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The role of nuclear electricity in a low-carbon world

NEIL HIRST

Headlines

- Nuclear power[a] will be essential for meeting the UK's greenhouse gas emissions reduction target, unless we can adapt to depend largely on variable wind and solar, or there is a breakthrough in the commercialisation of carbon capture and storage. The need may be greater if electricity becomes the preferred low-carbon solution for transport and heat.
- Investment in nuclear power is risky. Nuclear power stations take time to build and require heavy up-front investment, but should last for 60 years or more. In the US and Europe the cost of new builds has been high and construction performance troubled. As a result, it is difficult to attract private investment.
- We may regret building nuclear power stations if the cost of renewables continues to fall and we find solutions to the problem of the variability of these generation sources. On the other hand, if progress in reducing the costs of energy storage is insufficient, we may not be able to achieve climate targets without new nuclear generation capacity.
- Countries differ in their approach to nuclear power. The UK government's decision to procure a 3.2GW nuclear power station (Hinkley Point C) is a big risk. However, it also represents a crucial opportunity for the conventional nuclear industry, which is under significant financial stress, to rebuild itself. The successful completion of Hinkley Point C and reductions in the cost of subsequent nuclear power stations will be critical for the future of the industry in the UK.
- Small modular reactors (SMRs), currently being assessed by the UK government, could be largely factory built and less prone to construction delays. Smaller unit size should make them easier to finance and more flexible to deploy.
- Advanced reactor concepts, including advanced SMRs, are under development for the longer term. These aim to deliver low-carbon energy solutions, such as high grade heat for industrial processes, as well as improved economics and safety.

a This paper is concerned with nuclear *fission*, which is the only form of nuclear power that is likely to deliver substantial quantities of electricity in the next 30 to 50 years. Nuclear *fusion* is the subject of intense international research and may also have major potential to deliver electric power. But this is a prospect for the longer-term future.

Contents

Grantham Briefing Papers analyse climate change and environmental research linked to work at Imperial, setting it in the context of national and international policy and the future research agenda. This paper and other Grantham publications are available from **www.imperial.ac.uk/grantham/publications**

Summary

Nuclear power is the largest source of low-carbon electricity in the developed world and the second largest, after hydro, in the world as a whole.

In countries with limited hydro power, it is also one of the few options for low-carbon electricity that do not depend on local weather conditions. France, which largely relies on nuclear power for its electricity, has reduced the carbon intensity of its economy to less than half the average for developed nations.

Countries such as China, India, and Pakistan, where much of the growth in future energy demand will be concentrated, are continuing to invest in new nuclear power stations. However in the US and Europe nuclear costs are rising while the costs of wind and solar power have been declining sharply. Currently we cannot rely on variable renewables without the need for baseline generation such as nuclear. But energy systems are becoming more flexible. The increasing competitiveness of other low-carbon sources of electricity undoubtedly raises questions about the future of nuclear power, particularly in the West.

In addition to the pressure of competition, nuclear power has faced public concern, especially following the accidents at Chernobyl and Fukushima. The governments of Germany, Austria, and Italy have responded with policies that rule out new nuclear build. South Korea's new President was elected, in 2017, on a policy of phasing out nuclear power[1]. Even in France, which has led the way on nuclear power deployment, the new government is proposing a reduction in the share of nuclear power in favour of renewables.

The few new nuclear reactors that are under construction in the US and Europe have been plagued by cost and timetable overruns, and parts of the industry are in financial difficulty. Yet without new build, the retirement of existing nuclear stations threatens a significant step backwards for low-carbon energy. The phasing out of nuclear power in Germany is, at least for the time being, prolonging dependence on coal.

UK government policy supports a new programme of nuclear power and the recent agreement to guarantee the price of electricity from Hinkley Point C is a major first step. Much will depend on the successful construction of this station. There are four other proposals for nuclear power stations in the UK, discussed later in this brief. Unless costs can be significantly reduced these will prove more expensive than solar or wind energy.

There is growing interest in the concept of small modular reactors (SMR) in the UK and abroad. Their smaller unit size could allow power plants to be built unit by unit, reducing the cost of finance, and they will rely more on factory built components. The government is running a competition to identify designs that are most suitable for the UK and a wide range of concepts are being proposed.

A variety of radically new reactor designs, known as Generation IV, are under development. The aim is to improve safety and resistance to nuclear weapon proliferation, as well as to enhance economics and minimise the task of waste management. Commercial deployment is possible by 2030 but depends on political will and public acceptance.

The electric grids of the future will need to absorb increasing variable supply from renewables. Electricity storage, moderating demand at peak times and international energy trading are all expected to contribute to the flexibility of the system. Gas generation is well suited to provide flexible back-up, but is a carbon emitter. Nuclear power will mainly contribute baseload supply. But nuclear power stations will probably also have to operate with a degree of flexibility, and this will need to be reflected in future reactor designs.

In general, nuclear power is not well suited to adjusting output to meet changing demands, so-called load following. However it does not require the same degree of back-up as variable renewables. To be competitive in a low-carbon economy, nuclear power has to be cheaper than renewables, including the extra costs of providing the flexibility needed for a high proportion of renewables.

Government leadership will be essential. But if nuclear power is to fulfil its potential to provide reliable low-carbon electricity, the industry will need to demonstrate reliable construction, reduced costs, and greater flexibility of operation.

The climate challenge

According to the Intergovernmental Panel on Climate Change, emissions of CO_2, which are mainly derived from energy, must be reduced to near zero levels by 2100 if we are to meet agreed climate target[2]. The UK has set itself the target of an 80% reduction, from 1990 levels, by 2050. Since transport and industry are more difficult to decarbonise, this will require the virtual elimination of carbon emissions from electricity generation. And since low-carbon electricity is the most promising option for decarbonising transport and the heating of buildings, decarbonising the UK is also likely to require a large increase in electricity supply.

Renewables, especially wind and solar, are widely expected to play a big part in the decarbonisation process. There are a range of promising options being developed to maintain the reliability of supply with increasing shares of these variable renewables in the electricity mix. These include making demand more flexible and increased international links to access diverse sources of supply. Electricity storage, including the batteries of electric cars, may also contribute and there are encouraging signs that their costs are coming down. But, today, we cannot rely on renewables alone. Scenarios that show the UK's transition to a low-carbon energy system by 2050 feature new nuclear power stations as a prominent component in two different scenarios[3].

Nuclear reactors are generally designed to provide continuous base load power. But this also requires flexibility from other parts of the system to match demand. The case for including a substantial share of nuclear power in the generation mix will depend, to some extent, on the ability of future nuclear stations to operate flexibly.

Intermittent electricity generation is expected to add some additional costs to power systems[4]. The potential additional costs include:

- Short term reserve requirements
- Ensuring adequate capacity to meet demand
- Curtailment of renewables when in excess supply
- Transmission and network costs
- Impacts on the efficiency of thermal generation
- System inertia (a technical requirement to ensure the stability of the grid)
- Market impacts

The UK Energy Research Council's systematic review concluded that these costs remain relatively modest, at least where variable renewables contribute up to 30% of electricity supply, at an additional £5 or less per megawatt hour (MWh) of renewables generation. There is less evidence available at greater penetration levels, and the range of costs is much wider. For very higher penetration levels, such as 50%, studies suggest costs between an extra £15 and £45 per MWh.

More generally, the study concludes that "the additional costs of adding variable renewable generation to a system can vary quite dramatically depending on the characteristics of the remaining conventional plant, grid infrastructure, resource availability and location, and demand profile."

Besides hydro and nuclear, the other major source of continuous low-carbon electricity on the horizon is conventional fossil fuel generation with the underground storage of carbon dioxide emissions, known as carbon capture and storage (CCS). At present, it is mainly deployed in situations where the CO2 that is captured has a use in oil or gas recovery. A high price for carbon emissions, or other government incentives would be needed to make it more widely deployable. Currently available CCS technology captures about 85-95% of carbon emissions[5], so it is not yet a truly zero-carbon technology.

History and current role of nuclear power

The peak of investment in nuclear power in the West was in the mid-1980s. Around 30 gigawatt (GW) per annum of new nuclear capacity was commissioned in 1984 and 1985, mainly in Europe and the US[6]. Cheap gas as well as nuclear accidents at Three Mile Island in the US and Chernobyl in Ukraine, have since led to a drying up of new nuclear orders in the US and most of Europe.

However, France persevered with its nuclear mission and now gets 75% of its electricity from nuclear power. According to the Nuclear Energy Institute[7] there are 60 nuclear reactors under construction today, including 20 in China, seven in Russia, and five in India.

In 2016 nuclear power supplied 11% of world electricity, making it the second largest source of low-carbon electricity, after hydro[8]. Amongst the developed nations of the Organisation for Economic Co-operation and Development (OECD), nuclear power supplied 18% of electricity in 2016, making it the largest low-carbon source. Because France relied so much on nuclear power the CO_2 emissions intensity of its GDP was less than half the OECD average in 2014, and well below those of Germany or the UK which have relied more on renewables[9]. It is noteworthy that today the governments of both France and South Korea, countries that have been stalwarts of nuclear technology, have plans to moderate their dependence on nuclear power for the future.

What is the current status of nuclear power in the UK?

The UK has a long history of nuclear power, starting with the race to produce materials for nuclear weapons in the 1950s. The UK has also experienced nuclear safety issues at first hand. A fire at Windscale in 1957 is now considered to have been one of the most serious nuclear accidents to have taken place in the West, though the reactor concerned was not a power station[10]. The UK has acquired a legacy of nuclear buildings and materials that is expected to cost around £119 billion to manage over the next 120 years or so[11].

The UK developed two generations of its own gas cooled reactor designs, Magnox, and the Advanced Gas-cooled Reactor (AGR). The Magnox stations had all been retired by 2015. Seven AGR stations were commissioned between 1976 and 1989. The programme suffered severe cost and time overruns. However, these reactors have since become reliable operators, now at slightly below their original capacity, and they are the backbone of the UK's nuclear generation. They are all expected to be closed by about 2030 when further extension may no longer be viable.

The UK had gone out on a limb with this gas-cooled technology. Almost all of the rest of the world pursued pressurised water technology, ultimately derived from US nuclear submarine propulsion reactors. While gas cooled reactors have some clear safety and operational benefits, the initial performance of the AGRs was poor and the UK suffered the disadvantage of being outside the mainstream of nuclear technology. The UK eventually switched over and built one pressurised water reactor, Sizewell B, which came into operation in 1995. It was built on time and to cost. Sizewell B is expected to continue operating well beyond 2035, and possibly until 2055.

The last UK Government 2013 white paper on nuclear power supported "the successful delivery of the industry's planned 16GW domestic new build by 2030, representing at least 12 reactors over five sites"[12].

The Government's latest energy Reference Scenario, updated in February 2016, projects that electricity from nuclear power will rise from 56 terawatt hours (TWh) in 2017 (17% of the total) to 121TWh in 2035 (35% of the total)[13]. Sixteen gigawatts of capacity, operating at 90% load factor would deliver 126TWh per annum, more than equivalent to the white paper ambition.

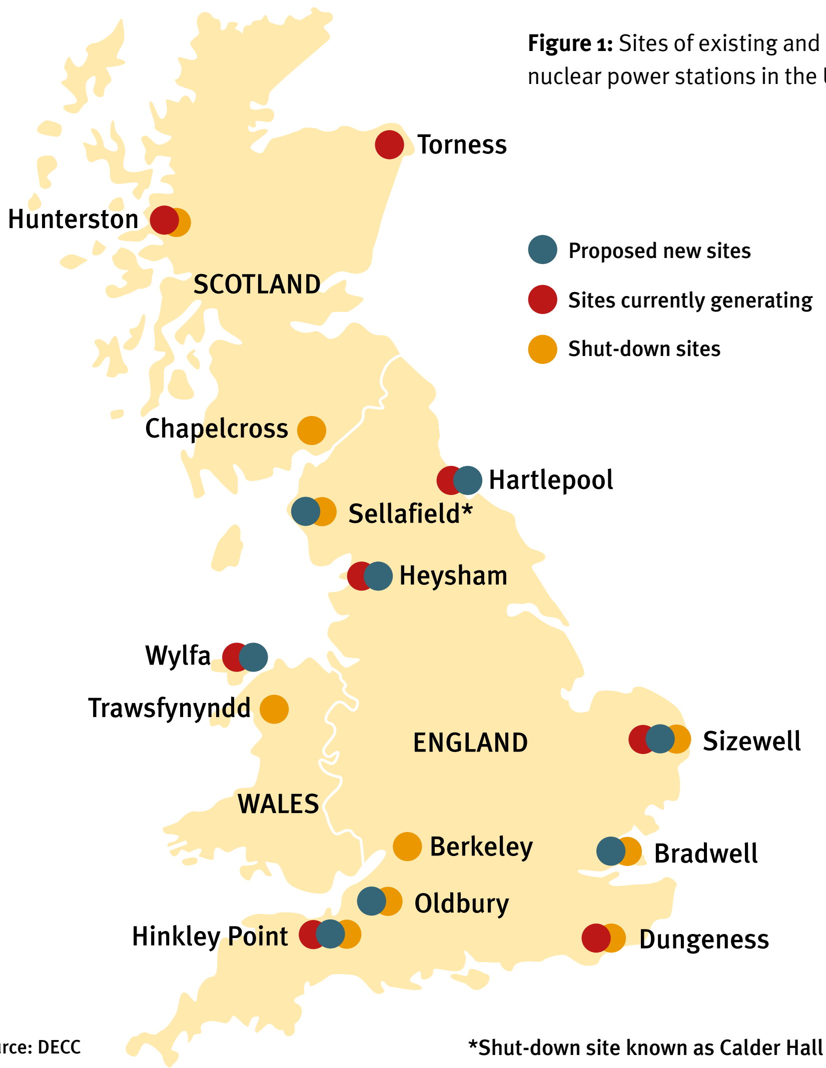
The sites of the UK's existing and proposed nuclear power stations are shown in the Figure 1 below[b].

Hinkley Point C and Sizewell

In 2016, the UK government reached agreement with French energy supplier EDF for the construction of a new nuclear power station, at Hinkley Point, in Somerset. Hinkley Point C is expected to come into operation in 2025 with a capacity of 3.2GW. It could supply about 7% of the UK's current demand on a winter afternoon. The project is owned two thirds by EDF and one third by CGN, the state-backed Chinese energy company.

There are three projects of the same reactor type (EPR) under construction today. One in Finland, one in France and one in China. The Finish and French projects have encountered long delays and big cost over-runs. The Finish plant, at Olkiluoto started construction in 2005 with a projected cost of €3.2bn and

Figure 1: Sites of existing and proposed nuclear power stations in the UK



Source: DECC

*Shut-down site known as Calder Hall

b Not including the Dounreay Prototype Fast Reactor (PFR) which did generate significant electric power although it was predominantly a research reactor.

an operating target of 2009. Now it is expected to cost €8.5bn and to start operating in 2018[14]. The French plant, Flamanville 3, began construction in 2007 with a projected cost of €3.3bn and an estimated operating date of 2013. Now it is expected to cost €10.5bn and begin operating in 2019. Flamanville has suffered particular problems with the quality of the steel in parts of its pressure vessel[15].

The two EPR units under construction at the Taishan nuclear power plant in China's Guangdong province are now scheduled to enter commercial operation in 2018 and 2019, respectively. This is approximately a year later than originally scheduled[16].

Two other nuclear projects are directly connected to the Hinkley Point Agreement[17]. EDF and CGN have reached provisional agreement on jointly developing two more nuclear power stations. One of these, at Sizewell in Suffolk, will be another EPR.

Bradwell

The other proposal agreed between EDF and CGN is for CGN to lead the development of a nuclear power station at Bradwell, in Essex, based on its own Hualong (HPR-1000) reactor design.

The HPR-1000 is a Chinese development of Western reactor designs that have been built in China in recent years. Construction of the first HPR-1000, Fuqing 5, began in May 2015, and the reactor is due to be completed in 2019.

Moorside

In addition to EPR and Hualong, two other reactor designs are currently under consideration for construction in the UK. The first of these is Toshiba Westinghouse's proposal to build an AP1000 reactor at Moorside, near Sellafield in Cumbria. Four Westinghouse AP1000s were ordered in the US and four in China. The US projects have suffered serious overruns, mainly due to difficulties in gaining approvals for factory built components and new regulatory requirements. Two of the four have been cancelled. However the Chinese AP1000s, after some construction delays, are now, at the time of writing, close to commissioning. Toshiba's US nuclear subsidiary, Westinghouse Electric, has filed for bankruptcy and there are now serious doubts over Toshiba's own future and its ability to pursue the Moorside project.

Wylfa and Oldbury[18]

Hitachi-GE are proposing to build two advanced boiling water reactors (ABWR) at Wylfa, on the Isle of Anglesey in North Wales. On a longer timetable they also aim to build two further ABWRs at Oldbury, in the West Midlands, drawing on their experience at Wylfa. ABWRs have been constructed successfully in Japan to time and budget. Japanese regulators shut them down, with the rest of the Japanese nuclear fleet, following the Fukushima disaster. Most, and possibly all, of them are expected to restart following safety reviews.

Cost

Cost is probably the most controversial aspect of nuclear power in the UK today. To get Hinkley Point C agreed the government has guaranteed an index linked price for its power, of £92.50 (2012 prices) per MWh over 35 years. This is more than twice the current wholesale price of electricity in the UK. It is also significantly above the prices of £74.75 for 2021/22 projects and £57.50 for 2022/23 projects for offshore wind in the Government's September 2017 auction. If the Sizewell EPR goes ahead the contract price of Hinkley Point C is reduced to £89.50 per MWh.

There is no simple comparison with the cost of offshore wind. Hinkley Point C will provide reliable power, whereas offshore wind power is intermittent. The Hinkley Point C price guarantee runs for 35 years whereas the offshore wind guarantee is only 15 years. On the other hand, Hinkley Point C will probably have at least 30 years of life after the price guarantee has ended, whereas the post-subsidy life of wind farms is expected to be much shorter.

However, the Hinkley Point C price is not necessarily a good guide to the true cost of a new nuclear programme, such as the government proposes, in the UK. The Hinkley Point EPR is the first of its kind in the UK, and no station to this design has yet been commissioned anywhere in the world. Furthermore, the UK has had no experience of new nuclear construction since Sizewell B was commissioned in 1995.

Even with this degree of government support, there is no certainty that Hinkley Point will be completed without further help. EDF, who are bearing two thirds of the cost, are experiencing considerable financial stress, and suffered the resignation of their finance director over the project[19]. If the project suffers serious delays, as other EPR project have done, completion may depend on the willingness of the French government to provide additional support.

On the other hand, if Hinkley Point is completed within time and budget, it will be highly profitable[20] and this could open the door for repeat orders of the EPR at somewhat lower cost, due to the experience gained.

Looking at the international scene, the International Energy Agency (IEA) and the Nuclear Energy Agency have published figures, in 2015, indicating that for South Korea and China, both of which have had sustained nuclear programmes, nuclear power is the cheapest option for new capacity coming on stream in 2020[21]. On the other hand the US Energy Information Administration, has released estimates in 2017 which show that for new capacity coming on stream in the US in 2022, nuclear power is more expensive than onshore wind, solar, or gas combined cycle with CCS, but less expensive than offshore wind or coal with 90% CCS[22].

The history of nuclear power costs has been chequered. There have been periods of sharply rising costs in the US and France, especially when safety regulations have been enhanced following the Chernobyl and Fukushima accidents. However, a comprehensive study of historic nuclear costs has shown that there have also been periods of cost decline and that South Korea, which has maintained its nuclear programme consistently, has experienced modestly declining costs[23].

Finance

The method used by the UK government to enable Hinkley Point C to be financed has excited controversy.

As described above, the government guaranteed the plant £92.50 per MWh (in 2012 prices), for 35 years. This approach should protect tax payers and electricity consumers from construction setbacks. Consumers pay nothing until and unless the plant is successfully completed and the price that they then pay is limited[c]. Bearing in mind the problems that have been experienced with the construction of other EPR power stations, there is merit in this approach. But it has been questioned, notably by the UK's National Audit Office (NAO)[24], for two reasons:

Firstly, this is an expensive way of financing what is in essence a long-term public project. BEIS estimated the investors' return, if the project is successful, at about 9% p.a. The NAO estimated that if the project was funded at the government's cost of borrowing, around 2%, and if construction was successful, then the price of electricity during the 35 year period could be as low as £27.50 per MWh, or even negative, because power generated after the price guarantee period might more than pay for the project. That is an extreme case, and of course renewable power would also be a lot cheaper if funded at government rates. But it illustrates the high cost of placing all construction risk in the private sector.

Secondly, the Audit Office is not convinced that the government has succeeded in insulating the public from construction risk. They point out that, in practice, if the project got into difficulty, the government could still be faced with the choice of re-negotiating the contract or finding alternative energy options.

It seems likely that the method of government support will be a live issue as the government takes its next steps in nuclear power procurement. There is a case for the government accepting some equity share, especially if confidence in construction prospects improves with experience. However the government also has to consider the implications for public debt, and other competing claims for public funds.

Baseload or flexible operation?

Nuclear power plants have high up-front construction costs but then operate for as long as 60 years with low fuel costs. Typically, the initial investment contributes 60 to 70% of the generating costs of a nuclear plant, whereas it is often less than a quarter of the costs of a coal or gas plant[25]. This means that consistent operation at close to design output is crucial to the economics of nuclear power. Modern pressurised water reactor (PWR) and boiling water reactors (BWR), such as those proposed for the UK, are designed to have load following capability, meaning they can respond to fluctuating demands for electricity. But this entails higher maintenance costs and some loss of fuel performance.

In a power system such as that of the UK today, where nuclear power provides 20% of generation and most of the balance is provided by fossil fuels, it makes sense for nuclear power to operate on baseload. In France, where nuclear power is dominant, some of the nuclear power stations operate in a much more flexible way.

In the UK Government's reference projection to 2050, renewables account for 42% of UK generation and nuclear power 34%[26]. In that case it is reasonable to assume that both renewables and nuclear power would need to provide a degree of flexibility but probably at least some nuclear power stations would operate on base load for most of the year. Other technologies, such as storage, will also contribute flexibility.

Nuclear power and nuclear weapons

As explained above, the early history of nuclear power in the UK is closely linked with the national drive to obtain plutonium for nuclear weapons during the cold war.

Today non-proliferation safeguards have a major influence on the industry. All civil nuclear power stations are subject to international inspection under the UK's safeguards agreement with the International Atomic Energy Agency and Euratom to prevent diversion of civil nuclear materials. The government has said that the UK will leave Euratom after Brexit and that alternative arrangements will be made to cover Euratom's safeguards functions.

Under its safeguards agreement, the UK retains the right to withdraw materials from safeguards for national security reasons. However, according to the Office of Nuclear Regulation, "such withdrawals from safeguards now involve only small quantities of material for use in instrument calibration or radiological detectors, or as analytical tracers or radiological shielding. Details of withdrawals... are available[27].

c The government provisionally agreed to guarantee up to £2b of bonds, subject to conditions. However the developers have said that they do not expect to use this facility.

Bearing in mind the large stocks of plutonium and other nuclear materials that the UK already holds at Sellafield, those concerned about possible links between new nuclear power stations and the nuclear deterrent have focussed on the possibility that a new programme of nuclear power stations may enhance UK engineering capabilities that are also relevant to the nuclear reactors that power Trident submarines[28].

Waste management

After cost, it is probably the management of high-level nuclear waste that has raised the greatest public concern. Since there are no plans to reprocess the fuel from future UK nuclear reactors, this is largely a question of the management of the spent fuel.

EDF's plan for Hinkley Point C is to transfer spent nuclear fuel, first to a pool for preliminary cooling and then to a longer-term storage pool, the interim spent fuel store (ISFS). Both these facilities will be on-site[29].

This is consistent with the Government's plan that used fuel should be stored on-site until long-term arrangements for a geological disposal facility (GDF) are in place[30]. The ISFS is designed to accept all the spent fuel for the life of the reactor, and the planning assumption is that removal from the ISFS will not begin until 2138. At that point it will be encapsulated on site and removed to the GDF.

Successive UK governments have been looking for geological sites to dispose of nuclear waste for many decades, but all efforts have foundered against local or regional resistance. The latest plan, set out in July 2014, is based on a voluntary approach, in the belief that the GDF will confer significant economic benefits on a locality that accepts it[31]. A new consultation on siting is due to be launched by the Government by the end of 2017, after which communities will be invited to express interest in volunteering.

No country yet has a permanent geological high level nuclear waste depository in operation. Finland has the most advanced repository, which is expected to start loading used fuel in the next few years. The US has been trying to win approval to use its site at Yucca mountain in Nevada, since the 1980s. Sweden and France have identified sites and are working towards their depositories.

While progress towards creating geological depositories for nuclear waste has been slow, many countries, including the UK, have allowed new nuclear construction to continue on the basis that used fuel can be safely stored on site under water for many decades into the future, as at Hinkley Point C.

The government's plan is that the intermediate level waste and spent fuel from Hinkley Point C will eventually be transferred to the government for disposal in the GDF[32]. The government has published a methodology for determining the price of this disposal service.

The price that the government has guaranteed for Hinkley Point C power has been calculated to take account of decommissioning and clean-up costs. EDF have made a funding arrangements plan for how they will meet these costs which is in the form of a contract with the independent company that will hold the money. This plan has been approved as prudent by the Nuclear Liabilities Financing Assurance Board.

Safety and Radiation

Nuclear power is very safe compared to fossil fuels which, according to the IEA, played a major part in the 6.5 million premature deaths attributable to air pollution in 2012 (both household and outdoor)[33].

A 2007 article in the Lancet[34] estimated fatalities from accidents and pollution in Europe at 24.8 per TWh of electricity generated for coal, 2.8 per TWh for gas, but only 0.074 for nuclear. This takes no account of the consequences of climate change. Renewables such as solar and wind also have very low fatality rates.

The Chernobyl nuclear accident of 1986 was, by far, the worst ever nuclear power disaster. According to a study published in 2005 by the eight relevant UN agencies with the governments of Russia, Belarus and Ukraine[35] up to 4,000 people could eventually die of radiation exposure. At the time of the report fewer than 50 deaths had been directly attributed to radiation from the disaster, almost all being highly exposed rescue workers, many of whom died within months of the accident, but others died as late as 2004. The relocation of some 350,000 people proved a "deeply traumatic experience".

Accidents at Windscale in 1957, and Kyshtym, Russia, in the same year also had serious consequences and caused some fatalities, but not on a comparable scale. A 1982 report carried out for the National Radiological Protection Board[36] estimated that the Windscale accident would eventually result in 32 deaths, although this has since been challenged as being significantly too low[37]. There are no reliable estimates of the consequences of Kyshtym because of the secrecy surrounding the incident.

The next most serious accident was Fukushima. According to the official UN Report[38] there was severe core damage and the release over a prolonged period of very large amounts of radioactive material to into the environment. Doses to the general public were estimated at low to very low. No discernible increased incidence of radiation induced health effects was expected. However the evacuation of 78,000 people from the area is reported to have caused more than 1,000 deaths and serious impact on mental and social well-being[39].

The most serious accident that has happened to a US nuclear power station was at Three Mile Island in 1979. There was a partial meltdown of the reactor core but, unlike the Chernobyl and Fukushima accidents, the containment building remained intact and held almost all the radioactive material. The consequences to the health of local residents were negligible[40].

The four reactor designs under consideration for construction in the UK today, the French EPR, the US/Japanese AP1000, the US/Japanese ABWR, and Chinese HPR-1000 are all large, one gigawatt plus, water cooled reactors. They are all Generation III or Generation III + designs, incorporating advanced safety features in the light of the Chernobyl disaster[41].

What new technologies are becoming available and when?

Figure 2 shows the timeline for the development of different generations of nuclear reactor design.

Generation III + nuclear power plants are described as "evolutionary designs offering improved economic and safety features". However intensive research and development work is taking place around the world, especially in the US, China, India, France, and Russia towards the deployment of Generation IV[41]. The broad aims of Generation IV are:

- Improved economics
- Enhanced safety, including passive safety features
- Minimal waste
- Proliferation resistance

There are nearly 100 different Generation IV concepts. Six of these have been identified by the Generation IV International Forum as being of the greatest interest;

- Gas- cooled fast reactor (GFR)
- Lead-cooled fast reactor (LFR)
- Molten salt reactor (MSR)
- Sodium-cooled fast reactor (SFR)
- Supercritical-water-cooled reactor (SCWR)
- Very-high-temperature reactor (VHTR)

Many of these designs offer a greater degree of passive safety, such as those that do not use pressurised coolants and do not require the types of emergency containment systems that pressurised water reactors do. They may also be cheaper and quicker to build and, in the case of fast reactors, offer the opportunity to recycle and reuse spent nuclear fuel that might otherwise be disposed of[42].

The SFR and the VHTR concepts are the most advanced and are receiving the most attention. The UK made major investments in large scale SFR and high temperature reactor prototypes during the 1970s and 80s, but these have since been decommissioned. China, France, Japan, Russia and India all have significant programmes.

The main advantage of the SFR over the PWR or BWR is that the coolant, sodium, has a much higher heat transfer capability and boiling point than water, making the reactor both more efficient and safer. However sodium can boil at very high temperatures and it reacts violently with water and air, so it requires careful management.

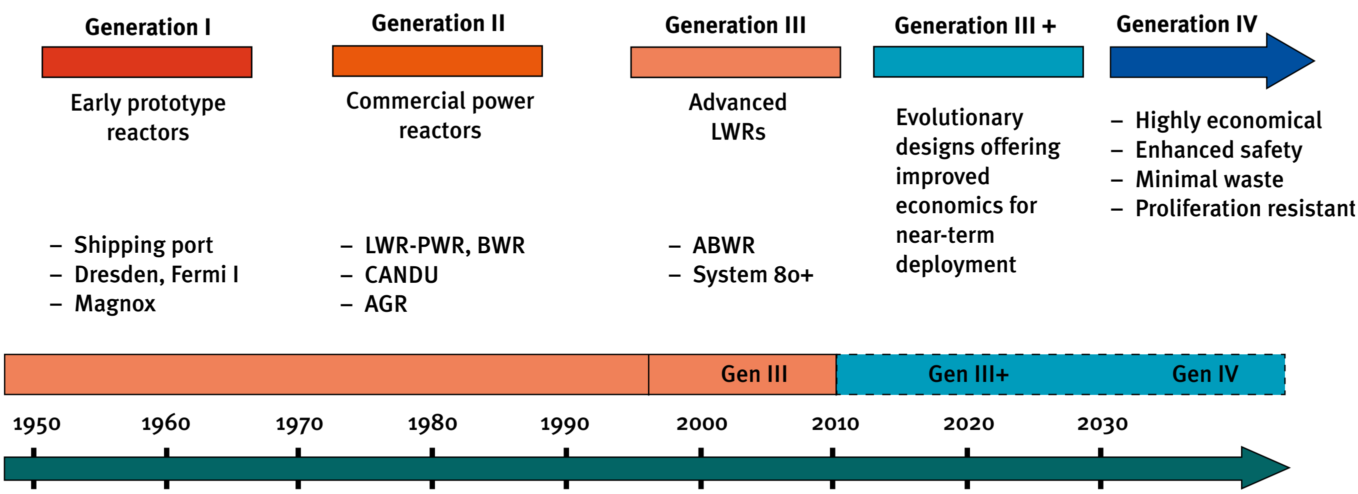


Figure 2: A technology roadmap for Generation IV nuclear energy systems (adapted from [42])

The main advantage of the VHTR is its safety. The large graphite core gives the reactor exceptional heat capacity, leading to very slow transients. There is also a strong negative temperature coefficient of reactivity – in other words if the reactor heats up this causes the nuclear reaction to slow. In addition, the triple isotope coated fuel (TRISO), a product of UK-based research during the 1970s (in the Winfrith Dragon reactor), can retain all fission products up to a very high temperature. The VHTR is also well adapted to provide heat for heavy industrial processes and to produce hydrogen in addition to power generation, which is usually the main purpose of civil nuclear reactors.

The validation of the design and performance of the SFR and VHTR concepts is at an advanced stage. The next stage, which could start during the 2020s, will be the licensing, construction and operation of full scale demonstration reactors.

This phase is expected to last for at least ten years and to cost several billion dollars.

The Problems of Scale, and the Proposals for Smaller Reactors.

The sheer size of the full-scale Generation III reactors being built today presents a problem. The expected cost of Hinkley Point C, £15-20bn, is a very large bet to place on a single project, especially where there have been construction problems with the design elsewhere. A huge amount of capital has to be tied up during an extended construction period.

For this reason, interest has been growing in the idea of smaller and medium sized reactors, known as SMRs. This includes smaller versions of conventional PWR and BWR designs as well as Generation IV technologies. They should not represent such daunting unit risk and the intention is that they can be largely, or wholly, factory made and easier to assemble on site. Smaller units could be built in succession with first payback coming earlier. The smaller unit size may also open up possibilities for deployment in locations where there is a use for heat as well as electric power, for instance in industrial processes.

A study prepared for the UK government in 2014[43] concluded that there was a potential global market for 65-85GW of SMRs, valued at £250-400bn. A thriving SMR sector with substantial UK content could therefore make an important contribution to the government's industrial strategy.

In March 2016 the UK Government launched the first phase of a competition to identify the best value SMR for the UK. The exercise has attracted more than 30 UK and international participants. About half of them are proposing relatively conventional PWRs or BWRs, while the rest include a variety of Generation IV technologies. In scale, the proposals range from a 400Mw PWR proposed by a group headed by Rolls Royce, to a ten megawatt high temperature reactor proposal being led by URENCO, the European uranium enrichment consortium. Some of the more conventional proposals could be deployed in the next ten to 20 years, but some other concepts are at less advanced stages of design. It is not clear how much government financial support, if any, the various options would require for commercialisation.

The government will have to decide soon which of these reactor concepts merits submission to the Office of Nuclear Regulation (ONR) for generic design assessment (GDA). GDA is a non-site specific procedure that can pave the way for licensing in the UK. It also carries a considerable international cachet. However the ONR is already heavily engaged in assessing the full-scale reactor designs under consideration for the UK, so the capacity for studying SMRs will be constrained.

Conclusion

Nuclear power is one of the largest sources of low-carbon electricity today. It has the potential to play a growing role in the future and its contribution may be indispensable if we are to meet climate change targets. Public concerns about safety and waste management have led some governments to rule it out. Investment in nuclear power continues in Asia. But in the US and Europe nuclear power has found it difficult to compete with cheap gas and with increasingly competitive renewables. The few reactors now under construction have suffered from major cost and time overruns and the industry has been damaged.

The UK government's decision to support a 3.2GW EPR is a big risk but it also represents a major opportunity for the industry to rehabilitate itself. The industry needs to complete this project successfully and then to drive down the cost of subsequent stations in the following programme of orders. Otherwise the future of large scale nuclear power in the UK, and perhaps elsewhere in the West, is in doubt.

Smaller scale nuclear reactors, or SMRs, are at an earlier stage of development. It is well worth exploring the benefits they could confer in terms of modular construction and more manageable units to finance. A successful SMR industry could contribute to the UK government's strategy for industrial revival.

Advanced reactor concepts could offer a greater degree of passive safety and may be cheaper and quicker to build. They will aim to provide opportunities, after an essential phase of nuclear new build, to deliver long-term low-carbon energy solutions, such as heat for industrial processes.

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