fired plant using less than 0.001% of fuel by weight. For example, a 1,000 megawatt (MW) coal station will burn

3.2m tonnes (Mt) of coal per year, compared with just 24 tonnes of enriched uranium oxide (UO_2) per year for a 1,000 MW nuclear power station (although it should be remembered that this UO_2 comes from 25,000–100,000 tonnes of mined ore).[3] The heat created in a nuclear fission reaction with uranium is used to generate steam which drives the plant turbine to produce electricity; hence, no CO_2 is emitted as a waste product, making nuclear electricity 'on a par' with renewables such as hydro and wind power when considering the operation of a nuclear plant, and nuclear power is certainly a low-carbon source of electricity when compared to fossil fuels.

Although the level of CO_2 emitted by nuclear power compares favourably with renewable energy sources, calculating the emissions can vary by one or two orders of magnitude due to the inherent complexity of the nuclear supply chain, making an accurate comparison very difficult.[4] Indeed, the logistical chain required for extracting and processing uranium can make a significant contribution to overall emissions depending on the fuel enrichment method employed (the older gas diffusion method versus the modern gas centrifuge process) and the existing power system that the process relies on (e.g. a national grid relying largely on coal). Furthermore, uncertain estimates surrounding the quality of uranium ore at the 'front-end' and the impact of decommissioning at the 'back-end' means, for some nuclear power plants, resulting greenhouse gas emissions can approach those of a natural gas-powered plant, many times higher than emissions from wind and other renewables.[5]

Globally, the nuclear power industry has been traditionally beset with problems involving the start-up, operation and decommissioning of nuclear plants, resulting in spiralling costs and threats to public health.[1,6–8] This is true of the UK industry as well, which has a history of poor economic performance, not to mention repeated incidents involving the release of dangerous material, although nothing as severe as the Windscale fire that occurred in 1957.[9,10] Despite decades of experience, the unique problem of storage and disposal of hazardous radioactive waste remains a concern for the nuclear industry, with the cost and potential health implications to be borne by future generations for centuries to come.[11]

Even without the concerns already raised, the long lead time required for construction of a nuclear power plant before it becomes operational means that nuclear power is almost certainly going to be irrelevant to the UK's CO_2 emissions targets prior to 2030. The cost of electricity per unit generated by nuclear power is currently no better than onshore wind power, without taking into account the future costs of cleaning up when a plant is finally decommissioned, and lengthy construction periods means nuclear is even more sensitive to already escalating prices, since so much of the cost of nuclear is in the initial captial required.[6,12] In comparison, the generation of electricity from wind power poses an insignificant threat to public health (see also Chapter 12), has seen costs decline over the last few decades, and can be considered a true renewable energy source.[13]

What is the current evidence?

Since the Government's commitment to reducing the UK's carbon emissions, nuclear energy has gone through a turbulent period of initial optimism followed by despondency. Despite being a mature technology with low operating carbon emissions, the question of whether the UK should invest in more nuclear power is dogged by concerns about environmental impact, economic viability, implementation, and safety.

Environmental impact

After Chernobyl, and prior to Fukushima, nuclear energy's role as a central plank of low-carbon energy production was undergoing a resurgence, enjoying greater public support than it had for decades.[1] This had instigated something of a sea-change in UK government policy, which had initially been very conservative about any future role for nuclear power in the early 2000s, to highlighting its potential as a means to decarbonise the electricity sector in 2005, to finally being acknowledged in the Electricity Market Reform (EMR) that financial incentives might be put in place to support new build.[14]

The case for specifically incentivising new nuclear development was a difficult one for the government to make, as successive UK adminstrations had pursued a liberalised policy since the late 1980s with regards to the energy market, and had relied on the privatised electricity sector to arrive at its preferred mix of generating technologies, within which framework nuclear had struggled.[9] With the environmental case for reducing carbon emissions becoming more prominent, and, indeed, legally binding, advocates of nuclear power within the main political parties began framing the need for low-carbon electricity in terms of ensuring Britain's energy security and the security of its citizens in the face of destabilising climate change.[15]

The greenhouse gas emissions (measured as 'grammes CO_2 equivalents per kilowatt-hour' or gCO_2eq/kWh) generated by nuclear power are impressively low compared with traditional fossil fuels, and generally perform as well as renewable energy sources such as wind or solar, although some factors of the nuclear life cycle can result in a higher range of values. A comprehensive review of more than a hundred life cycle assessments (LCAs) published for nuclear generation give an average level of emissions of 66 gCO_2eq/kWh

compared to 960 gCO_2eq/kWh for coal and 443 gCO_2eq/kWh for natural gas, although the average emissions are higher than those for true renewable energy sources: e.g. short-rotation forestry wood-fired steam turbines (i.e. biomass generation) of 35 gCO_2eq/kWh; a hydroelectric reservoir emits 10 gCO_2eq/kWh; crystalline solar PV emits 55 gCO_2eq/kWh; and wind turbines* of various configurations (onshore and offshore) has an average of 34 gCO_2eq/kWh.[5,16]

A different group took a similar number of published LCA studies, but also differentiated between technologies in more detail – this is a useful step since there are many different types of nuclear reactor used around the world. More than 80% of reactors operating today use ordinary water as a moderator† and coolant, which is known as light water reactor (LWR) technology. Focusing on LWR nuclear plants, this second study reported average emissions to be 25 gCO_2eq/kWh, compared to 1,000 gCO_2eq/kWh for coal-fired power stations.[17] The same research group reported an average of 16 gCO_2eq/kWh for various wind turbine configurations, using more than 100 published LCA estimates.[18] This group also studied the fuel supply chain for nuclear in detail, something that is rarely examined in LCAs or even reported at all.[17] This is a very important aspect of the nuclear life cycle, since the mining of uranium ore creates a significant environmental impact.[19] Furthermore, advocates of nuclear power as a means to decarbonise the electricity sector project a tripling of the world's nuclear generating capacity, something that will place a strain on uranium resources and require increased mining of lower-grade ores and the discovery of new uranium deposits, leading to greater environmental impacts.[19,20] Looking to the future, if nuclear power capacity increases worldwide the environmental impact due to the front-end operation will only get worse, with greenhouse gas emissions even surpassing 100 gCO2eq/kWh.[17,21]

This sensitivity to the quality of uranium ore is a significant factor for any expansion of nuclear power, because the long lifespan of a nuclear facility and the amount of capital resources that have to be invested in new build creates a significant degree of technological 'lock in', which makes it more risky as a means of delivering reductions in CO_2 emissions, especially since most new build is likely to rely on reactor designs that are 'once-through' for uranium fuel.[20] This serves as a reminder that nuclear power, although relatively low-carbon during its operation, is ultimately not a renewable source of energy in the same way that wind is. Finally, there are great uncertainties over the back-end stages of mine reclamation, not to mention decommissioning and dismantling of the retired power plant itself, a financially and environmentally costly stage that places liability on future generations.[5,17,19]

Economics and efficacy of implementing new nuclear build

The cost of generating electricity using nuclear power has grown steadily more expensive since the 1970s, and the industry has a notoriously poor record for estimating construction and realisation costs.[1] The enormous complexity of nuclear power stations, non-uniform designs and increasingly stringent safety requirements means that the industry has been unable to capitalise on institutional experience and capacity (so-called 'learning-by-doing') nor on economies of scale. In its heyday of the 1960s and 70s, nuclear build in the United States saw cost overruns of anywhere from 100 to more than 250%.[1] There is an argument that the lull in nuclear's fortunes following Three Mile Island undid any benefits derived from learning-by-doing at that point, but the problem is not just one found in the USA. France is considered the nuclear success story, going from a small number of early gas-cooled reactors in the 1960s to the completion of 58 LWR plants by 2000 that supply almost 80% of the country's electricity, most of these being installed and coming online between 1980 and 1990.[6] This was possible due to a unique institutional setting that permitted centralized decision-making from government, regulatory stability, and dedicated efforts for standardised reactor designs, all realised through a powerful nationalised company, the electric utility ÉDF.‡

However, despite lower operating costs, the expansion of the French nuclear industry has occurred against a backdrop of substantial escalations in the cost of building nuclear facilities. In real terms, the cost of new nuclear build in France grew almost two-and-a-half times§ over the period 1974 to 2000.[6] The two most recent construction projects of advanced third generation (Gen III+) reactors, one of which is in the French commune of Flamanville (the other is on the island of Olkiluoto in Finland), have been bedevilled with safety issues and rising costs since their inception, causing repeated delays and leading to increased risk of electricity shortfalls in France at critical times of the year.[9,22] The cost of these newest facilities – designed and built by leading nuclear companies with arguably more experience over the last 40 years than anyone in the world – has been eye-watering for investors and developers alike: Flamanville-3 has seen a cost escalation

* The LCA of wind power is discussed in more detail in Chapter 2.

† By 'moderating' the fast neutrons in a fission reaction the rate at which these neutrons impact other uranium atoms to create more fission reaction cascades is increased, thus improving the overall fuel efficiency. Ordinary (or 'light') water is commonly used, but some nuclear plants use heavy water (deuterium) or graphite as a moderator instead.

‡ This is Électricité de France, which operates in the UK under EDF Energy.

§ This would be three-and-a-half times if the enormously expensive 'N4' reactors are included. The N4 design is an antecedent of the European pressurised reactor (EPR) design. The EPR is one of several advanced third generation (Gen III+) reactors.

of nearly 10% per annum since development began in 2006, whereas Olkiluoto-3 has seen an annual escalation of more than 12% since 2004.[12] The current estimate for the full construction cost of Flamanville will be €10.5bn, more than double the original price tag, and it is expected to come online in 2018, almost six years overdue.[12,23]

In the UK, there has been no new nuclear capacity introduced since 1995, despite the fact that all but one of the UK's ageing fleet is likely to be retired by the middle of the next decade (several plants will last to 2025, but this will be achieved only by extending them past their original scheduled retirement date).[24,25] A history of escalating costs, regulatory uncertainty and adherence to liberalised market principles in the UK has made private investors wary of spending huge amounts of money on new nuclear build, and nothing has happened to allay these fears given the recent experience at Flamanville and Olkiluoto.[1,9,14]

Although supporters of nuclear energy point out that renewables have received a greater boost from the government under the Renewables Obligations (RO) scheme introduced in 2002, this overlooks the fact that the RO grew out of the Non-Fossil Fuel Obligations (NFFO) that were implemented in the preceding decade as a means to support the nuclear power industry, which was unable to function on the energy market following privatisation in 1989.[26] Due to the private sector's reluctance to take on the risk of lifetime costs of the nuclear-generated electricity industry the state-owned Nuclear Electric received 95% of the funds (roughly £1.2bn a year) gathered from the NFFO levy on electricity bills. In fairness, most of these costs were needed to run those reactors that were a legacy from Britain's first forays into nuclear development in the 1950s and 60s. The private sector, however, was tasked with a commitment to build four new nuclear plants, but was unwilling to take on even that commercially risky venture.[9] In the end, Nuclear Electric oversaw the building of just one new LWR station, Sizewell B, at a cost of £3bn.

Once Sizewell B opened in 1995, the government felt more confident in the reliability of this new plant together with a collection of older plants,** and embarked on finally privatising the nuclear sector with the formation of British Energy. This new company floated on the stock exchange for £1.7bn, around half of the cost it took to build Sizewell B, but by 2002 British Energy had collapsed in the face of low electricity wholesale prices (meaning lower revenue streams) that could not compensate for the operating costs of running its fleet.[9] The government stepped in with an aid package that was estimated by the European Commission would total more than £10bn in cash payments.[27] A later UK government review estimated that the taxpayer, at a minimum, had assumed a liability of £5.3bn (in 2006 prices).[28]

The first of the new Gen III+ reactors to be introduced to the UK is planned to be Hinkley C, using the same European Pressurized Reactor (EPR) design so bogged down at Flamanville and Olkiluoto. Two EPRs are being built in China as well, although increasing costs of the Gen III+ designs have also raised concerns in China because the lead times are still significant, during which time capital costs keep rising. Construction on China's first EPR began at Taishan in 2009 with an operation date originally set for 2013, but the operational date for the Taishan-1 is now delayed until 2017.[29]

In the UK, even more uncertainty has surrounded the eventual cost of construction for Hinkley C, with the original budget of £5.6bn in 2008 having ballooned to £18bn.[63] After much wrangling with EDF Energy (the British subsidiary of ÉDF) the UK government has offered a 'strike price' of 9.3 p/kWh under the new Contracts for Difference scheme, similar to onshore wind's 9.5 p/kWh but with several important differences.EDF Energy's strike price will increase with inflation, the government is committing to a 35 year contract for the CfD – renewables are only offered 15 years – and £10bn of Hinkley's construction costs have been underwritten with a government loan guarantee.[64] The longer duration of the CfD reflects the longer payment periods for nuclear, but will expose consumers to greater price uncertainty as the wholesale price of electricity is likely to change substantially over this longer period. Under the current CfD system falls in the price of wholesale electricity are offset by top-up payments, paid for by the government. It is estimated that future top-up payments through the HPC CfD have increased from £6.1 billion to £29.7billion since the strike price was agreed in 2013.[64] The government has also committed to a £2bn debt guarantee for Hinkley Point C. If this guarantee is ever called on, it could lead to taxpayer losses.[64]

None of these conditions have been extended to renewables, and onshore wind's strike price will fall to 7.9–8.3p/kWh by 2017. In addition, onshore wind generators must submit competitive bids as part of the process of their CfD allocation.[30] This appears to be in complete contradiction to the government's stated aims in 2011's EMR White paper, which said, 'New nuclear stations should receive no public support unless similar support is available to other low-carbon technologies.'[31] Energy consumers will also bear a larger burden, because the cost of generation from nuclear is likely to continue to rise, and this will be the case in both the UK

**These were the advanced gas-cooled reactors built over the 1960s and 70s. The older Magnox plants (so called because of the alloy used for cladding the uranium fuel rods) were deemed unsaleable and were not included in British Energy's portfolio.

and more experienced markets like France.[12,23] Given typical cost escalations, project overruns and historical capacity factors, it is likely that the cost of nuclear power in the UK will be at least 10 p/kWh but may well exceed even 16 p/kWh, which is higher than the current rate for offshore wind's strike price of 15.5 p/kWh, generally considered to be the most expensive option for renewable energy that is commercially viable.[12] When details of the strike price for Hinkley C initially emerged, there was some criticism that a strike price of 9.25 p/kWh[64] was far too high, allowing EDF Energy to make windfall profits in comparison to cheaper energy generated by other European operators. What seems more likely is that the UK government has actually come closer to the true cost of nuclear expansion.[23]

The hidden financial burden of decommissioning also inhibits investment, involving yet more uncertainty over the fate of spent fuel (see Radioactive Waste below) and the looming spectre of non-operational assets having to be managed for generations.[††] Partly as a result of liabilities incurred by the bankruptcy of British Energy,[28] the 2008 Energy Act mandates operators of nuclear plants to assume liability for clean-up costs through a decommissioning programme that must be fully funded, making it illegal to run a nuclear facility without a government-approved programme in place.[24] The core structure of a nuclear plant becomes increasingly radioactive over its life, and decommissioning costs for a reactor site can be of the same order of magnitude as construction estimates. These costs are considerable, and continue to go up – the Nuclear Decommissioning Authority (NDA) estimated the liability at £73bn in 2007, representing an average increase of 9% every year since government estimates in 2002.[25] Since then the cost has continued to increase with the total estimated at £117bn as of 2016.[32]

In the UK, nuclear operators are required to have insurance to meet claims in the event of an accident. In the case of Hinkley Point C this insurance only covers the first €1.2bn of cost; the UK government (and consequently tax payers) will meet any extra costs over this amount, should they arise.[64] Although there is some merit in the idea that the UK nuclear industry as a whole can make a profit through spin-off technologies involved with commissioning and decommissioning, this contribution is small in comparison with the public cost to manage the legacy of existing UK plant.[33]

†† As part of its £10 billion valuation for the aid package given to British Energy (see p.6 above), the European Commission acknowledged the huge uncertainties of their final cost estimate due to the extremely long time periods involved. The Commission's report stated that British Energy, 'Would not expect to begin dismantling an AGR until at least 85 years after a station has ceased generating, while spent fuel management must continue indefinitely.'

It is accepted economic practice to appraise future liabilities of a development by taking the total cash sum needed to pay for the liability and discounting it over the project's lifetime, so expressing it in terms of the amount that should be invested in today's prices so that it earns interest until it is needed – this is the discounted value. This is an intuitive and sensible approach for owners of expensive plants, who must gauge future costs to them and their creditors over several decades. By discounting, the cost to operators of a nuclear facility for decommissioning are minor, making up roughly 2-4% of the cost of generation when set against the facility's entire lifetime.[12,23] However, the periods that apply when considering decommissioning liabilities are in the order of a 100 years from the time the project starts. For instance, the UK's existing nuclear legacy will last into the 22nd century.[32] In this light, one might question the usual assumptions of discounting. The nuclear industry has a notoriously poor record on cost estimates for upfront processes like construction, but it is being asked to accurately forecast, a century in advance, the cost of back-end processes that have not yet been widely achieved commercially, such as dismantling and cleaning of nuclear sites. In the case of spent fuel disposal, the process has not even begun. The investments must also have a negligible risk of failure at the required rate of interest, something that the recent financial crisis should remind us is certainly not assured. If there is a significant shortfall in funds by the time decommissioning is necessary, future generations will have no choice but to undertake cleaning up and fuel disposal using public resources – there is no option to 'default' on this kind of liability.

One might ask why a 50 year-old energy industry still requires so much public financial backing, even seeing costs go up in a 'negative learning' process as the complexity of nuclear systems increases.[6] It could well be that the inherent properties of nuclear power, being large-scale, inflexible and requiring formidable levels of engineering excellence in construction and operation to ensure safety and efficiency, means that it will remain a hugely expensive and commercially risky venture. In the past, governments could simply dictate energy policy and leave it to nationalised utilities to hash out the details. Nationalised companies could borrow cheaply on government terms and absorb significant losses, confident that costs could ultimately be recovered from the taxpaying consumers beholden to their retail monopolies.[14] Given the enormous technological and financial resources required, the capital-intensive start-up costs of nuclear power plants and the lengthy lead times before shareholders begin to see returns, it is difficult to see how a genuinely private UK nuclear sector can function in today's liberalised electricity market. This will have a major impact on the UK's attempts to effectively transition to renewable energy sources, because nuclear will continue to devour a disproportionate share of financial and political resources at the expense of more viable options in terms of energy efficiency and developing renewables further.[9]

The level of subsidy received by renewables is often criticised (see chapter 3), but the need for subsidies is not unprecedented when one considers that renewable energy technologies are in their infancy compared to nuclear, and that, in its nascent years, nuclear power received enormous subsidies (principally thanks to the weapons potential that came from it.[34]) Since the 1950s, nuclear power has received the bulk of national research and development (R&D) budgets in energy technology. From 1974 to 1992, nuclear received more than 50% of public R&D spending on low-carbon technology in mainly OECD nations; by 2012 that share had fallen to around 30%.[35,36] Although energy research's share of government R&D spending in the OECD nations has fallen from 12% to 4% since the 1980s, nuclear has remained the single largest beneficiary during that time.[35]

Whilst it is difficult to make detailed evaluations of the specific outcomes and returns from energy R&D, studies have shown positive results. For example, the European Union has estimated an internal rate of return of 15% from the period 2010 to 2030 for its R&D investments in its Strategic Energy Technology Plan,[35] although the evidence above suggests this is unlikely to come in the form of cheaper nuclear power.[6] In the United States, the Department of Energy found that its investments between 1978 and 2000, amounting to $17.5bn (in 2012 prices) provided a yield of $41bn; however, this was primarily R&D investments for energy efficiency and fossil energy.[35]

Finally, the 'full' cost of nuclear electricity may be impossible to determine unless the nuclear industry is made to work with full indemnity insurance.[37] Existing and future generations will be saddled with the negative impacts should a nuclear accident occur, but the nuclear industry is able to waive the cost of full-liability insurance cover for critical accidents as such risks are not commercially insurable according to European international treaty.

The only real comprehensive insurance mechanism comes from the Price–Anderson Nuclear Industries Indemnity Act in the USA. Price–Anderson means US operators are paying roughly US$700,000 in annual premiums per reactor, and the insurance pool would cover up to $13bn for any single accident.[23] Thankfully, the largest accident in the USA to date was Three Mile Island in 1979, which resulted in no fatalities and financial impacts to the public were easily covered by the fund. Economically speaking, though, one is reminded of the words of a former commissioner for the Nuclear Regulatory Commission:

> *'The abiding lesson that Three Mile Island taught Wall Street was that a group of NRC-licensed reactor operators, as good as any others, could turn a $2bn asset into a $1bn cleanup job in about 90 minutes.' (Peter Bradford, quoted by Matthew Wald in the New York Times, 2 May 2005.)*

The estimated cost, according to the Japanese Government, of the Fukushima clean-up operation, however, will cost an estimated £142bn over several decades, far exceeding the $13bn provision made under Price–Anderson, which is considered to be by far the most generous payout.[38] Indeed, in Europe, damage cover only extends to €1.4bn (roughly $1.8bn), half of which is met by the operator's insurance and the remainder matched by the relevant government.[23] Japan's laws governing the nuclear industry require operators secure ¥120bn (roughly $1.2bn) in liability coverage. Governments, which means ultimately society's tax money, have to find the resources to make up any shortfall. As discussed above in relation to financing nuclear power, the public has no choice to not pay. This amounts to an implicit subsidy that has given nuclear a substantial economic advantage in avoided costs, and it is unlikely to be removed if nuclear is to remain a central plank of government policy.[37,39]

Safety of nuclear power

As explained above, one reason for the escalating cost of nuclear facilities is the stringent safety requirements.[1] Nuclear power is an unforgiving technology because an accident may result in catastrophic effects that can affect populations and ecosystems over a wide area. In essence, climate change can be argued to have the same widespread impacts as a severe nuclear accident – if not more so – and this has become one central arguments that is driving policies in favour of expanding nuclear power, since nuclear power can provide security to society through its ability to generate low-carbon electricity (although see Environmental Impacts above).[15] Indeed, a recent study suggested that the long-running operation of nuclear power plants over several generations in many industrialised countries has enormously reduced the level of avoidable deaths that would have been caused if coal had been used in its place, since nuclear electricity has mitigated a significant amount of airborne pollutants that would otherwise have been emitted by coal-fired electricity.[40]

Nuclear accidents, like all industrial accidents, are typically caused by human error, either lapses in awareness or miscalculations.[41] In light of this, and following several accidents in the 1950s and 60s, nuclear plant designs over the last 40 years have applied principles of reliability, redundancy and separation of safety systems from the plant process systems.[42] This 'defence-in-depth' is the cornerstone of modern nuclear plant design. However, the fact that nuclear power has developed, through hard-won and sometimes tragic experience, the ethos of making it 'fail safely' underscores the inherent dangers of the technology. This inherent danger and the probabilistic nature of the risk[§§] is a feature common to all industry, but few expose the public to the same level of hazard should systems catastrophically fail. The nuclear industry operates under impressively exacting safety standards, but in many cases safety principles are based on idealised situations and do not take into account the randomness of real events and human fallibility.[7]

Despite high-profile incidents in the past, the nuclear industry safety record is in fact very good, with a worldwide fatality rate expressed as 0.007 deaths per gigawatt of electricity per year (0.007 deaths/GWey) due to accidents – a statistic that is markedly better than coal (5.92; although 90% of this is due to China), oil (0.95) and natural gas (0.12).[43] Even with attributed deaths from Chernobyl, the figure for nuclear is just 0.03 deaths/GWey, although the total number of fatalities that will eventually result from Chernobyl is subject to some debate. Wind power, between 1975 and 2012, has 80 reported fatalities, many of which occurred in the early days of small kilowatt-scale turbines and were due to owners or maintenance staff failing to follow precautions, such as not using fall protection gear or working on turbines that were rotating at the time; one incident was a suicide.

As the wind industry rapidly expanded and began deploying many more megawatt-scale turbines, the rate of fatalities per unit of electricity has declined by three orders of magnitude since the 1980s and now stands are around 0.00003 fatalities per gigawatt-hour.[44] Based on data for the UK and Germany (countries with some of the largest uses of offshore and onshore wind, respectively) the fatality rate for wind is around 0.005 deaths/GWey, although offshore (0.009) is notably more dangerous than onshore (0.002).[43]

It is clear that in terms of fatality risk, both nuclear and wind far outperform fossil fuel electricity generation. Although the risk of fatal accidents is not negligible for wind, its decentralised nature and lack of inherent hazards in the form of dangerous radionuclides strongly limits its catastrophic potential should a major incident occur. A failure of nuclear reactor core containment can have severe consequences in terms of fatalities, many thousands of times greater than wind.[43] The attribution of deaths due to 'latent mortality' with regards to the Chernobyl disaster remains a contentious issue. Most epidemiological studies have focused on thyroid cancer and leukaemia, because the radioisotopes iodine-133 (133I), caesium-134 and caesium-137 (134Cs, 137Cs) were released in large quantities from the reactor core and contributed the most to the dose that surrounding regions were exposed to.[45]

In fact, there is little evidence of leukaemia cases being directly attributable to the Chernobyl disaster, but data for the incidence of thyroid cancer (note: incidence is the number of cases, not the number that result in death) suggest that the radiation leak was responsible for around 4000 cases by 2005, and it is estimated this will rise to 16,000 cases across Europe by 2065.[46] When one considers the additional incident cancers (other than of the thyroid) may be roughly 25,000 over the same period, the figures make for sobering reading. It is important to note, however, that across that same period the population of Europe is expected to suffer from hundreds of millions of cases of cancer from all causes. Indeed, it would be difficult for a normal epidemiological study to register this elevated incidence of cancer against such a large incident background,[46] which underlines the imprecision inherent in trying to account for the true cost of such an event.

The relationship between received dose and disease incidence is complex, and the dose regime that populations surrounding Chernobyl were exposed to is still not known in adequate detail.[47] It is safe to say that some of the more outlandish claims of hundreds of thousands of deaths resulting from Chernobyl can be ignored.[45] But each one of those cancer cases from the many thousands that are attributable to Chernobyl, even though a very small fraction of the number of cases expected to occur in the normal course of events, represents a desperate, and sometimes fatal, tragedy for those involved. Even 50 years after the atomic bombing of Japan in the Second World War, data were still being revised in the face of unexpected health detriments to exposed victims, and less than 30 years has passed since Chernobyl.[47]

In the public's opinion, due to the potentially catastrophic nature of a nuclear accident, the nuclear industry (and government) has failed to show that it operates under a reasonable level of safety given the hazards involved. This remains a major factor preventing the acceptance of nuclear-generated electricity as a valid source of low-carbon energy. Communities are questioning the viability of nuclear with regards to what constitutes a 'normal accident' and whether society should embrace the inherent risks in nuclear. Arguably, society has made the same decision before with regards to fossil fuel energy, which clearly comes with significant risks.[8] This doubt is not surprising: the disaster at Fukushima Daiichi caused by the tsunami of 11 March,

[§§] That is to say, there may be great uncertainty surrounding the calculation of the exact risk, but that there is risk is evident. It is well known that most people have a limited understanding of risk and how to make decisions accordingly – in particular, we tend to be less concerned over low-probability risks, but, when they eventually occur, we tend to overestimate their likelihood and impact.

2011, was the result of a natural hazard that was supposedly beyond what designers had envisioned, even though the threat seismic activity poses to nuclear facilities is well known.[7] The tsunami completely overwhelmed a sophisticated, multi-layered safety system and left the nation's nuclear industry improvising its response on an hour-by-hour basis. The Fukushima emergency shows that even the most considered 'belt-and-braces' safety system can be undermined by a combination of extreme natural events and human oversight.[***] The effects of the massive radioactive leak as a result of three reactor core meltdowns will be felt for decades to come.[38] Although the amount of radionuclides from Fukushima released to the surrounding area was much lower than what occurred at Chernobyl (it helped that the majority of the material went out to sea), the likely number of excess cancer deaths will be in the region of 500–1000. That this is a relatively low number is in large part thanks to the prompt preventive action taken by Japanese authorities.[48]

There will also be long-term detriments to surrounding environments; effects are already being seen on local species in the 30 km exclusion zone around Fukushima.[49] These results echo what has been found at Chernobyl, where species viability has been compromised by decades of exposure to longer-lived radionuclides.[49,50] Furthermore, field-based ecological assessments have challenged the dose thresholds derived for radioactive elements, with doses received by organisms in the field seemingly having a greater effect than predicted by laboratory models.[51] This ecological data further underscores the uncertainty surrounding the full long-term effects that will result due to chronic exposure of populations to radionuclides accidentally released to the environment.

In the UK, despite promises that things are now much safer, as recently as 2005 the Thermal Oxide Reprocessing Plant (THORP) plant at Sellafield was found to have leaked 83,000 litres of liquid containing 22 tonnes of uranium fuel into a sump for a period of eight months before being discovered; the leak only came to light at the plant because the follow up accountancy system noticed there was missing nuclear material. The contents did not escape into the environment since they were caught in the secondary containment tank, but the inspector's report made it clear that the plant operated under an 'alarm-tolerant culture', at one point stating:

> *'The HSE investigation team found that there were significant operational problems with the management of a vast number of alarms in THORP, resulting in important alarms being missed.' (See ref.10: M. Weightman, HSE report, 2007, 13, para 67.)*

In the USA, the Government Accountability Office (GAO) issues regular reports on the country's Nuclear Regulatory Commission (NRC). A review of plant performance from 2001 to 2005 noted 98 incidences of a plant's failure to comply with NRC regulations and industry standards such that it had an effect on overall plant safety (out of more than 4000 incidences).[52] It should be stressed that most of these 98 cases were of low-to-moderate risk, but 12 were deemed to be significant. In all, 75% of the US's operating nuclear plants were placed on additional oversight by the NRC in that five-year period due to data reported for individual indicators that were outside of NRC's acceptable performance category. Whilst only a fraction of a percent of all data reported (30,000 reports in total) this still represents more than 150 incidences.

In Europe, the delays with the Olkiluoto plant are also caused primarily by safety concerns of the Finnish regulatory authority (STUK), although there was also some public disquiet among independent parties over why it took STUK so long to discover non-compliant components.[53] Other designs for new Gen III+ reactors also have lingering safety concerns (and no operational experience, since none have been finished).[1] This has led to delays over construction in China at Sanmen (a different site to Taishan and incorporating a different reactor); although construction is proceeding much more smoothly than European projects, Sanmen-1 is still not in operation more than three years after its scheduled start date of August 2013.[†††] It is expected to be in commercial operation by the end of 2017.[65]

The same reactor design, the AP1000, is awaiting approval from the UK's Office for Nuclear Regulation (ONR). In 2011 the ONR issued a report listing 51 issues with the design that must be resolved before the AP1000 can be approved for use in the UK.[54] No resolution has been pursued since, although NuGeneration (owned by Toshiba, the parent company that owns the AP1000 design) is planning to build three AP1000 reactors next to the existing Sellafield site. The ONR states that, 'The 51 issues requiring resolution span 13 of the GDA assessment areas, and are technically challenging. Therefore we expect the completion of GDA for the AP1000 reactor design to take a number of years.'[55]

It is commendable that the nuclear industry acknowledges that it should operate with exceedingly high safety standards, but the desirability of relying on a source of power that must 'fail safely' or else risk dire

*** Questions were raised during the aftermath of the crisis when the operator admitted to multiple inspection failures just weeks before the disaster (see Tabuchi, Onishi and Belson, New York Times, 21 March, 2011; A1, A6).

††† See 'First concrete at Sanmen,' World Nuclear News, 20 Apr, 2009, www.world-nuclear-news.org/NN_First_concrete_at_Sanmen_2004091.html

consequences should surely be questioned. From an economic point of view, if nothing else, the inherent risk means that a large, capital-intense facility like a nuclear plant, on the very small chance that they do fail, will fail spectacularly, and will require enormous amounts of time, money and resources to repair.[8]

Radioactive waste

The problem of radioactive waste impinges on both human safety and the environment and represents a major technological challenge.[11] Nuclear waste from nuclear power plants is in the form of spent nuclear fuel or what remains after that spent nuclear fuel is reprocessed. Spent fuel can be reprocessed by converting it to a mixed-oxide fuel (MOX) that is a mixture of uranium and plutonium oxides. Reprocessing spent fuel to MOX is carried in the UK at the THORP facility (although no operating UK reactor uses it) and reprocessing and MOX usage is a central feature contributing to the efficiency of France's nuclear fleet.[56,57] It can increase energy recovery of the original fuel by up to 30%, reducing the demand for natural uranium in fresh fuel.[20] Mixing plutonium fissile material with uranium to produce MOX for subsequent re-use in a reactor is also a useful way to reduce stockpiles of weapons-grade plutonium, something that is carefully balanced in the French system so that no spare inventory remains (in the civil programme at least – France does possess a nuclear arsenal).[57] By contrast, the UK possesses the largest stockpile of plutonium in the world, partly because the UK reprocessed spent fuel on behalf of other nations, but to a large extent because of decisions taken in the early days of Britain's nuclear programme to stockpile it for weapons use and for a potential future fleet of fast-breeder reactors that subsequently never got off the ground.[58]

The spent nuclear fuel and waste streams from reprocessed spent fuel are known as high-level waste (HLW) and are highly radioactive.[42] The main radioactive content in HLW is from spent nuclear fuel (>99%)[11] that contains a mixture of fission products, mainly caesium-137 (^{137}Cs) and strontium-90 (^{90}Sr) both have a half-life ($t_{½}$) of roughly 30 years. Various decay products of fissile material in the fuel give rise to longer-lived products, such as americium-241 (^{241}Am, $t_{½}$ of 430 years), americium-243 (^{243}Am, $t_{½}$ of 7,400 years), plutonium-239 (^{239}Pu, $t_{½}$ of 24,000 years) and technetium-99 (^{99}Tc, $t_{½}$ of 213,000 years). Those listed here are some of the most problematic due to their radioactivity and movement through biological and geological systems, but it is by no means a comprehensive list. In reactor core meltdowns the most important radioisotopes are those that are most volatile and easily dispersed into the environment and have a short t½ so radiological exposure is particularly acute. In Fukushima, the main radioisotopes included 131I, 137Cs and xenon-133 (^{133}Xe).[38] Note most of the products listed above in HLW move more slowly through environments and are not as easily dispersed.

The problem inherent with fissile products in spent nuclear fuel is that the HLW produced has a very lengthy radiological toxicity and so must be isolated and contained for a sufficient period such that it no longer poses a threat to human health and the environment if exposed.[11] In fact, the majority of radioactive waste from a nuclear plant is low-level or intermediate-level waste and can be safely stored for several decades to allow any contaminants to decay, after which point it can be disposed of reasonably safely.[42] The remaining HLW is more problematic, since short-term storage is a troublesome issue itself. For instance, the UK's Nuclear Decommissioning Authority is finding that many of the decommissioned sites around the country contain a mixture of toxic and radioactive materials that generate a great deal of heat and require careful handling and storage to minimise the danger (a costly and hazardous exercise).[25]

The UK's high-level waste is predicted to be 478,000 m^3 by the 22nd century (equivalent to filling the Albert Hall five times over).[59] This waste is highly toxic and must be made safe: it is generally solidified in borosilicate glass, a process called 'vitrification' that is mainly carried out at Sellafield.[25] The government has agreed to take on liability for disposing spent fuel and intermediate level waste from Hinkley Point C.[64] What to do with this waste after that is still moot, and one that government and the industry have not been able to resolve completely. Spent nuclear fuel in storage at nuclear facilities, not to mention the plutonium stockpile, also represent a considerable hazard in the event of a malicious attack designed to release large amounts of radioactive material into the surrounding area.[58] The French authorities admitted to a recent spate of drones flying over several nuclear facilities on October 2014, with no clues as to who is operating the aircraft.[‡‡‡]

The preferred recommendation of the UK government is for a geological repository, and this has been reiterated by the Committee on Radioactive Waste Management (CoRWM) as the best available approach when compared to the risks of other management schemes.[60] As they have done previously, CoRWM has taken pains to point out that the position adopted on the issue is presented to the public in terms that are too simplistic and optimistic, and have cautioned that the uncertainties over geological screening at the depths associated with a nuclear repository should not be underplayed when dealing with communities.[60] The only

‡‡‡ See A. Neslen, 'Three arrests fail to staunch mystery of drones flying over French nuclear plants,' Guardian, 6 Nov, 2014, www.theguardian.com/environment/2014/nov/06/arrests-myster-drones-flying-french-nuclear-plants

area in England to date (the Scottish Parliament has ruled out a geological repository) that had progressed to site assessment stage was west Cumbria, but a local county council voted to stop the process in January 2013, ending a three-year consultation process. No other regional authority has expressed an interest in hosting a repository.[61]

After two decades of extensive research by various countries, only two identified sites have been able to progress, one in Finland (at Olkiluoto) and the other in Sweden (Forsmark).[11] The most well known case study, that of the Yucca Mountain repository in the USA, suffered a setback in 2011 when the Department of Energy (DOE) and the NRC withdrew from the licensing process following many years of public opposition from Nevada residents. The Yucca Mountain site was considered one of the most comprehensive evaluations performed for a geological repository, and the withdrawal decision by the government agencies caused a great deal of recrimination. Because of the large amounts of nuclear waste accumulating at American nuclear facilities, many operators are in the process of suing the federal government for the closure of the Yucca licensing process, since there is now no agency to take this decades' worth of waste from them and it must still be managed. These legal actions are likely to cost the American taxpayer tens of billions of dollars over the coming decades.[62] It appears material hazards and financial burdens continue to define nuclear power.

Conclusions

Nuclear electricity offers significant reductions in greenhouse gas emissions in comparison to fossil fuels, with savings almost comparable to many renewable sources of energy. Given the long-term effects of elevated CO^2 levels in the atmosphere and the continuing environmental detriments created by fossil fuel extraction and combustion, there is a pressing need to decarbonise the energy sector. In terms of modern low-carbon generation technolgies, nuclear power has been established the longest, with a record of producing electricity stretching back to the mid-1950s. Indeed, a recent study suggests that the long-running operation of nuclear power plants over several generations in many industrialised countries has enormously reduced the level of avoidable deaths that would have been caused if coal had been used in its place.

Considering this, expanding nuclear power would seem poised to play an important role in the future of low-carbon energy and climate change mitigation, and comparisons are often drawn suggesting that wind power is not needed as nuclear power could be expanded to serve the same needs. But investment in nuclear energy represents an enormous commitment, with any meaningful expansion of the UK's nuclear capacity likely to come from the public purse. The benefits of such a policy are by no means clear, but what is certain is that the legacy of such a policy would place a financial and environmental burden on future generations that is difficult to predict. Nuclear power's operating characteristics will also tie the UK to the old-style model of a heavily centralised power system that makes it far more difficult to integrate renewable sources of electricity, because baseload nuclear power cannot adapt to the operational demands of a grid that contains a significant proportion of generators relying on wind and solar. Nuclear only contributes to the electricity energy needs of the UK – it cannot meet the demand for transport or heating which are dominated by fossil fuels. The UK's electricity production consumes roughly one-third of the nation's primary energy supply, mostly in the form of fossil fuels (about 75%).[§§§] At most, this is a theoretical maximum of 27% of the UK's total fossil fuel demand that can be replaced. Much the same can be argued for wind power (and other renewables), but wind does not have the same safety and environmental problems, and can be removed more cheaply and quickly if a better solution presents itself.

The salutary lesson to be taken from nuclear's difficult first 60 years is that cleaner, low-carbon generation is key to improving societal well-being, and an ideal solution would be if this can be achieved by combining energy efficiency with sustainable sources of energy that do not give rise to the myriad safety concerns that nuclear does. Evidence suggests that any benefits accrued from low-carbon nuclear electricity comes at a considerable financial cost, and the trend of the last five decades is that these costs will continue to go up, not down. In contrast, support for burgeoning wind and solar industries has seen prices tumble, whilst nuclear has been blighted by safety issues, unfortunate accidents and financial uncertainty.

Even the new generation of reactors have failed to prove themselves financially viable, although they do display an impressive range of safety features that the industry hopes will signal that nuclear power is finally 'turning the corner'. Unfortunately, the history of the current generation of reactors, most recently the disaster at Fukushima, has shown that it may be impossible to adequately design for events beyond the realm of regular expectations. Though the risk of failure itself may be very slim, nuclear remains a technology with considerable catastrophic potential. Whilst modern energy systems do provide a bounty of benefits, energy accidents degrade human health and welfare, and destroy natural environments. The effects are particularly far-reaching when one examines the whole energy

§§§ I. MacLeay and A. Annut, 2013, 'Chapter 1 – Energy,' Digest of United Kingdom Energy Statistics 2013, (London: The Stationery Office/TSO), 11–40.

supply chain of fossil fuels and also the long legacy of nuclear power.

Clearly, every benefit yielded comes at a cost. This is inescapable given how integrated energy infrastructure is in modern society. If society wishes to maintain its current level of energy consumption and continue to rely on conventional, large, centralised power systems running on fossil fuels and nuclear then it will have to embrace these risks to a certain extent. But if society is to transition successfully to a low-carbon future, the options must be assessed in terms of their desirability to society instead of from a reductionist and technocratic perspective. Nuclear power certainly delivers an abundance of low-carbon electricity at present, but its ability to sustain this over the next century is questionable if its global capacity is to expand sufficiently to make a meaningful impact on carbon emissions. Meanwhile, its ability to deliver electricity cheaply appears to be receding ever further, and it is difficult to see how imposing large amounts of inflexible baseload power will contribute to the diversified renewable energy sector the UK is trying to achieve. Coupled with the inherent risks arising from the complex and unforgiving nature of the technology, the better option would seem to be investing resources in alternatives. In the words of one commentator:

> *'While nuclear power is still a looming presence in our energy policy, it will continue to consume a grossly disproportionate share of the resources and political attention. How else can the dismal quality of the UK housing stock and the poor rate of exploitation of the UK's enviable renewable resources be explained?' S. Thomas, Energy Policy, 2010, vol.38, 4908.*

The industry in the UK has not shown that it has learnt from mistakes of the past, and seems poorly placed to compete in the privatised electricity market of today. The flexible, modular approach that wind power and other renewables offer means that technology and policy can be fine-tuned or redirected as the situation requires, without entrenching UK energy sector in a costly and potentially risky enterprise that would draw on resources for years to come and saddle future generations with intractable problems they did not ask for. Time is running out before CO_2 levels in the atmosphere reach a limit that will make it difficult to recover from, but this threat should not be tackled by exchanging one hazard for another.

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