September 2010 Energy Research Partnership Technology Report

# Nuclear Fission

# The Energy Research Partnership

The Energy Research Partnership is a high-level forum bringing together key stakeholders and funders of energy research, development, demonstration and deployment in Government, industry and academia, plus other interested bodies, to identify and work together towards shared goals.

The Partnership has been designed to give strategic direction to UK energy innovation, seeking to influence the development of new technologies and enabling timely, focussed investments to be made. It does this by (i) influencing members in their respective individual roles and capacities and (II) communicating views more widely to other stakeholders and decision makers as appropriate. ERP's remit covers the whole energy system, including supply (nuclear, fossil fuels, renewables), infrastructure, and the demand side (built environment, energy efficiency, transport).

ERP is co-chaired by Professor David Mackay, Chief Scientific Advisor at the Department of Energy and Climate Change and Nick Winser, Executive Director at National Grid. A small in-house team provides independent and rigorous analysis to underpin ERP's work.

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**Cover image**: Sizewell A & B nuclear power station, with the twin Magnox reactors (now closed) on the left and the Pressurized Water reactor on the right.

## Contents



## The Energy Research Partnership Technology Reports

The ERP Technology Reports provide insights into the development of key low-carbon technologies. Using the expertise of the ERP membership and from wider stakeholder engagement, each report identifies the innovation challenges that face a particular technology, the state-of-the-art in addressing these challenges and the current activity in the area. The work identifies critical gaps that will prevent key low-carbon technologies from reaching their full potential and makes recommendations for investors and Government to address these gaps.


This report has been prepared by the ERP Analysis Team, led by Richard Heap, with input from ERP steering group members and their organisations. Chaired by Dame Sue Ion FREng, the members of the Steering Group were: Mike Farley (Doosan Power Systems), Charles Carey (Scottish and Southern Energy), Mike Colechin (E.ON), Stephen Elsby (EPSRC), Steven Walsgrove (DECC). The views are not the official point of view of any organisation or individual and do not constitute government policy.



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# Summary

Over the next decade and a half, all but one of the UK's reactors will be closed down and decommissioned. Current plans will see a new build programme to replace this capacity using Generation III reactors, which are a progression from existing designs of Light Water Reactors. This is expected to deliver up to 16 GW of capacity by 2025. Beyond that the UK has not set out any plans for how nuclear power will be deployed.

Most scenarios of the UK energy system out to 2050 include nuclear power as a component of the energy mix. A review of a range of scenarios for a secure, reliable and low carbon energy system in 2050 suggest between 12 and 38 GW of installed capacity will be required. With the first new reactor being operational no earlier than 2018, this could require 1 new power station per year being brought on line up to 2050. This demand could be met using Generation III technology, but with similar growth forecast globally, the market they operate in will change over their 60 year life span with increasing demand for uranium and a need to address concerns over proliferation and security. A new generation of nuclear technology (Generation IV) is likely to be deployed post 2040, but it requires a significant global RD&D programme to deliver it.

Nuclear technology is one of the few technologies where the power plant and supporting assets invested in today and over the coming two decades will persist in a post 2050 era and through to 2100. They will outlive many of the companies involved in their initial investment. Their role therefore needs to be mapped within the context of a long-term energy plan to enable provision of the necessary RD&D.

## Global context

Nuclear power generation is expected to expand significantly over the next few decades. Two main factors will affect the global market and the development of nuclear power. The first is the increasing global demand for uranium, which could restrict its availability and increase its price. The second is the need to address proliferation issues regarding the fuel cycle and the risk of fissile material being diverted for weapons. Both of these issues may be partly addressed through developments in the fuel cycle, from the type of fuel used to the management and treatment of the spent fuel, with material being recovered and recycled to produce new fuel. These technologies and processes will be complemented by new reactor designs allowing more efficient fuel cycles to be developed. However, reducing the risk of proliferation will require an international framework to be in place to support these technologies.

New reactor designs are also expected to see nuclear power stations providing outputs additional to electricity, such as co-production of hydrogen or high-grade process heat. These could be smaller reactors that could be deployed to meet a variety of demands, for example near an industrial centre.

A number of international RD&D programmes are underway to develop advanced reactor systems and fuel cycles, including the Generation IV International Forum (GIF) and the European advanced reactor programme. These are expected to build prototype Generation IV fast reactors post 2020 with commercial deployment after 2040. International collaboration provides low cost access to the technology, where the high costs and long lead times would make these projects prohibitive for individual states.

## UK context and RD&D requirements

UK nuclear RD&D and supply chain have been in decline since the completion of the Pressurised Water Reactor (PWR) at Sizewell B. The focus shifted to maintaining the existing fleet, improving waste management processes and decommissioning. The advanced reactor design research programme was shelved and the substantial research infrastructure which underpinned it dismantled and disbanded. The break-up of BNFL as part of the restructuring of the nuclear industry from 2005 resulted in the ramp down of RD&D in the UK, which included future reactor systems (Generation IV) and associated fuel cycle activities.

The current plans are to build a number of new reactors to replace the existing capacity and this is driving some supporting RD&D and supply chain development. But beyond this there is no clear plan as to how nuclear power is expected to develop. Several scenarios indicate that additional nuclear capacity may be required by 2050, and indeed further capacity may be required beyond then, with some of the later reactors, post 2040, potentially being Generation IV reactors. However, the strategy for providing the fuel, managing the waste and running 10 reactors, is very different from a system with 30 reactors, many of which could still be operating post 2100. Over this time uranium is expected to become more expensive as competition increases, which combined with increasing amounts of radioactive waste is leading to the development across the globe of advanced systems and fuel cycles to recycle the spent fuel. In this respect the UK has two options; it can either be involved and influence the global development of the technology, or buy it in from other countries at a later date as required. Both of these options have RD&D implications, not least to ensure that the UK retains sufficient expertise to keep these options open.

It is important to note that nuclear technology is one of the few technologies where the assets invested in today and over the coming two decades will persist in a post 2050 era through to 2100. In addition, new technologies that are likely to be important for the industry in the future have long lead times and are high cost. Decisions on nuclear fission technology can therefore not be left solely to the market and diverse individual company interests.

A long term strategy is needed for the development of nuclear power in the UK. It needs to include a review of the possible global futures, including the availability and price of fuel, the security and proliferation risks and the potential for the UK to benefit from the global market. This is a matter of urgency and needs to happen by 2012 if the UK is to be able to maintain its world renowned expertise.

In the absence of a clear plan to help inform long-term RD&D planning, there are a number of RD&D activities that need to take place:

- **Support for existing reactors**
  Supporting RD&D is aimed primarily at ensuring plant safety and potential life extension, where possible. Alongside this RD&D continues into management processes for waste produced by the current and earlier reactors and decommissioning.

- **RD&D for current new build**
  Over the next 15 years the UK is aiming to replace its existing nuclear power generating capacity, with the first supplying power by 2018. These are expected to be Generation III reactors, which are a more advanced version of Generation II Light Water Reactors. The first of these are being built in Finland and France, followed by the USA, China, India, the UAE and Korea. RD&D to support their deployment in the UK is mainly industry led, but there are opportunities for UK experience and expertise to improve the component fabrication and joining, manage safety case development and mitigate materials degradation within the international collaborations.

  Some of the key risks to the new build programme, particularly in the supply chain, have been identified including the limited availability globally of ultra-large component manufacturing capacity and plant assembly. The establishment of the Advanced Manufacturing Research Centre has sought to address some of these issues and develop the UK supply chain. The proposed loan to Sheffield Forgemasters would also have provided a significant opportunity to develop the UK supply chain and address the global shortage of manufacturing capacity.

  Delivering the necessary skills and capability to support a new build programme will require a coordinated effort between industry and the research bodies. Analysis indicates that with a concerted effort it will be possible to deliver 12 reactors by 2025. However, particular focus will be needed on a few key capabilities. It is proposed that a single organisation is tasked with coordinating the various bodies involved. Efforts would be further enhanced by an active RD&D programme to attract and train skilled personnel for the development and long-term operation of the plant. Any delays in the programme may reduce confidence by the developers and have a detrimental effect on skills, particularly with growing international competition. A review is also needed to assess the demand for a skilled workforce across the various generating technologies, particularly where the sectors may be competing for similar or transferable skills, such as project management, electrical engineers and construction.

  There is a strong business case for a healthy and vibrant research base in the UK that would support the national nuclear programme and provide the necessary skills, but would also provide benefit from exploiting the growing global market.

- **Beyond capacity replacement**
  Without any long term guidance, further expansion of nuclear capacity in the UK is likely to use Generation III reactors. If the generating capacity increases consideration will be needed of how the supply integrates into the energy system and how issues of flexible supply are addressed.

  More advanced reactor designs are likely to become available post 2020, with fast breeder reactors expected after 2040. Even though there is no clear indication if they will be deployed in the UK, we would do well to prepare the way and keep options open. Furthermore, some of the RD&D for advanced reactors and Generation IV will provide benefits to Generation III development.

  However, the UK is not actively involved in these international programmes, which impairs its ability to develop its capabilities and capitalise on its expertise. This lack of commitment and meaningful role in the development of the technology also makes it difficult for the UK to aspire to any sort of leadership in non-proliferation activities.

## International engagement

Although the UK is not a reactor vendor it has internationally recognised expertise and capabilities, particularly from earlier advanced reactor and fuel cycle RD&D programmes. For example, the National Nuclear Laboratory has developed world class expertise and experimental capabilities relating to reprocessing and recycling technologies, uniquely combining RD&D on advanced processes with experience from supporting current and past UK industrial operations. Over the last decade, UK innovations have been taken up within international advance fuel cycle programmes (e.g. US, India, China, France and Europe). Engagement in international programmes would provide opportunities to further develop the UK's expertise and supply chain. However, the current UK skill base is supported almost entirely through participation in the European Framework 7 programme, which ends between 2012 and 2014. The strength of this position is at risk of being lost without long-term plans and commitments to international programmes. Furthermore, this will become harder to recover as those involved in the programmes retire. Without any long-term strategy the UK will by default stop activities associated with the recycling of spent fuel in the next few years and its world class current capability in this area will decline over the next decade. This would make it difficult for the UK to develop fuel cycle technology associated with Generation III and IV reactors, should it wish to deploy these systems in the future and close off the possibility of selling these services to the expanding global market.

If the UK is to retain these skills to be in a position to provide expert and informed input to future UK nuclear policy options, exploit opportunities within future European programmes and maintain influence internationally, there is a time window of about 3 years to develop an appropriate national level programme.

Another key driver for RD&D in nuclear technology is to support the UK's declared intention of being at the forefront of international efforts to prevent nuclear proliferation. With the announcement to establish a National Nuclear Centre of Excellence, this will include coordinating its expertise to contribute to the development of a low carbon, proliferation resistant fuel cycle. The experience and expertise developed from the advanced reactor and fuel cycle programmes could also be applied to this. But for the UK to attain any form of global standing in this area will require being involved in international RD&D programmes, particularly for Generation IV and advanced fuel cycle systems. Such programmes include the European Generation IV programme in the SET plan and the international Generation IV Forum (GIF).

## Recommendations

A long-term strategy is needed for the development of nuclear power in the UK, combined with a detailed roadmap for the development of nuclear RD&D. This is a priority to inform decisions about RD&D, the development of which will be determined by how the UK chooses to address a number of key issues. These include:

1. The long term role of nuclear generation in the UK and the potential need to develop new fuel cycle and reprocessing technologies.
2. Capitalising on the growing international deployment of nuclear fission: Selling fuel cycle technologies and services into the international market, developing an industrial base and contributing to the development of key technologies.
3. Defining the UK's role in non-proliferation debates which will require supporting RD&D to inform positions and support international developments.

Given the long lead times and development plans for these technologies, the roadmap should go out to 2050 and beyond. This is a matter of urgency and needs to happen by 2012. Without a clear plan to guide investment the UK is at risk of losing its world renowned expertise.

There is a strong business case for a healthy and vibrant research base in the UK that would support the national nuclear programme and provide the necessary skills, but would also provide benefit from exploiting the growing global market. To support the development of this research base the UK needs to be involved in international RD&D programmes, particularly for Generation IV and advanced fuel cycle systems. Such programmes include the European Generation IV programme in the SET plan and the international Generation IV Forum (GIF). Involvement in these programmes provides low cost access to technologies that will complement existing skills and expertise and will provide credibility to the UKs international ambitions.

Some of the new Generation IV reactor designs include small, high temperature reactors that could cogenerate heat for industrial processes as well as electricity. These reactors are expected to be available before 2030 and could be used to displace fossil fuel based energy production. A review should be carried out to assess the potential of this technology to reduce emissions in the UK. This will help inform the RD&D roadmap.

The UK should also develop an industrial strategy for the development of nuclear power in the UK. Developing a strong research base and defining a long term nuclear strategy will encourage inward investment. This should go beyond developing the supply chain to considering attracting the major technology companies. Such a strategy will also inform the RD&D roadmap.

An important part of the strategy and roadmap is engaging the public to help inform decisions about how the technology should develop. This should be considered in the wider context of addressing the UK's energy and climate change challenges.

The development of the roadmap should be 'owned' by DECC and involve a broad range of bodies, including industry, supply chain companies, utilities, developers, academic and research bodies, and government departments. The work could have been led by the National Nuclear Centre of Excellence (NNCE), which is currently operating in shadow mode, in association with the National Nuclear Laboratory, given their strategic position. However, the future of this entity in its current form is in doubt, although the NNL together with the University of Manchester and Imperial College have expressed willingness to continue the work on priority topics, with funding sought from those departments directly interested on a topic by topic basis. NNL could therefore take the lead, with DECC taking overall 'ownership'.

ERP could support this work to ensure that nuclear energy RD&D needs are set within the context of an overarching understanding of the UK's evolving energy landscape. It is recommended that in addition to the development of a long-term strategy the following issues need to be considered:

- The demand for a skilled workforce across the various generating technologies, particularly where the sectors may be competing for similar or transferable skills, such as project management, electrical engineers and construction.
- How the proposed generating capacity integrates into the energy system, particular the provision of a flexible supply.
- The socio-economic and environmental impacts of the technology and how the public will interact with it.

# 1 Introduction

The aim of this report is to set out the landscape for RD&D into nuclear fission in the light of several recent reports covering specific areas, including skills[1], RD&D capabilities, capacity[2] and supply chain[3]. It aims to produce a comprehensive analysis that identifies the technology options for nuclear fission and the innovation needs and timeframes across the spectrum of RD&D.

The report provides a review of roadmaps and scenarios for nuclear energy in the UK, Europe and globally out to 2050, setting out how it might develop and the scale of capacity that could be installed. This includes identifying novel technologies and the potential role and benefits they might play. The report outlines the challenges that nuclear technologies face, in terms of their integration into the energy system and their public acceptability, and identifies the RD&D requirements to address these. The report also flags up the role that the UK could play in the global development of nuclear technologies, highlighting the areas where the UK has advantage and where it could make a contribution.

Nuclear energy is back on the agenda and plans are underway for building new reactors. However, as with other power generation technologies, there are a number of socio-economic and environmental issues that need to be addressed in order to gain public acceptance. The report recognises the importance of addressing these issues, but the focus of this report is on the technology development and RD&D needs.

Similarly it is recognised that the recommendations in this report will require public investment in RD&D. The report does not include analysis of this investment, it rather seeks to highlight the issues and the importance of being sufficiently aware of options for detailed review. Providing such detail is outside of ERP's expertise, but this analysis should be part of any subsequent work.

1. Identify the current and future engineering gaps and RD&D needs and timeframes.
2. Review international activity and identify opportunities for collaboration.
3. Review novel technologies and the potential role and benefits they might play.

# 2 Context

The demand for nuclear energy is increasing globally, driven by security of supply concerns and the need to provide low carbon electricity. In the UK it is now seen as playing an important and enduring role in enabling the UK to meet carbon reduction and security of supply aspirations in the electricity sector. A strategy for energy and climate change prepared by Government for summer 2009 confirmed the role of nuclear energy and the deployment of new reactors. In addition, the Government has recognised that there is a need for a substantial and diverse programme of activity on nuclear energy involving industry and academia.

With this renewed interest in nuclear fission come concerns over the long term sustainability of the current uranium based fuel cycles and the need to prevent nuclear proliferation, with fissile material potentially being diverted to weapons.

## 2.1 Nuclear power in the UK

Over the next 15 years all but one of the UK's existing nuclear power stations will be closed. Table 1 lists the current reactors that are in operation with their expected decommissioning dates. The blue area in Figure 2.1 illustrates how this is expected to affect output. Following consultation 10 sites have been identified where new reactors could be built. If all the sites were utilised then it is expected that between 12 and 17 GW of capacity would be added, depending on the type of reactor deployed[4]. In response, several consortia have committed to a new build programme, which is expected to see up to 16 GW of new plant being built on these sites. Using modelling by Cogent, the green area in Figure 2.1 illustrates how this might develop, if 12 reactors were built by 2025. The graph indicates that the new build will mean capacity in 2025 will exceed the current capacity.

[1] Cogent (2009, 2010) *Renaissance Nuclear Skills Series: 1&2*
[2] EPSRC/STFC (2009) *Review of nuclear physics & nuclear engineering* http://www.epsrc.ac.uk/newsevents/cons/Pages/nuclear.aspx
[3] NIA (2008) *The UK capability to deliver a new nuclear build programme*
[4] DECC 2009, Draft Nuclear NPS, EN-6, Page 272, Paragraph A15.

| Station | Type | Generation started | Planned closure date | After life extension? | Operator |
|---|---|---|---|---|---|
| **Wylfa** | Magnox | 1971 | 2010 | | Magnox North |
| **Oldbury** | Magnox | 1967 | 2010 | | Magnox North |
| **Hinkley Pt B** | AGR | 1976 | 2016 | Yes | British Energy |
| **Hunterston B** | AGR | 1976 | 2016 | Yes | British Energy |
| **Dungeness B** | AGR | 1983 | 2018 | Yes | British Energy |
| **Hartlepool** | AGR | 1983 | 2014 | | British Energy |
| **Heysham 1** | AGR | 1983 | 2014 | | British Energy |
| **Heysham 2** | AGR | 1988 | 2023 | | British Energy |
| **Torness** | AGR | 1988 | 2023 | | British Energy |
| **Sizewell B** | PWR | 1995 | 2035 | Possibly out to 2045/55 | British Energy |

*Table 1: Decommissioning dates for existing nuclear power plants*

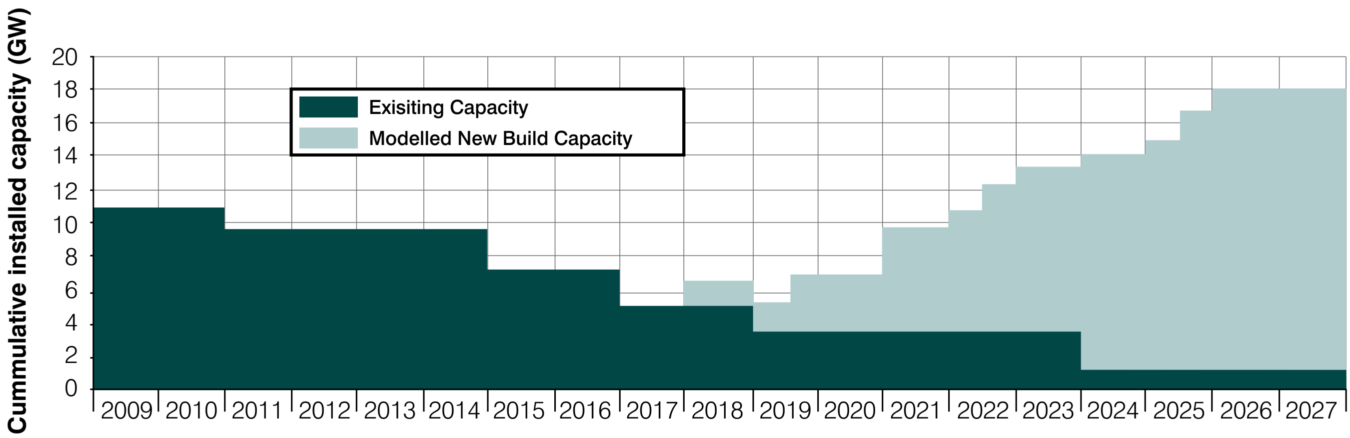


*Figure 2.1 Cogent model to illustrate how a programme of 12 new nuclear power stations to deliver 16 GWe by 2025 might develop (Cogent 2010 )*[5]

The investment for building the 16 GW of new nuclear capacity is expected to be between £40 billion and £64 billion[6], equivalent to £2,500/kW and £4,000/kW. Three consortia are currently involved and are expected to build reactors on the following sites, based on the assumption that connection agreements already exist[7]:

- EDF who are looking to build 4 EPRs totalling 6.4 GW capacity at Sizewell and Hinkley Point;
- Horizon Nuclear Power, a consortium between E.ON and RWE, are intending to build 6 GW, either 4 x EPR or 6 x AP1000, at Oldbury and Wylfa;
- Iberdrola, GDF Suez and Scottish and Southern Electricity have plans to build 3.6 GW – this could be 2 x EPRs or 3 x AP1000s, at Sellafield.

[5] Cogent (2010) *Next Generation. Skills for New Build Nuclear. Renaissance Nuclear Skills Series:2*
[6] Nuclear Industries Association and KPMG (2010), *Securing Investment in Nuclear in the Context of Low-Carbon Generation*
[7] World Nuclear Association (2009) *Nuclear Power in the United Kingdom*

## 2.2 Global context

The nuclear renaissance is a global phenomenon. At present, 438 reactors are operating worldwide, totalling 374 GW capacity, delivering 15% of electricity. Fifty two reactors are being built, primarily in China and Russia, with a further 143 (157 GW) on order or planned and 344 reactors proposed delivering 363 GW[8]. Significant longer term growth is expected in China and India, but there is some uncertainty about how this growth might continue in the rest of the world. Estimates by the World Nuclear Association, based on national declarations of intent, suggest that by 2060 global capacity may increase to between 1,140 and 3,688 GW, continuing to expand to between 2,000 and 11,000 GW by 2100. The IEA Energy Technology Perspectives 2010[9] suggests that in 2050 the installed global nuclear capacity will reach 1,200 GW providing 24% of the global electricity generation.

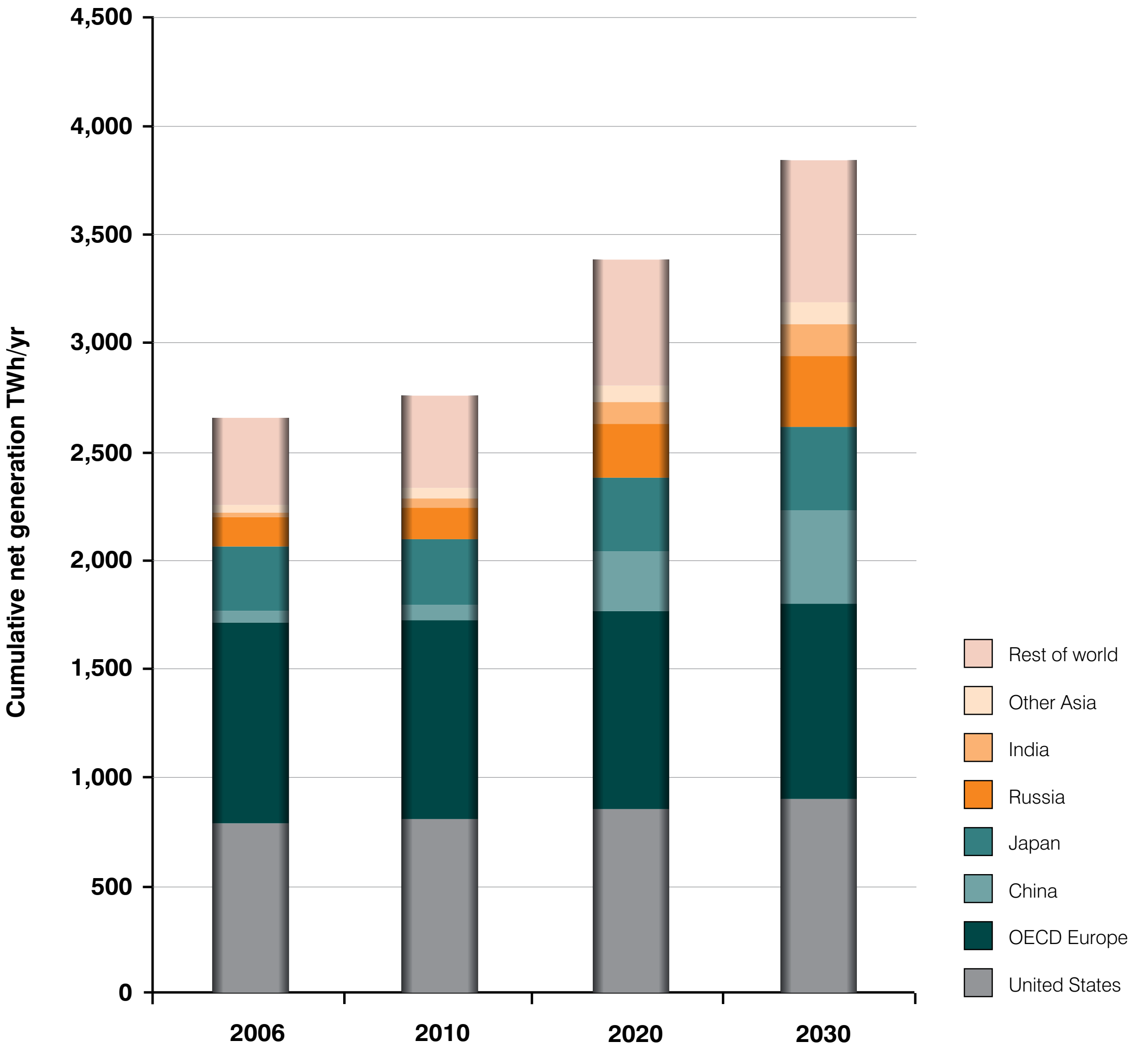


*Figure 2.2 Projections of world net electricity generation from nuclear power, by region (adapted from EIA 2009[10])*

[8] World Nuclear Association (2010), WNA Nuclear Century Outlook, **www.world-nuclear.org/outlook/nuclear_century_outlook.html**
[9] IEA (2010) *Energy Technology Perspectives. Scenarios and strategies to 2050*
[10] EIA (2009) *International Energy Outlook 2009*

## 2.3 Nuclear fission as a low carbon technology

A number of studies have been conducted into the greenhouse gas emissions from nuclear power. The direct emissions from the generation of electricity are negligible; most of the emissions are indirect coming from the construction, decommissioning, waste management and the mining, transportation and processing of uranium. A review of the evidence conducted for the BERR White Paper on Nuclear Power in 2008[11] concluded that the life-cycle $CO_2$ emissions were in the range of 7-22 $gCO_{2eq}$/kWh. This is comparable to figures published by the IAEA, illustrated in Figure 2.3, which is based on analysis of existing reactors. Comparison with life-cycle emissions from other generation technologies those from nuclear, even at the high end of the range, are comparable to wind and considerably lower than fossil fuels.

Various stages of the life cycle are energy intensive. For example, fuel enrichment, where using very low grade ore, 0.01% uranium, (which would be an extreme example), the estimated energy inputs could rise to 3.15% of output, with emissions rising to about 30 $gCO_{2eq}$/kWh[12]. Technology improvements are reducing emissions, such as the global phasing out of old gas diffusion enrichment processes, which produces an order of magnitude more GHG emissions compared to centrifuge enrichment. At the other end of the fuel cycle, reprocessing of fuel can account for 10% to 15% of the total greenhouse gas emissions.

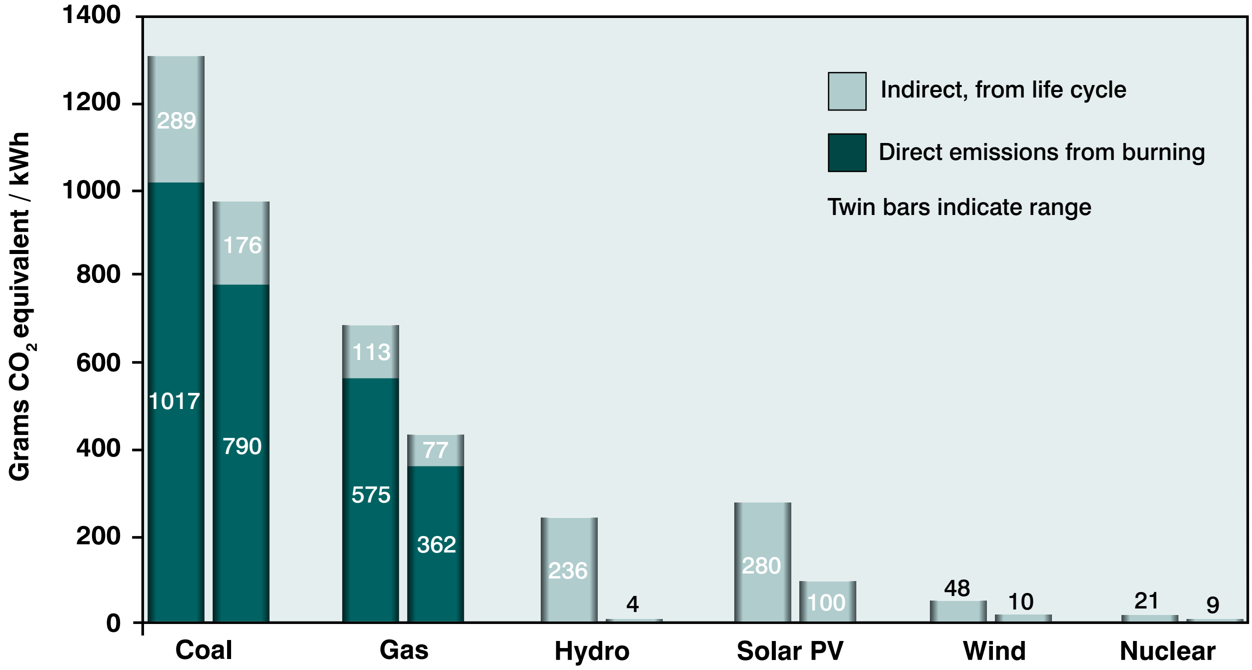


*Figure 2.3 Comparison of life-cycle greenhouse gas emissions from various electricity generation sources, showing high and low estimates (source IAEA[13])*

[11] http://www.berr.gov.uk/files/file43006.pdf
[12] http://www.world-nuclear.org/education/comparativeco2.html
[13] IAEA (2000) *Climate Change and Nuclear Power*

# 3 Technology options

Developments in nuclear power include a range of interlinked technologies. The main component is the reactor and the associated electricity and heat generating technologies. Beyond the reactor are a number of technologies that make up the rest of the fuel cycle. These include fuel enrichment and fabrication technologies, the design of which is dependent on the type of reactor used, although developments in these processes can improve the performance of the reactor. In addition, there are the waste management technologies, where the spent fuel is cooled, stored and either prepared for final disposal or reprocessed to separate out elements that could be reused for fuel.

## 3.1 Reactor technologies

Nuclear reactors can be classified in a number of different ways, such as by type of reaction, cooling system, end use and by generation. The type of reaction for a fission reactor is either thermal or fast and is determined by the speed of the neutrons used to create the fission reaction. The commonest cooling systems are either gas, water (both regular, or 'light', water and deuterium (heavy) water) or molten salts or metals, such as lead or sodium. The water based cooling system can either be boiling water, where the heat is transferred as steam, or highly pressurised liquid phase systems. Advances in the high temperature gas cooled systems are moving towards temperatures over 1,000$^{o}$C, but RD&D is required to develop new materials that can withstand these conditions.

**Thermal reactors**
Most current reactors, including Generation III, use a thermal reaction where fast moving neutrons produced by the breakdown of fissile material are slowed by a moderator material. At this lower speed the atoms in the fuel, mainly uranium, are split releasing heat and more neutrons which go on to perpetuate the fission process. In thermal reactors fast moving neutrons will not cause fission so are of no benefit. The cooling system can also be used as the moderator. Safety advances in reactors take advantage of this as a safety system, so if the coolant is lost, there is nothing to slow the neutrons, so the fission reaction stops. Although a back up cooling system is required as the reactor core will continue to heat up after the coolant loss.

**Fast reactors**
Fast reactors, which are classified as Generation IV, use the fast neutrons to stimulate fission and therefore do not require a moderator to slow the neutrons down. Molten salts and metals are used as coolant as they do not slow the neutrons. However, to do this requires more enriched fuels that have a greater proportion of uranium 235. In thermal reactors, some of the slow moving neutrons are absorbed by the atoms in the fuel, leading to a transmutation to another radioactive element, such as actinides plutonium and americium. These actinides can be difficult to handle in the spent fuel, being highly radioactive and producing considerable amounts of heat. In fast reactors the neutron speed is more likely to cause fission than transmutation, making much more efficient use of the fuel. They are also able to use various actinides, which would otherwise have to be treated as waste. For example, plutonium 238 and americium, which are not fissile and therefore cannot be used in a thermal reactor, can be put into a fast reactor and converted into a fissile fuel.

This ability to 'breed' fuel could reduce the demand for new fuel, particularly uranium, by up to 100 times. The other actinides, such as plutonium 239, are mainly products of fission reactions and are found in spent fuel from thermal reactors. These are often difficult elements to manage as a waste material, as they have a very long half-life and generate considerable amount of heat requiring cooling in pools for several years. As a consequence breeder reactors can effectively close the fuel cycle, requiring very little new fuel and reducing the amount of material going to geological disposal as well as making it easier to manage.

## 3.2 Fuel Cycle

There are a number of stages in the fuel cycle. Figure 3.1 illustrates the two different reactor types and the possible fuel cycles[14]. A once through system would see material entering the system and exiting in a final repository. Developments in the fabrication technologies, where the fuel is prepared and manufactured, have improved the performance and efficiencies of existing reactors. Developments in the enrichment processes have also improved the efficiencies of the processes.

The addition of technologies to recycle and reprocess spent fuel means that material can be retained in the system and used as fuel, thereby reducing the inputs and wastes. However, the choice and design of the processing technologies has implications for security and proliferation resistance, by making hazardous materials more readily available during stages of the reprocessing. For example, separating plutonium and other actinides from the spent fuel, so they can be recycled to new fuels, could make them more available therefore they could potentially be diverted from legitimate use. Appropriate security and detection technologies would therefore be required to prevent access to and misuse of the material. Similarly, the potential to redeploy the technologies for other uses, such as enrichment to make weapons grade material, also presents a hazard.

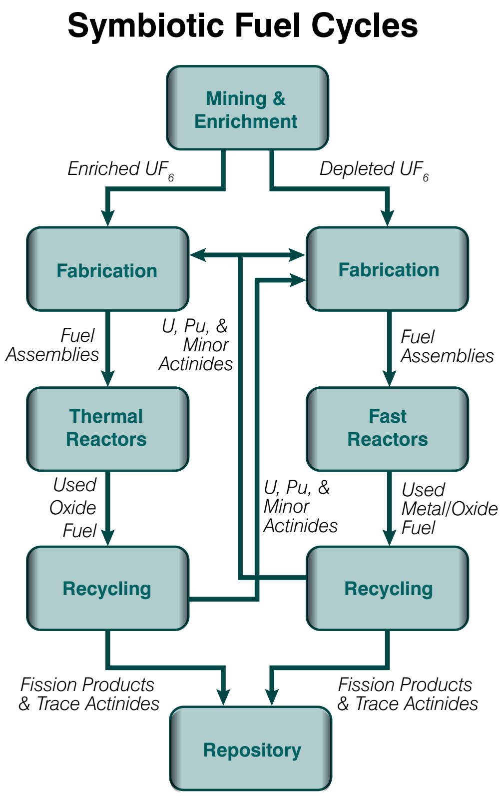


*Figure 3.1 Pathways and interactions of material through the thermal and fast reactor fuel cycles (DOE 2002)*

Uranium provides the basis for almost all the fuel currently used in existing reactors. The current global demand for uranium is about 67,000 tonnes per year. Known conventional resources amount to about 4.7 million tonnes, although estimates suggest that there could be over 15 million tonnes. At 2004 levels of generation this supply would last 270 years[15]. With the development and deployment of more efficient reactors, combined with fuel recycling and fast breeder reactors, the supply of fuel is unlikely to be a serious concern.

Thorium, which is thought to be 3 times more abundant than uranium, can also be used to make fuel. Naturally occurring thorium (Th-232) is not fissile, but after irradiation with slow thermal neutrons can be converted to fissile uranium (U-233). Unlike uranium-235 that is used in conventional reactors, U-233 is more likely to split (fission) when hit by a slow moving neutron than absorb the neutron. The products of absorption (transmutation) are also less hazardous, so the waste contains considerably less long-lived actinides, including plutonium, and is therefore easier to manage and prepare for disposal. In addition, using thorium as a fuel reduces the proliferation risks for weapons use as there is less fissile plutonium and the waste requires remote handling due to the presence of high gamma emitting isotopes. Thorium is also a much more efficient fuel, as the higher rate of fission means greater energy output per unit of fuel than uranium based reactors.

However, the requirement to pre-treat thorium to turn it into a fuel, which requires uranium and plutonium to seed the fission, makes it a less attractive option. In addition, the prevalence of a mature industry based on uranium and uranium is readily available, has meant that thorium systems to date have attracted little attention. India has shown the most interest, partly due to its abundant indigenous resources and restrictions on access to global supplies of nuclear material, as it is not a signatory of the Non-Proliferation Treaty. Even so, India will deploy uranium based fuel in reactors procured and deployed in the foreseeable future. At present in Europe, there are no short or medium term industrial prospects for the deployment of the thorium cycle and is therefore not regarded by the SNETP[16] as an RD&D priority, although it may become more attractive in the long term.

[14] US DOE, GIF (2002) *A Technology Roadmap for Generation IV Nuclear Energy Systems*
[15] IEA (2008) *Energy Technology Perspectives. Scenarios and Strategies to 2050*
[16] EU Sustainable Nuclear Energy Technology Platform.

## 3.3 Reactor development

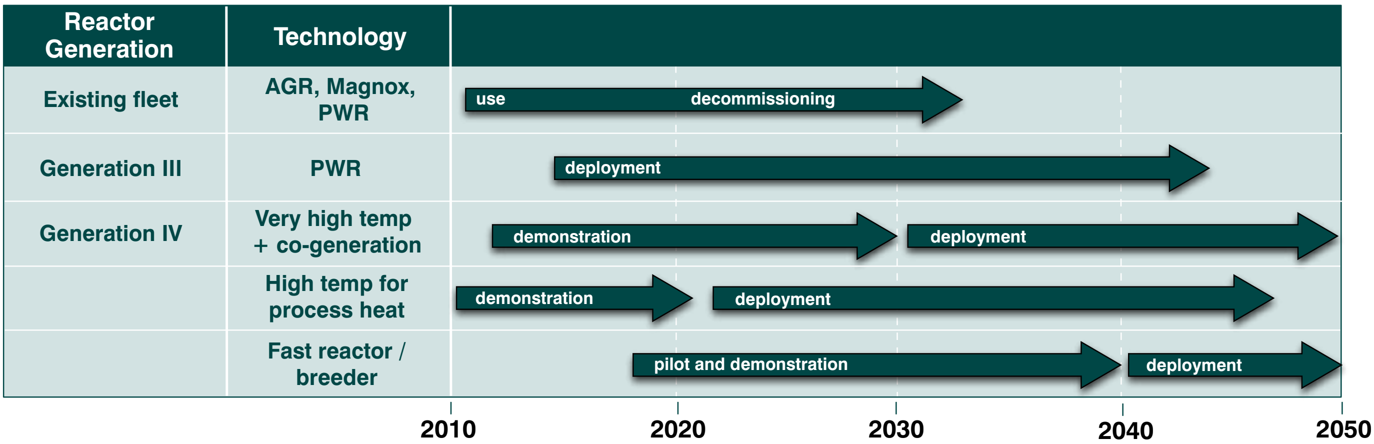


*Figure 3.2 Timeline of nuclear reactor development relevant to UK*

### 3.3.1 Generation I and II

The UK built a number of different designs for their reactors each requiring slightly different support RD&D and producing a wide variety of spent fuel. All but 2 of the Generation I power stations in the UK have been closed, leaving the two Magnox reactors at Wylfa and Oldbury, which are expected to close in 2010, depending on the remaining supply of fuel. Magnox reactors are graphite moderated. Magnox derives its name from the magnesium oxide cladding used to contain the fuel.

Unlike most other countries the UK's Generation II reactors are mainly Advanced Gas-cooled Reactors (AGR) rather than the more widely used Light Water Reactors (LWR). This unique situation means the UK is dependent on its own expertise to maintain the reactors. These are due to be closed over the next 15 years, leaving the UK's only civil LWR, the Pressurised Water Reactor (PWR) at Sizewell B. This became operational in 1995 and is based on a Westinghouse design, which was substantially modified to meet the UK licensing process. Sizewell B, which generates 3% of the UK's electricity, is scheduled to close in 2035, although this may be extended to 2045/55 with the application of global experience in LWR's.

Light water reactors (LWR's) are the main technology deployed globally. These are either Pressurised Water Reactors (PWR) or Boiling Water Reactors (BWR).

### 3.3.2 Generation III

Generation III reactors are mainly evolutions of the Generation II systems, with enhanced safety systems, reliabilities and efficiencies. Improved efficiencies in the reactor and generating system, and the fuel cycle makes them more economic, as well as reducing the amount of waste they produce.

At present the two reactor designs most likely to be built in the UK are the Westinghouse AP1000 and Areva's EPR; both are classified as Generation III reactors. They are both pressurised light water reactors.

### 3.3.3 Generation IV - Fast breeder and very high temperature reactors

Generation IV reactors are still in development. There are six types of reactor being considered by the Generation IV International Forum (GIF). They are divided into two main types: a) advanced thermal reactors and b) fast reactors, with breeding potential.

**a) Advanced thermal reactors**

Advanced thermal reactors are developments of Generation III but operate at very high temperatures. A number of countries are working on these reactors including China, South Africa and USA. South Africa has made significant developments in the Pebble Bed Moderated Reactor (PBMR), but this has been delayed indefinitely due to funding problems. Similar designs are being developed by the Chinese and US, but are further away from demonstration.

- Very high temperature reactor - a graphite-moderated, helium-cooled reactor with a once-through uranium fuel cycle;
- Supercritical water cooled reactor - a high-temperature, high-pressure water-cooled reactor that operates above the thermodynamic critical point of water.

Development of high temperature reactors is also driven by the potential to use the high-grade heat for industrial processes (oil, chemical and metal industry, synfuels and hydrogen production, seawater desalination, etc.) with the potential to be co-located close to industrial centres. Very high temperature (VHT) reactors also have the potential to produce hydrogen directly from splitting water, a much more efficient process than electrolysis. The Next Generation Nuclear Power programme in the US is aimed at delivering commercial VHT reactors in the early 2020s. The main challenge is developing materials that can withstand the extreme temperatures and pressures.

**b) Fast reactors**

The technology for fast reactors has been around for many years and a number of pilot plants have been built in France, Russia, China, Japan and India and of course the 2 early UK demonstrations and prototype fast breeder reactors at Dounreay. There are three main types of system being developed, distinguished by the cooling system:

- Sodium cooled fast reactor - a sodium-cooled reactor with a closed fuel cycle for efficient management of actinides and conversion of fertile uranium;
- Lead cooled fast reactor - a liquid-metal-cooled reactor using lead/bismuth with a closed fuel cycle for efficient conversion of fertile uranium and management of actinides;
- Gas-cooled fast reactor - a high-temperature, high-pressure water-cooled reactor that operates above the thermodynamic critical point of water.

The most promising of these is the sodium cooled fast reactor. The UK sodium cooled fast reactor at Dounreay contributed to the science underpinning the technical feasibility of the system. However, the programme was closed in 1994, when the global expansion of nuclear power collapsed and the constraints on uranium faded. The main challenge now is to improve the economics of the system and develop technologies to prove the safety systems.

A fourth system, the molten salt reactor has been proposed following early development in the 1950's. This system produces fission power in a circulating molten salt fuel mixture reactor, which like the other fast reactors is capable of recycling actinides in the fuel cycle.

India is also developing reactors, with a long term focus on exploiting thorium as the primary fuel instead of uranium.

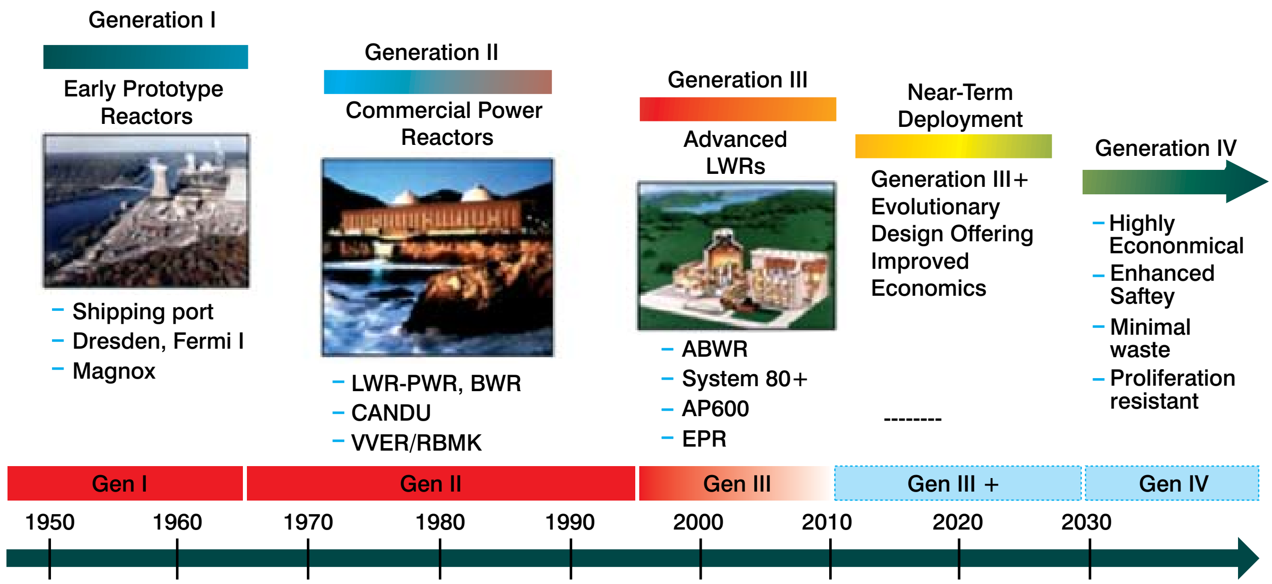


*Figure 3.3 Timeline for generations in the development of nuclear fission. Generation IV expected to be deployable after 2030 and offering significant advances in sustainability, safety, reliability and economics. (DoE 2002[17])*

[17] US DOE, GIF (2002) *A Technology Roadmap for Generation IV Nuclear Energy Systems*

# 4 Future of nuclear energy in the UK

How nuclear energy develops in the UK is dependent on three main issues, which in turn will affect what RD&D is required. The first is the scale of deployment of nuclear energy in the UK, which will influence decisions about waste management and reactor designs. Second is the UK's contribution to the Non-Proliferation Treaty, where it has recently set out its ambitions and established a Centre of Excellence to coordinate an RD&D programme to support its activities and position. Finally, the growing global renaissance in nuclear energy offers a number of opportunities for UK RD&D and industry, which it may be able to exploit more fully with some stimulation.

These three drivers for nuclear fission RD&D are highly interrelated and are likely to lead to similar outcomes. However there is currently no long-term strategy for how the technology will be deployed, in terms of scale, what or whether new reactor designs may be deployed and whether the UK will be involved in its development or will buy off the shelf once it becomes available. A roadmap that brings the various drivers together is essential.

## 4.1 Scenarios for deployment

The most significant determinant of RD&D is the scale of deployment.

The current proposals for the UK look to replace existing generating capacity of approximately 12 GW of power with about 16 GW. This will be delivered using between eight to twelve reactors of an existing design. Beyond that there are no plans for any further expansion.

Analysis of a range of energy scenarios for the UK out to 2050 indicate that this is likely to be the minimum amount of generating capacity require from nuclear to deliver the energy security and $CO_2$ reduction targets to 2050. There is some uncertainty about how much nuclear capacity will be deployed. Table 2 illustrates some examples of the capacity that may be required out to 2050.

| | |
|---|---|
| **Parsons Brinckerhoff, 2009[18]** | 2050 require min 16 GW - max 25 GW.<br>Build rate: Max 1.5 GW/yr, expected 1.2 GW/yr. |
| **UKERC Carbon Ambition Scenario, 2009[19]** | 2000 = 12 GW<br>2035 = 9 GW<br>2050 = 29 GW |
| **UKERC range for all scenarios[20]** | 2035 = 9-30 GW<br>2050 = 12-38 GW |
| **MacKay Plan C[21]** | Up to 70 GW by 2050 (note: supply/not capacity)<br>First built in 2018, add 2.2 GW per year |
| **Committee on Climate Change, 2008[22]** | Limit on nuclear and CCS [check] expansion of 3 GW/yr up to 2030 and 5 GW/yr after 2030. |
| **Royal Academy of Engineering, 2010[23]** | 30 nuclear power plants likely to be required by 2050. |

*Table 2: Scenario examples for scale of nuclear deployment*

[18] Parsons Brinckerhoff (2009) *Powering the Future: Mapping our low-carbon path to 2050*
[19] UKERC (2009) *Making the transition to a secure and low-carbon energy system, UKERC Energy 2050 Project*
[20] *ibid*
[21] MacKay (2009) *Plan C, Supplement to Sustainable Energy – Without the Hot Air*
[22] CCC (2008) *Building a low-carbon economy*
[23] RAEng (2010) *Generating the Future: UK energy systems fit for 2050*

### 4.1.1 Factors affecting deployment

In the modelling a number of factors were significant in determining the outcome. The most significant of these were the timing, availability and cost of CCS, the cost of natural gas, the overall carbon reduction target for the generation sector and the scale of demand for electricity. The cost of nuclear was also considered an issue, particularly as the reactors that will be deployed were new, leading to variations in cost assumptions.

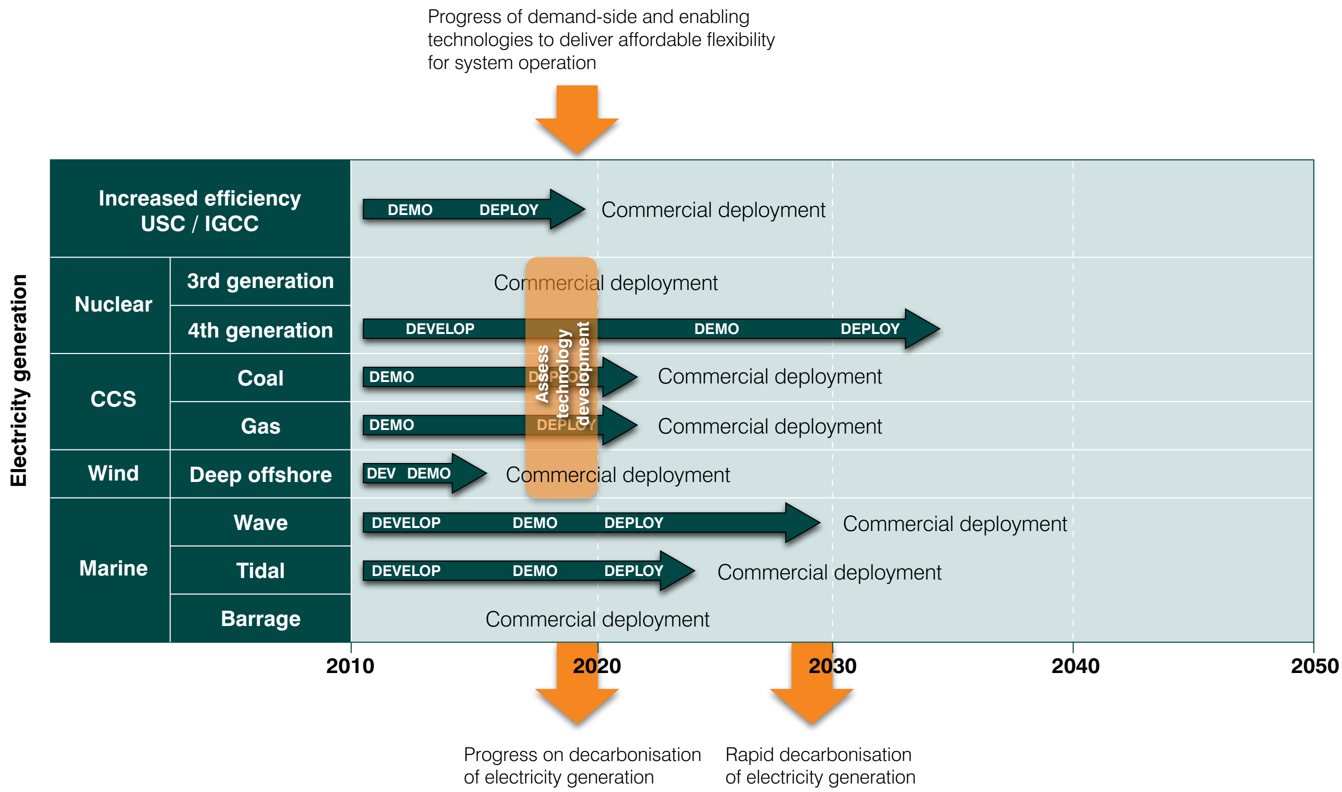


*Figure 4.1 Timelines for technology development showing nuclear fission in relation to other electricity generation technologies (ERP 2010[24])*

The most significant determinant was the performance of fossil fuels with CCS, which is likely to compete directly for providing base load power. As the orange box in Figure 4.1 illustrates, the development of wind, CCS and nuclear power are closely interrelated. Should CCS be delayed or prove more expensive than predicted then nuclear is likely to play a much more significant role. Similarly, nuclear will be required to play a more significant role should the residual emissions from CCS prove expensive or difficult to reduce.

Higher emission reduction targets also saw an increase in the scale of nuclear deployment. Some of the scenarios see nuclear being deployed on a larger scale if emission reduction targets are set higher. Indeed, difficulties in reducing emissions from one sector of the economy may require greater cuts from others. This may lead to the energy sector cutting emissions by 85% or 90%. Looking at the long term modelling by the IPCC, cuts of this scale may be required soon after 2050, meaning the 80% targets of 2050 should not be regarded as an end point. Given the longevity of nuclear plant (60+ years) it would be worth considering what will be expected of them beyond 2050.

The timing of the deployment is also important, which is also affected by the potential build rate. Achieving higher emission targets sees earlier and stronger deployment. It is worth noting that few scenarios make specific distinction of the potential contribution of Generation IV reactors.

### 4.1.2 Current status

Ten sites around the UK have been identified where new reactors can be built. At present there are proposals for up to 16 GW of new nuclear capacity to be built across some of these sites. There is space available for further reactors on some of the sites already identified, but there are currently no plans for any additional build on these or other sites nominated following the 2010 consultation on the topic.

[24] ERP (2010) *Energy Innovation Milestones to 2050*

# 4.2 Scenario options

The scale of deployment plays a significant role in determining how nuclear fission develops in the UK and therefore the RD&D requirements. The replacement of existing capacity or only a small increase is likely to be manageable within the existing infrastructure. However, a significant increase in capacity, as indicated by the scenarios, would put greater demand on the waste management and fuel supply systems and require more skilled personnel. Technology developments and the associated RD&D programmes could alleviate these. In addition an appropriately skilled workforce and supply chain will need to be developed, new technologies are being developed that will be able to co-generate process heat and electricity, which could affect how the energy system develops.

The following two scenarios (Section 4.2.1 and 4.2.2) illustrate how nuclear fission might develop in the UK and set out the issues that need to be considered to achieve them. Section 4.2.3 considers alternative nuclear reactor technologies that are currently not being considered in the UK, and the role they could play in the energy system, which goes beyond electricity generation. It should be noted that while the scale of nuclear generating capacity is an important driver for nuclear fission RD&D, there are other factors, such as proliferation resistance and global market opportunities, which also need to be considered. These will be explored later in the chapter.

### 4.2.1 Current new build programme

**Reactor types and technology**

The current new build programme is likely to be either Westinghouse's AP1000 reactor or Areva's larger European Pressurised Water Reactor (EPR), both of which are Generation III reactors. How many will be built will depend on which designs are chosen, as they have different power outputs, with the AP1000 delivering about 1,100 GW and the EPR 1,600 GW. How long they will take to build will depend on a number of factors, some of which are commercial, but also on the planning and approval processes. In addition, an appropriately skilled workforce and supply chain will need to be developed.

Modelling by Cogent of the level of skills required and the timing of them to deliver the proposed new build programme suggests that it would be feasible to build 16 GW of capacity by 2025. A possible timeline for 12 units consisting of equal number of EPR and AP1000 reactors is illustrated in Figure 4.2. However, any delays particularly in the early stages would disrupt this. The proposed build rate is half that achieved in France in the 1970s. However, the situation now differs in that these reactors are a new design of which there is only limited previous experience and will therefore require some initial learning and development. Unlike the 1970s, capacity will also need to be increased in several key skills. Although the modelling is regarded as feasible, it is expected that there will be delays.

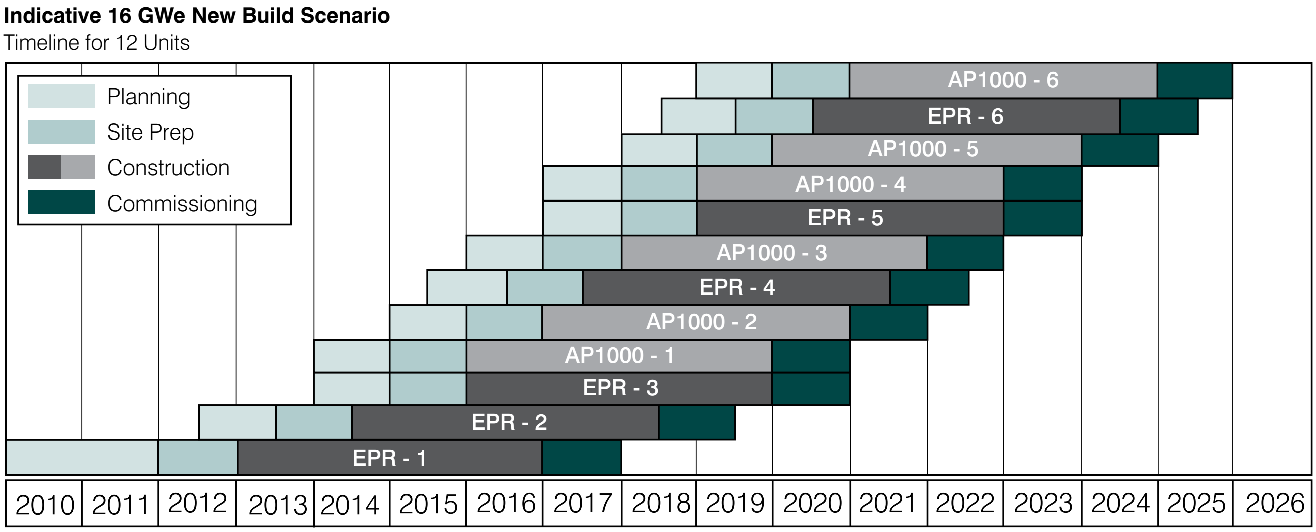


*Figure 4.2 Scenario example timeline for phasing of new build reactors in UK (Cogent 2010[25])*

[25] Cogent (2010) *Next Generation. Skills for New Build Nuclear. Renaissance Nuclear Skills Series:2*

**UK supply chain**
The UK supply chain is expected to contribute a majority of the components. Estimates suggest that 70% of components could come from UK suppliers. The announced investment in the Nuclear Advance Manufacturing Research Centre at the end of 2009 is a useful contribution to the new build programme.

If the timeline indicated by Cogent in Figure 4.2 is to be achieved it will require a concerted effort from industry to ensure that the supply chain is in place.

**Waste management**
If no further nuclear generating capacity was added, the current programme could be delivered using the present waste management techniques, with no demand for the development of advanced fuel cycles or fuel reprocessing. It would of course require additional space in the geological disposal sites, with interim storage for the spent fuel while it cools.

As the new reactor designs have a higher burn up rate than earlier generations of reactors, the amount of power output per unit of fuel is greater. Consistency in the design of reactors being deployed and therefore waste produced, will simplify the waste management procedures. It is expected that the proposed new build programme can be managed by the existing waste management procedures.

**Skills**
The current programme of replacing existing capacity could be delivered by maintaining the existing RD&D and skills base. A review by Cogent on the skills requirement, which was endorsed by the EPSRC/STFC[26] review, considered that this capacity replacement new build could be delivered using the present workforce[27]. However, it was noted that it would still require a recruitment rate of 500-1,000 every year to 2025, due to the high level of retirements as a consequence of the current age profile of the work force. With the appropriate incentives in place, a clear commitment to nuclear power may be a sufficient incentive. However, any delays in the delivering the programme, particularly in the early stages, could affect the delivery with consequences on the availability and cost of the workforce.

Cogent noted that the major challenge will be balancing the workforce between short-term expansion in decommissioning, medium term contraction in energy production, and long-term expansion in new-build commissioning and operation.

Competition for the skills and capacity is likely to come from similar developments across the world and from other large construction projects.

Delivering the new build programme will require a steady flow of graduates into the nuclear fission industry. The EPSRC/STFC review concluded that the UK should therefore maintain its university teaching capacity in nuclear-related areas – encompassing many disciplines such as physics, chemistry, engineering and materials. The review panel recommended that the best way to maintain teaching capacity was to continue to support research and development in universities in cutting-edge areas such as Generation IV technology and advanced fuel cycles. They also noted that long-term investment in these RD&D programmes was justified, because trained nuclear personnel will be required over a number of decades. The review panel members felt that a vibrant research base was justified and indeed necessary to maintain the UK's capacity in nuclear power across all sectors of the nuclear industry.

### 4.2.2 Longer term nuclear build programme

As the scenario analysis in Section 4.1 shows, the scale of deployment for nuclear power in the UK may need to be significantly higher than currently planned. Taking 30 GW capacity by 2050 as a rough estimate will require between 19 and 27 reactors, depending on the design. If all the reactors were to be built as quickly as possible, the last reactor will come on line in 2035, based on a build rate of 1.2 GW per year. This rate may increase with experience and from the greater confidence that the longer term commitment provides. However it will still be at risk from delays.

**Reactor types and technology**
The first reactors are likely to be Generation III, as proposed in the current new build programme. Although it is possible, a more extensive nuclear programme could see more reactor designs being approved. It is possible that by the time the last few reactors are being planned the first commercial Generation IV fast reactors will become available. However, at this stage it is not known how they will compete economically and therefore whether the market will build them out of choice. Their economic competitiveness will depend on issues associated with the global supply and demand of uranium and concerted efforts to reduce the capital cost per kW installed, which is currently at least 25% higher than LWR technology.

**Supply chain**
The initial build rate is likely to be the same as the previous scenario. This may accelerate as more reactors are built and the experience and supply chain develops. Commitment to a long term nuclear programme will also build confidence in the industry and help underpin investments.

[26] EPSRC/STFC (2010) *Review of Nuclear Physic and Nuclear Engineering*
[27] Cogent (2010) *Next Generation. Skills for New Build Nuclear. Renaissance Nuclear Skills Series:2*

**Waste management**
A programme of this size would produce a considerable quantity of waste and increase the demand for uranium. With similar increases in demand for fuel globally it is possible that over the course of the reactor's lifetime there may be constraints on supply. Pressure will also rise on waste management facilities, both interim and long-term storage, with a need to manage the waste sustainability to reduce the environmental impacts and the security and non-proliferation threats. The EU's Sustainable Nuclear Energy Technology Platform (SNETP) in its strategic research agenda, suggest that reprocessing and fast reactors will become an attractive way to deal with waste as waste inventories grow. It therefore becomes much more likely that the UK will need to have recycling and the ability to deploy Fast Reactor technology, as nuclear generating capacity grows.

**Skills**
Further expansion of the nuclear fission fleet beyond replacing the existing capacity will require an expansion of the skills base and the RD&D capacity. Additional personnel will be required across the whole spectrum of top-end skills in the civil nuclear industry. Delivering this will require maintaining and enhancing the supply of skilled personnel into the industry.

The review panel for the EPSRC/STFC considered that a major increase in nuclear engineering research and development would certainly be required in the following areas: sustainable fuel cycles, Generation IV reactor systems, efficiency and sustainability in current Generation III designs, waste management, homeland security, nuclear forensics and radiological engineering. The present level of nuclear engineering research and development activity in the UK would be wholly insufficient both in terms of scope and volume. It was noted that, whilst a portion of the research and development would be performed by industry, that the intellectual challenges presented in many of the aforementioned areas would demand a significant increase in university-based research. Partnerships between academia and industry would be key to facilitating the technological advances required. The current Research Council portfolio would therefore need to significantly expand, and more courses in nuclear science and technology would be required both at undergraduate and graduate level.

### 4.2.3 Alternative technologies

In addition to developing fast reactors, Generation IV RD&D programmes include developing thermal reactors. The main developments are around increasing the temperature of the cooling system with the potential to utilise this heat to supply industrial processes including hydrogen production by steam reforming. Nuclear power stations would therefore co-generate electricity and process heat. There are currently no plans for the deployment of these high temperature reactors (HTR) in the UK, but the technology is being developed in a number of countries including the US, where reactors are likely to be located near industrial sites. The first prototypes for these reactors are expected around 2020. The heat from the reactors could be used to displace fossil fuel based industrial processes, such as fertiliser production, desalination and various chemical manufacturing and processing.

The main challenges for High Temperature Reactors, is the development of heat exchangers and heat transport systems, combined with the modification of industrial processes to utilise the new heat supply. RD&D is also needed in the fuel and waste produced, as well as addressing licensing issues. One or two UK companies have been actively involved in progressing the non-nuclear technologies that support the HTR system, for example heat exchangers and gas blowers for the South African Pebble Bed Modular reactor. However this project is now in abeyance, and UK participation in the nuclear reactor and supporting fuel cycle ceased when the rights to the technology were ceded to Westinghouse when it was sold to Toshiba. Nevertheless, the UK still has skills from these earlier development activities that could be brought to bear in the European Framework Programme 8 (FP8) and on a similar timescale in the United States, should the UK wish to participate in these international programmes.

What is needed is a review of the potential this technology may offer the UK for decarbonising its energy landscape. This would enable informed decisions to be taken on the appropriate level of RD&D and whether or not the UK should plan to invest significantly more. The UK has specific, internationally recognised, niche capabilities associated with its knowledge base of graphite. However, these will decline as the existing Generation II AGR reactors progressively retire unless proactive steps are taken to refresh and build a capability that would support deployment of HTR's in the post 2030 era. The current level of research council funding would not sustain such an objective.

As well as HTR's, where the UK may well have a role to play, small modular reactors are attracting increasing interest internationally. Overseas reactor designers already have designs under development, such as the light water reactor IRIS (International Reactor Innovative and Secure) led by Westinghouse, with similar systems are being developed by Japanese and French vendors. Should these initiatives gain momentum the UK needs to ensure it has positioned itself to take advantage, probably by encouraging UK manufacturing and technology companies, such as Rolls Royce and Doosan, to participate in international development initiatives.

#### 4.2.4 Summary of scenario options

The above scenarios illustrate the importance of the Government setting out clear plans for new nuclear build and the impact it has in terms of trained personnel and scope and volume of research and development activity. It is important to note that nuclear fission is not a technology which can be left solely to the market and diverse individual company interests. Nuclear technology is one of the few technologies where the assets invested in today and over the coming two decades will persist in a post 2050 era through to 2100.

It is therefore clear that a high-level national strategy for nuclear is required, with a roadmap which defines how our future nuclear capability is to be achieved. This needs to be done on such a timescale as to enable industry, the higher education sector and the research councils to realign their priorities, to create the required intellectual and technological capacity. It should be noted that the scenarios are illustrative only, and that a thorough, in-depth analysis of workforce and RD&D needs would be required as part of the roadmapping exercise.

The ERP, in common with the EPSRC/STFC panel, supports the recommendations made in the 2008 House of Commons Innovation, Universities and Skills select committee report on engineering which highlighted the need for a comprehensive roadmap for nuclear, to be owned by the Office of Nuclear Development. The panel recommended that the roadmap should consider the need for a balanced portfolio of research in nuclear engineering in the UK to serve the short-, medium-, and long-term needs of the country. The panel recommended that key strategic input should come from the National Nuclear Laboratory, in consultation with industry and policy makers. The panel felt that planning the future research agenda will only be possible with a comprehensive roadmap. The Research Councils have a key part to play in developing this roadmap and the panel encouraged proactive engagement with this process.

Similarly, ERP supports the review panel's emphases on the importance of a diverse research portfolio in nuclear engineering to ensure future economic impact. The EPSRC/STFC Review noted that the Research Council portfolio is heavily geared towards decommissioning and waste management with a sub-optimal level of research into forward looking areas such as reactor design[28].

[28] EPSRC/STFC (2010) *Review of Nuclear Physic and Nuclear Engineering*

## 4.3 Key issues

How nuclear technology develops will depend on the scale of the deployment. The drivers for its development will come from within the nuclear power sector but also from the wider energy system. The main demands within the sector will be from possible global constraints on the supply of nuclear fuel, the need to address non-proliferation concerns, technologies to manage the wastes and the development of a skilled workforce. From the energy system, flexibility in the supply system will need to be addressed as increasing amounts of variable renewables are added to the system.

The current programme to replace existing capacity is not likely to place any significant new demands on the technology. The need for flexibility in the system can be met by other technologies and systems. But several scenarios indicate that substantially more nuclear generation will be required to meet the 2050 targets, putting greater pressure to address the issues that are likely to arise.

In addition, new developments in the technology may also open up new options, including co-generation of hydrogen, supply of industrial heat.

### 4.3.1 Flexibility

At the same time as this new nuclear capacity is being built, it is expected that there will be a similar increase in variable renewables, particularly wind. By 2050, overall demand for electricity is expected to be 50% higher than current demand, possibly double. Without additional nuclear capacity this demand will be met by increasing capacity in wind or fossil fuel with CCS. Concern has been raised that with an increasing proportion of variable wind and other renewables there will be insufficient flexibility in the system to provide a secure and stable electricity supply. It is unclear how this service will be provided, with some scenarios requiring over 20 GW of open cycle gas turbines providing the back up and flexibility.

Nuclear power is often referred to as providing base load power. However, it is entirely possible to build a reactor that can load follow and therefore provide an additional degree of flexibility to the electricity supply system. The existing reactors in the UK were not designed to provide flexibility, such as frequency response, or short term modifications in output. In France the situation is different; with nuclear providing over 75% of the electricity supply some power stations were designed to provide frequency response and load following services. The new EPR reactor being built in Flamanville, France, will also be able to provide flexibility. For any new plant in the UK to have this flexibility it will have to pass appropriate safety assessments and meet requirements of the Grid code and market arrangements. One of the other main reasons that reactors are not operated in this way is because it is less economic.

As the amount of variable renewables on the supply system increases, providing a reliable supply will require greater management. Various options have been proposed, including greater demand-side management, use of energy storage systems or part-loaded open cycle gas-fired power stations. Nuclear power is likely to need to contribute to the flexibility. How much will depend on the development of these other technologies, the scale of the carbon emission reductions required from the energy sector and on a favourable business model. It is also possible that future reactor designs will be able to provide the flexibility at lower cost.

### 4.3.2 Waste management and the fuel cycle

The current UK position for new reactors is a once-through cycle, with deep geological disposal likely to be the preferred option. Such disposal is already being planned for legacy waste from existing power plant. The wide range of reactors that have been deployed by the UK in the past has meant that it has a diverse inventory of waste. The new fleet of Generation III reactors will produce smaller quantities of waste and, given the similarity of the reactors, will produce a more consistent range of material.

An alternative to geological disposal is reprocessing of the spent fuel to extract components that could be used to prepare new fuels for re-use in reactors. The UK has some reprocessing capabilities and fuel preparation, which it developed over 50 years of operating a closed fuel cycle programme. The associated RD&D programme in advanced reactors and fuel cycle has also meant it has developed skills in this area. The existing reprocessing facilities are currently contracted to process some UK and overseas waste, but are not intended to be used beyond that. Without a long term plan the UK is at risk of losing this capability.

Recycling of fuel and closing the fuel cycle is directly linked to the development of new reactors, particularly fast breeder reactors. A potentially valuable opportunity exists for the UK to apply its expertise and capability to the development of new fuel cycles and fast breeder reactors. However, to deliver this the UK would need to engage with international programmes, as the UK does not have the capacity to develop them on its own.

The UK, through the National Nuclear Laboratory, has world class expertise and experimental capabilities related to reprocessing and recycling technologies, quite uniquely combining research and development on advanced processes with experience from supporting current and past UK industrial operations. Over the last decade, UK innovations have not only benefited the Sellafield site but have also been taken up within international advanced fuel cycle programmes (e.g. US, India, China, France, Europe). However, the current UK skill base is supported almost entirely through participation in the European Framework 7 programme, which ends between 2012 and 2014. If the UK is to retain these skills so as to be in a position future UK nuclear policy options, exploit opportunities within future European programmes and maintain influence internationally, there is a time window of about 3 years to develop an appropriate national level programme.

The development of a closed fuel cycle has a number of benefits. Not only does it reduce the amount of waste requiring final disposal, but it also reduces the demand for uranium, as valuable fissile material can be recovered from the spent fuel. This can be further enhanced by the use of fast breeder reactors, which, during burn up of the fuel can breed new fuel. Concerns over the future availability and cost of uranium have led to the establishment of a number of international programmes in Europe, the USA, China and India to develop fast breeder reactors and new fuel cycles. The UK also has a significant stockpile of separated civil plutonium that, as part of a long term strategy, could be utilised as a major asset in a future closed fuel cycle in a similar way to that planned for the current French nuclear strategy.

#### 4.3.3 Non-proliferation

With the further global expansion of nuclear power there is concern about the risks of fissile material being diverted for use in weapons. Material could be available both in the preparation of the fuel as well as the management of spent fuel and nuclear waste. As a signatory to the Non-Proliferation Treaty the UK has declared an intention to be at the forefront of delivering on the obligations of the treaty. This includes the securing of fissile material, but also ensuring the safe expansion of nuclear power to developing countries. In order to deliver this the UK announced in 2009 that it would set up a National Nuclear Centre of Excellence (NNCE), to provide strategic guidance on how to deliver the UK's objectives. The NNCE had been set up with the aim of being in place in time for the Non-Proliferation Treaty talks in May 2010 but now faces an uncertain future.

One option for new states to gain nuclear power is for existing nuclear countries to manufacture the fuel and dispose of the waste for them, thus reducing the risk of misappropriation of nuclear material and technology. This business model would have to be developed by international agreement, but the UK could become a supplier.

Whichever scenario the UK follows, the global use of nuclear energy is expected to significantly increase. In this context, the requirement for research and development into counter-terrorism technologies and nuclear forensics would increase, as well as the need for a proliferation-resistant fuel cycle and a robust, well-informed regulatory structure where the UK would wish to influence any international initiatives and can only do so if actively engaged in relevant cutting edge research and development. This means that the UK needs to be actively participating now in global efforts to develop proliferation resistant fuel cycles and to be proactively part of the global endeavour to bring fast reactors and high temperature gas-cooled reactors, and their associated fuel cycles, to the point that they are realistically deployable options.

#### 4.3.4 Global market and UK RD&D development

A further consideration that will influence how nuclear technology could develop in the UK is how much it can contribute to the international development of nuclear technologies. The UK has developed considerable experience and expertise in a number of key areas of nuclear technology. With the growing global interest in nuclear power there is likely to be a number of markets for UK supply chain companies and services. Experience gained from deploying cutting edge reactor designs in the current new build programme, will provide some opportunities.

Furthermore, the nuclear sector would become a significant part of the UK economy. It would therefore make good business sense to have a healthy, vibrant research base within the UK. Not only would this aid the supply-chain of skilled personnel to industry, but would also ensure that the UK retained the intellectual property (IP) generated, and that associated spin-off companies would be spawned within the UK.

#### 4.3.5 Public acceptability

How nuclear power develops in the UK will be affected by public acceptance of the technology. This is a complex area with many issues and concerns that need to be considered, which affects if and how deployment goes ahead. Recent polls indicate that opposition to nuclear power is decreasing in the UK and across Europe. However, understanding and responding the reasons for this, and what the issues are, is vital for the development of nuclear power in the UK.

It is important to note that public acceptability affects not just nuclear but many other energy technologies. The context is also important with technology options often compared against each other. With regards to tackling climate change nuclear power is being increasingly recognised as a viable low carbon option. However, public opinion favours renewable technologies as there are concerns about the safe and secure operation of a nuclear power plant and the risk of a major incident and from the hazards posed by radioactive waste. The development and deployment of nuclear power and the management of its wastes must therefore respond to these concerns.

At present the proposals are for only one round of new reactors to be built. It is unclear whether there is a limit to the number of reactors that the public would regard as acceptable, and whether there are constraints on the type of technologies used. Further expansion and the potential deployment of new reactor systems and waste management processes will require an ongoing programme of public engagement to answer these questions.

How these issues will be addressed needs to be considered when developing the roadmap to ensure they happen in a timely fashion so as to inform the development of the technology.

# 5 RD&D Activity

## 5.1 UK RD&D

Following the shelving of fast reactor research in the UK, the RD&D focus shifted to supporting existing fleet including life extension, safety and fuel cycle along with waste management and decommissioning. The majority of RD&D supporting the waste management end of the fuel cycle is funded by the Nuclear Decommissioning Authority (NDA) and its Site Licence Companies with reactor operations primarily the responsibility of British Energy. The Health and Safety Executive and other industrial organisations fund some applied RD&D. The Research Councils, primarily EPSRC, fund University research, with the coordination of these activities through a Letter of Agreement Group which involved British Energy, HSE (Nuclear Industry Inspectorate), National Nuclear Laboratory, NDA and MOD / AWE.

More recently the Letter of Agreement group has been expanded to include a wider group of public departments and bodies involved nuclear research as well as industrial members[29]. This broader Nuclear Research Coordination Group has a focus across the nuclear field including future reactor systems and associated fuel cycles, as well as maintaining UK capability and ensuring that the UK can be an intelligent customer. By coordinating the public-private research, the group aims to establish a world class academic base, which can support the development of the industry in the UK and provide a source of trained and skilled personnel. In achieving this it provides valuable guidance as to how the industry could develop in the UK.

The National Nuclear Laboratory (NNL), which is operated by a consortium of Serco Battelle and the University of Manchester, carries out some internally funded research, which support its commercial activities. The NNL provides a number of research programmes and operates several leading research facilities. When fully commissioned the facilities at the NNL's Central Laboratory in Sellafield will be world leading and would be ideally suited to supporting fuel cycle RD&D. Part of its remit is to maintain and support UK technical capabilities. A majority of its current business comes from the NDA and Site Licensing Companies (which run NDA owned sites) with 20% coming from British Energy and the MoD. Its main objectives are:

- identify and preserve key nuclear scientific and technical skills and facilities
- lead and integrate UK strategic technology programmes
- provide independent technical advice to the UK Government and its agencies
- operate world class facilities for research
- assist in the development of the market for the provision of nuclear research.

The Research Councils fund a range of nuclear research into technology options, waste management and new ideas. Most of the funding is through the EPSRC, which includes the Keeping the Nuclear Option Open (KNOO) programme, which is a £6.2 million, 4 year programme concluded at the end of April 2010. A follow up programme, has been agreed, Nuclear Fission Consortia call, with funds totalling £7.5m. EPSRC also funds the SPRIng (Sustainability Assessment of Nuclear Power: An Integrated Approach). The EPSRC also fund DIAMOND: Decommissioning, Immobilisation and Management of Nuclear wastes for Disposal programme. The topics for the managed calls are identified through consultation with academics and other stakeholders (including the Nuclear Research Co-ordination Group) and are often supported with industry funding. In addition individual research councils also provide funding through responsive mode schemes, the topic of which is determined by the research group.

### 5.1.1 Decommissioning and legacy waste management

The NDA are responsible for the decommissioning and clean up of the UK's civil nuclear reactors and is the implementation body for delivering a geological disposal facility. The RD&D programme is orientated around supporting research relevant to their activities. The funding is primarily focused at promoting innovation in the supply chain to tackle decommissioning and waste management issues identified by the NDA, but part of the direct funding is focused on engaging the academic community.

The Research Councils also fund waste and decommissioning RD&D mainly through the DIAMOND: Decommissioning, Immobilisation and Management of Nuclear wastes for Disposal programme, which is aimed at addressing gaps in the knowledge and develop novel technologies for waste management. In addition, it funds a number of other posts and activities that are relevant to waste management and geological disposal.

### 5.1.2 Waste management and fuel cycle

The UK has good expertise in this area and globally recognised skills and facilities. However there is no longer a national programme covering the nuclear fuel cycle and unless the UK considers a longer term strategy the RD&D skills and capabilities in this area will be severely depleted in the next decade.

[29] Membership includes: NDA, HSE, Research Councils, Ministry of Defence, National Nuclear Laboratory, Atomic Weapons Establishment, DECC, EDF, Environment Agency and Rolls Royce.

### 5.1.3 Reactor technologies

Since the closure of the UK's fast breeder programme the focus for civil nuclear has been on reactor safety and life extension. Development has also continued for submarine propulsion applications of reactors, there may be opportunities for enhancing the skills and capability for civil developments.

As with the fuel cycle developments, the UK has developed world class skills and expertise in some key areas that are relevant to the global development of nuclear technologies, particularly for Generation IV reactors.

### 5.1.4 Generation IV

The UK currently retains expertise in this area, but does not have an active RD&D programme. The main funding for this area comes from the research councils via the Nuclear Fission Consortia call (the follow on to the KNOO programme) and responsive mode mechanisms. The UK has withdrawn from international programmes to develop Generation IV (see below). As a result it is has limited opportunity to collaborate and to exploit the expertise and capabilities that it has in this area.

UK Strengths – structural graphite and high temperature weld performance could be beneficial to prototype development and in the longer term design and fabrication of commercial Generation III reactors.

### 5.1.5 Proliferation resistance

In addition to developing the fuel cycle and fuel preparation to reduce the risk of proliferation, RD&D is needed to develop detection and forensic capabilities.

In 2009 the government announced its intention of being a global leader on non-proliferation issues and announced the establishment of the Nuclear National Centre of Excellence to support this objective. The NCE, which has yet to be formally established, will not fund RD&D directly but will act as a coordinating body and develop strategies for delivering. Its focus is likely to include the fuel cycle, waste management and disposal issues.

### 5.1.6 Supply chain development

With the advent of a new nuclear build programme there has been renewed support for developing the UK supply chain. A number of initiatives have been put in place that will support and stimulate its development. This is supported by the Nuclear Industries Association, along with the RDA's.

In December 2009 the establishment of the Nuclear Advanced Manufacturing Research Centre (NAMRC) was announced, with £15million coming from the Strategic Investment Fund under the government's Low Carbon Industrial Strategy. A further £8million was allocated to upgrade the nuclear laboratories at Manchester University's Dalton Institute, which will support the NAMRC. The centre is aimed at bringing together university research and industrial expertise to develop manufacturing techniques and components that will meet the demand for new nuclear power stations. The academic lead is Sheffield University with the support of the University of Manchester. Rolls Royce is the lead industry partner with founder members being Areva, Westinghouse, Rolls Royce, EDF and Sheffield Forgemasters. Membership is likely to be expanded as the centre develops. It is aimed at stimulating and supporting the UK supply chain companies, to help them compete with international companies.

Following the withdrawal of the government loan to the Sheffield Forgemasters, it is unclear if the proposal to develop UK capability for ultra-large component manufacture will go ahead.

A recent £2million funding call from the TSB to fund feasibility studies is aimed at attracting new businesses and innovation to strengthen the nuclear supply chain.

# 5.2 International programmes

### 5.2.1 Generation IV International Forum (GIF)

GIF was established in 2002 to help coordinate international activities around the development of Generation IV nuclear fission reactors. It has thirteen members: Argentina, Brazil, Canada, China, France, Japan, South Korea, Russia, South Africa, Switzerland, UK and USA and Euratom. The Forum was established in response to the common interest and benefit of developing Generation IV reactors and to identify areas for collaboration on research.

Six types of nuclear energy system are considered for further development employing different reactor designs and fuel systems. The six systems proposed for study are:

- Very high temperature reactor
  - a graphite-moderated, helium-cooled reactor with a once-through uranium fuel cycle;
- Supercritical water cooled reactor
  - a high-temperature, high-pressure water-cooled reactor that operates above the thermodynamic critical point of water;
- Gas-cooled fast reactor
  - a high-temperature, high-pressure water-cooled reactor that operates above the thermodynamic critical point of water;
- Sodium cooled fast reactor
  - features a fast-spectrum, sodium-cooled reactor and closed fuel cycle for efficient management of actinides and conversion of fertile uranium;
- Lead cooled fast reactor
  - features a fast-spectrum lead of lead/bismuth eutectic liquid-metal-cooled reactor and a closed fuel cycle for efficient conversion of fertile uranium and management of actinides;
- Molten salt reactor
  - produces fission power in a circulating molten salt fuel mixture with an epithermal-spectrum reactor and a full actinide recycle fuel cycle.

In addition, cross-cutting work focuses on the economics, risk and safety as well as proliferation resistance and physical protection.

The UK was an original signatory to the Forum and agreed to participate and share in the research programmes. However, in 2006 the UK withdrew from active status in GIF, to become an observer, and withdrawing UK Government funding for UK researchers to participate in GIF activities. This prevents UK researchers and GIF participants from sharing facilities under the GIF programmes.

Russia, China and India all have active nuclear programmes and are developing Generation IV reactors.

**US nuclear RD&D programme**

The US RD&D programme is managed by the Office of Nuclear Energy in the Dept of Energy. Its main objectives are:

- Extend the useful life of existing nuclear power plants;
- Enable new plants to be built through its Nuclear Plant 2010 (NP2010) Program;
- Reduce the carbon footprint of transportation and industry. This looks at the options for co-generation of process heat and hydrogen from very high temperature reactors. This is led by the Next Generation Nuclear Plant (NGNP) initiative, which is part of the Generation IV program;
- Develop a sustainable fuel cycle through a Fuel Cycle Research and Development Program that addresses issues of radiotoxicity, recycling, and creating widely acceptable solutions to the challenges of nuclear waste;
- Prevent proliferation. Developing techniques and materials to prevent proliferation are addressed of the Fuel Cycle Research and Development program.

The programme is reviewed by the Nuclear Energy Advisory Committee. A recent review made the following recommendation with respect to the US nuclear programme: "To terminate our planning horizon at 2030 would be a serious mistake. New concepts can take many decades to go through laboratory-scale and engineering-scale development before getting to commercial scale."

### 5.2.2 European Energy Research Alliance

EERA has established a programme on nuclear RD&D. The primary focus for the collaborative projects is on materials for Generation IV nuclear fission. Exact projects have yet to be identified, but short-term proposals relating to the FP7 and a longer term strategy are being considered.

The Research Councils have been encouraging towards participation of UK funded research in EERA collaborative programmes, particularly where this will add value to existing programmes. This may lead to modification of existing project plans, which the Councils have stated they are prepared to consider on a case-by-case basis. Additional funding may also be required and will be considered, but this will have to be applied for in competition with other research proposals.

As noted in ERP's international engagement work, while it is positive that participation in EERA coordinated projects is recognised as being beneficial, it is too early to say how the process will work in reality and how long it will take.

### 5.2.3 Euratom

Euratom was established through a Treaty in 1957 with the aim of harmonising nuclear resources and research activities across the European members. This includes pooling knowledge and infrastructure and funding, but also ensuring security through a framework of centralised monitoring. It is legally separate from the European Community and has its own research framework programme.

The broad aims of the Euratom research programme is to develop and assemble knowledge and to improve scientific and technical competences and know-how in support of safety, security, reliability, sustainability and cost-effectiveness of nuclear energy. It funds research in both nuclear fission and fusion.

UK researchers and industry participate successfully in Euratom projects. Some of the key benefits participation provides are access to facilities, a pooling of knowledge and being able to address the wider research picture. In addition, it provides an opportunity to promote the expertise of UK organisations.

Euratom also has programmes relating to Generation IV, but these are difficult for UK researchers to access as there are no national programs on Gen IV with which to contribute funding or coordinate activities.

### 5.2.4 Sustainable Nuclear Energy – Technology Platform

Established in September 2007, the SNE-TP is a European technology platform that promotes RD&D into nuclear fission technologies. It has a membership of about 70 European stakeholders from industry, research and academia, technical safety organisations and non-governmental organisations.

In 2009 it published its Strategic Research Agenda which aims to set out a basis for joint research priorities, with the aim of supporting the ambitions for nuclear fission in the SET plan. The key priorities are:

- To maintain the competitiveness of existing and future Light Water Reactors;
- Develop advance fuel cycles for waste minimisation and resource optimisation;
- Develop Generation IV fast reactors with a closed fuel cycle. With primary emphasis on Sodium Fast Reactors and a secondary system of either a lead or gas cooled fast system;
- Alternative nuclear energy systems capable of producing process heat as a co-product from High Temperature and Very High Temperature reactor systems;
- Developing competences and research infrastructure.

The SRA sets out roadmaps for the development of these technologies with key milestones that need to be achieved. The development and construction of prototypes and demonstration reactors is the objective of the nuclear European Industrial Initiative (EII).

### 5.2.5 European Industrial Initiative (EII) and the EU Generation IV roadmap

The long-term sustainability of nuclear energy is the main driver of the European Industrial Initiative (EII) on nuclear fission. In particular, the EII is focused on enabling the commercial deployment of Generation-IV nuclear reactors by 2040. Two reactor concepts are included in the EII: a prototype sodium cooled fast reactor (SFR), which will be coupled to the electricity grid, and a demonstrator reactor of an alternative fast neutron design, either lead or gas cooled, not coupled to the grid. The decision on whether to favour the lead or gas cooled reactor as the alternative technology will be taken around 2012 on the basis of the conclusions of research programmes currently on-going.

In addition, the initiative will design and construct pilot fuel fabrication facilities to produce the fuel for both demonstration plants by the start of their operation in 2020, as well as all the necessary supporting research infrastructures for such a programme of advanced reactor design and construction. Operation of the prototype and demonstrator reactors from 2020 will allow a return of experience that, coupled with further RD&D, will enable commercial deployment starting from 2040.

At the same time, a coordinated programme of cross-cutting research will be conducted in all aspects of nuclear reactor safety, performance, lifetime management, waste handling and radiation protection to serve both the development of future Generation IV reactors but also the continued safe and competitive operation of current nuclear plants that in 2005 provided 30% of EU electricity (15% of total energy demand). The cost of the Initiative is estimated at €5-€10 billion over the next ten years.

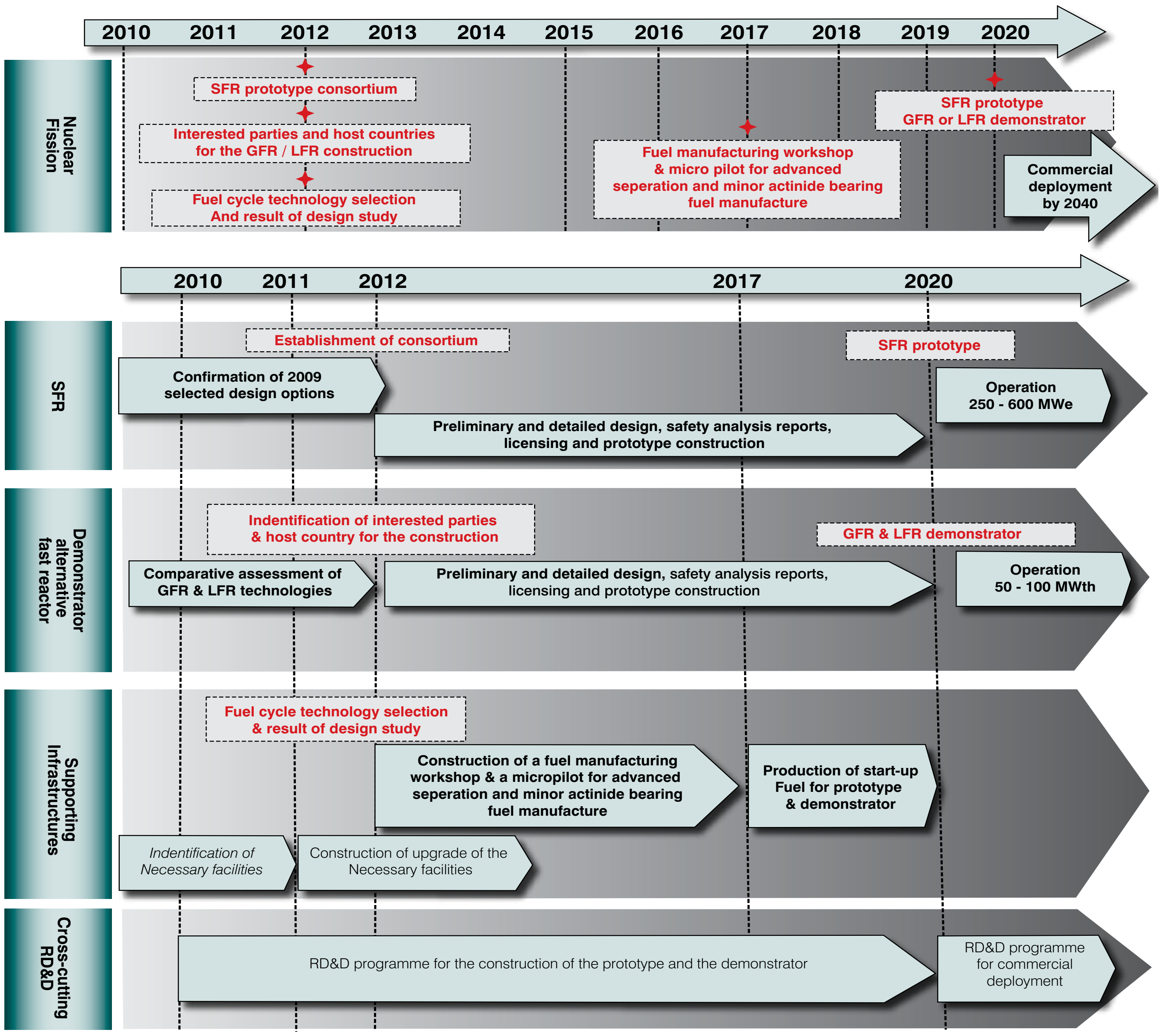


*Figure 5.1 European roadmaps for nuclear technology development EC(2009)[30]*

The European Industrial Initiative on Sustainable Nuclear Energy technology has set out a number of technology objectives to be achieved to deliver a commercial reactor by 2040. The Sodium Fast Reactor is considered the reference technology for fast neutron reactors. The objectives are:

1. Through the design, construction and operation of a prototype sodium fast reactor and of an alternative technology (either gas or lead cooled fast reactor), demonstrate that fast neutron reactors:
   - are able to exploit the full energy potential of uranium by extracting up to 100 times more energy than current technology from the same quantity of uranium;
   - have the ability to 'burn' (i.e. eradicate though nuclear transmutation in the reactor) the 'minor actinides' produced in the fuel during reactor operation by recycling these minor actinides in fresh fuel, and in so doing significantly reduce quantities, heat production and (by factors of up to 1000) hazardous lifetime of the ultimate waste for disposal;
   - attain safety levels at least equivalent to the highest levels attainable with Generation II and III reactors;
   - eliminate proliferation risks by avoiding separation of weapon's grade fissile material at any point during the fuel cycle;
   - can attain levelised electricity and heat production costs on a par with other low carbon energy systems.

[30] European Commission COM(2009) 519 final, Investing in the Development of Low Carbon Technologies (SET-Plan)- A TECHNOLOGY ROADMAP.

2. The refurbishment and/or design, construction and operation of infrastructures needed to support the design and/or operation of prototype and demonstrator FNRs, in particular:

- fuel fabrication facilities to develop and manufacture driver fuel and minor actinide bearing fuels for the prototype and demonstrator;
- facilities for the development of materials and components, code validation and qualification, and design and validation of safety systems.

3. A comprehensive programme of RD&D supporting all aspects of the design, construction and operation of the prototype, demonstrator and support infrastructure. Cross-cutting RD&D will also benefit current reactors in terms of maintaining safety and radiation protection, increasing performance and competitiveness, ensuring lifetime management, and implementing solutions for waste management.

# 6 Conclusions and recommendations

There are three main drivers for nuclear fission RD&D in the UK; energy supply and associated skills provision, opportunities to exploit the growing global market and the UK's ambitions under the Non-Proliferation Treaty. The emphasis that is put on each will affect the RD&D agenda, although there is considerable overlap between the RD&D programmes to support these objectives and they will be largely complementary.

The existing RD&D programmes are likely to be sufficient to support the current plans for new build to replace current generating capacity. However, any major expansion of the generating capacity, or ambitions in either exploit the global market opportunities or in leading in non-proliferation programmes will require an enlarged RD&D programme.

One of the most significant questions is the UK's role in the development of future reactor and fuel cycle technologies. The long timescales and high costs mean that these are mainly multi-national collaborative programmes, which the UK currently only holds an observer status. The UK has expertise and facilities that it can contribute to these programmes and engagement would be beneficial to most of the UK's ambitions. This would help develop alternative waste management options for an enlarged nuclear generation programme, it would explore new technologies for secure and proliferation fuel cycles and also provide opportunities to sell into the global market.

A roadmap for how UK RD&D should develop is therefore needed. The development of a roadmap should involve a broad range of stakeholders including the NDA, NNL, RCs, TSB, FCO, industry (both generators and supply chain) and regulators. Its development should be coordinated by an organisation such as the National Nuclear Centre of Excellence, which is currently operating in shadow mode.

However, guidance is needed as to the UK's long-term ambitions for nuclear fission, in terms of the three drivers.This will inform the direction of the roadmap and give confidence to the stakeholders and investors involved. Part of this may be that the UK will remain an informed customer and will buy in the technology as required.

In the absence of a roadmap and an indication of the long term nuclear ambitions, the current RD&D programme should ensure that it is able to support the necessary skills development for the planned new build programme. The RD&D programme should also ensure that there is a transfer of knowledge from individual experts who are due to retire, in order to retain the experience from the UKs earlier advanced reactor and fuel cycle programmes.

This report has made no attempt to quantify the scale of effort and resource that will be necessary to deliver the various RD&D programmes. This is, in part, beyond the expertise of the resource available to ERP, but also is almost impossible in the absence of a clear plan and roadmap.

It is important to note that nuclear fission is not a technology which can be left solely to the market and diverse individual company interests. Nuclear technology is one of the few technologies where the assets invested in today and over the coming two decades will persist in a post 2050 era through to 2100.

# Recommendations

A long-term strategy is needed for the development of nuclear power in the UK, combined with a detailed roadmap for the development of nuclear RD&D. This is a priority to inform decisions about RD&D, the development of which will be determined by how the UK chooses to address a number of key issues. These include:

1. The long term role of nuclear generation in the UK and the potential need to develop new fuel cycle and reprocessing technologies.
2. Capitalising on the growing international deployment of nuclear fission: Selling fuel cycle technologies and services into the international market, developing an industrial base and contributing to the development of key technologies.
3. Defining the UK's role in non-proliferation debates which will require supporting RD&D to inform positions and support international developments.

Given the long lead times and development plans for these technologies, the roadmap should go out to 2050 and beyond. This is a matter of urgency and needs to happen by 2012. Without a clear plan to guide investment the UK is at risk of losing its world renowned expertise.

There is a strong business case for a healthy and vibrant research base in the UK that would support the national nuclear programme and provide the necessary skills, but would also provide benefit from exploiting the growing global market. To support the development of this research base the UK needs to be involved in international RD&D programmes, particularly for Generation IV and advanced fuel cycle systems. Such programmes include the European Generation IV programme in the SET plan and the international Generation IV Forum (GIF). Involvement in these programmes provides low cost access to technologies that will complement existing skills and expertise and will provide credibility to the UKs international ambitions.

Some of the new Generation IV reactor designs include small, high temperature reactors that could cogenerate heat for industrial processes as well as electricity. These reactors are expected to be available before 2030 and could be used to displace fossil fuel based energy production. A review should be carried out to assess the potential of this technology to reduce emissions in the UK. This will help inform the RD&D roadmap.

The UK should also develop an industrial strategy for the development of nuclear power in the UK. Developing a strong research base and defining a long term nuclear strategy will encourage inward investment. This should go beyond developing the supply chain to considering attracting the major technology companies. Such a strategy will also inform the RD&D roadmap. An important part of the strategy and roadmap is engaging the public to help inform decisions about how the technology should develop. This should be considered in the wider context of addressing the UK's energy and climate change challenges.

The development of the roadmap should be 'owned' by DECC and involve a broad range of bodies, including industry, supply chain companies, utilities, developers, academic and research bodies, and government departments. The work could have been led by the National Nuclear Centre of Excellence (NNCE), which is currently operating in shadow mode, in association with the National Nuclear Laboratory, given their strategic position. However, the future of this entity in its current form is in doubt, although the NNL together with the University of Manchester and Imperial College have expressed willingness to continue the work on priority topics, with funding sought from those departments directly interested on a topic by topic basis. NNL could therefore take the lead, with DECC taking overall 'ownership'.

ERP could support this work to ensure that nuclear energy RD&D needs are set within the context of an overarching understanding of the UK's evolving energy landscape. It is recommended that in addition to the development of a long-term strategy the following issues need to be considered:

- The demand for a skilled workforce across the various generating technologies, particularly where the sectors may be competing for similar or transferable skills, such as project management, electrical engineers and construction.
- How the proposed generating capacity integrates into the energy system, particular the provision of a flexible supply.
- The socio-economic and environmental impacts of the technology and how the public will interact with it.

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**Energy Innovation Milestones to 2050 – March 2010**

Analysis setting out how and when selected new energy technologies are expected to develop and what the key innovation challenges are to their deployment. This study reviewed a wide range of public and private sector energy scenarios to 2050 – to explore where they agree or diverge and where critical decision points will be.

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**ERP report on Heat Workshop – January 2009**

The Energy Research Partnership, Energy Technologies Institute and Royal Academy of Engineering organised a workshop to examine the role of heat in the UK's energy system. Heat accounts for about half of the UK's current $CO_2$ emissions and was the subject of a consultation by Government. The workshop was designed to raise the level of thinking on heat as an issue, help guide ETI's future work on heat, and inform participants' responses to the consultation.

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