Research Councils UK Energy Programme Strategy Fellowship

ENERGY RESEARCH AND TRAINING PROSPECTUS: REPORT NO 9

NUCLEAR FISSION

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Research Councils Energy Programme

The Research Councils UK (RCUK) Energy Programme aims to position the UK to meet its energy and environmental targets and policy goals through world-class research and training. The Energy Programme is investing more than £625 million in research and skills to pioneer a low carbon future. This builds on an investment of £839 million over the period 2004-11.

Led by the Engineering and Physical Sciences Research Council (EPSRC), the Energy Programme brings together the work of EPSRC and that of the Biotechnology and Biological Sciences Research Council (BBSRC), the Economic and Social Research Council (ESRC), the Natural Environment Research Council (NERC), and the Science and Technology Facilities Council (STFC).

In 2010, the EPSRC organised a Review of Energy on behalf of RCUK in conjunction with the learned societies. The aim of the review, which was carried out by a panel of international experts, was to provide an independent assessment of the quality and impact of the UK programme. The Review Panel concluded that interesting, leading edge and world class research was being conducted in almost all areas while suggesting mechanisms for strengthening impact in terms of economic benefit, industry development and quality of life.

Energy Strategy Fellowship

The RCUK Energy Strategy Fellowship was established by EPSRC on behalf of RCUK in April 2012 in response to the international Review Panel's recommendation that a fully integrated 'roadmap' for UK research targets should be completed and maintained. The position is held by Jim Skea, Professor of Sustainable Energy in the Centre for Environmental Policy at Imperial College London. The main initial task is to synthesise an Energy Research and Training Prospectus to explore research, skills and training needs across the energy landscape. Professor Skea leads a small team at Imperial College London tasked with developing the Prospectus.

The Prospectus contributes to the evidence base upon which the RCUK Energy Programme can plan activities alongside Government, research, development and demonstration (RD&D) funding bodies, the private sector and other stakeholders. The Prospectus highlights links along the innovation chain from basic science through to commercialisation. It is intended to be a flexible and adaptable tool that takes explicit account of uncertainties so that it can remain robust against emerging evidence about research achievements and policy priorities.

One of the main inputs to the Prospectus has been a series of four high-level strategic workshops and six in-depth expert workshops which took place between October 2012 and July 2013. The main report, **Investing in a brighter energy future: energy research and training prospectus**, was published in November 2013. This is one of nine topic-specific documents supporting the main report. All reports can be downloaded from: www3.imperial.ac.uk/rcukenergystrategy/prospectus/documents/reports. This first version of the Prospectus will be reviewed and updated on an annual cycle during the lifetime of the Fellowship, which ends in 2017.

This report is the product of work conducted independently under EPSRC Grant EP/K00154X/1, Research Councils UK Energy Programme: Energy Strategy Fellowship. While the report draws on extensive consultations, the views expressed are those of the Fellowship team alone.

Contents

Executive Summary

This report covers research into nuclear fission, including research in reactor design and construction, operation and maintenance, the fuel cycle and reprocessing, decommissioning and clean-up and long-term storage of waste. This area has been the subject of a number of substantial reviews in recent years, including a comprehensive long-term strategy developed by government in association with industry. The Fellowship team therefore decided to carry out a 'light-touch' prospectus report in this area, in order not to duplicate already-existing work. A one-hour session was held at the 2nd meeting of the Nuclear Universities Consortium for Learning, Engagement and Research (NUCLEAR) consortium to engage with researchers, test preliminary conclusions from workshops covering other areas of energy research and identify areas in which research support could be improved. The conclusions of this meeting, along with a review of currently-available research frameworks, form the bulk of this report.

Key points arising from the workshop discussion and review of roadmaps and research frameworks include:

- While national coordination in the sector has improved greatly in recent years, international collaboration does not take place according to an overarching framework or goal structure, and no single organisation or advisory group has responsibility. In particular, greater European engagement should be encouraged, helping UK researchers to gain a greater proportion of research resources and the UK to have a greater influence on the direction of European research.
- As in many other energy research areas, the adoption of Centres for Doctoral Training (CDTs) has provoked a mixed response. Nuclear researchers seem more positive towards CDTs than in other areas, due in part to the multi-university structure of nuclear fission CDTs. However, it was felt that CDTs needed to be less narrowly focused to allow more niche research areas to be included, and that PhD students attached to large programme grants would add value both for the student and for the grant.
- Nuclear research tends to take place over very long timescales, and research into a new generation of reactors will be a very long-term goal. Policymakers and the Research Councils will need to take this into account if the ambitious goals outlined in the Industrial Strategy are to be accomplished. A research portfolio robust against political uncertainty and covering a range of UK nuclear futures should be considered.
- Access to international databanks and facilities is very important. Care should be taken to ensure that UK researchers can access these important international resources.
- Skills in the nuclear sector are often multi-domain, and incorporate a range of disciplines. This needs to be fully accounted for when considering cross-council projects and overarching joint programmes. Skills and training programmes should be benchmarked against the skills UK industry requires in order to ensure that researchers can work on industrial projects where necessary.

Acronyms

2DS	two degree scenario
ABWR	advanced boiling-water reactor
AGR	advanced gas-cooled reactor
BBC	British Broadcasting Corporation
BBSRC	Biotechnology and Biological Sciences Research Council
BIS	Department for Business, Innovation and Skills
CASE	Collaborative Awards in Science and Engineering
CCS	Carbon Capture and Storage
CDT	Centre for Doctoral Training
DECC	Department of Energy and Climate Change
DOE	Department of Energy (US)
EPSRC	Engineering and Physical Sciences Research Council
EPR	European Pressurised Reactor
ESRC	Economic and Social Research Council
ETI	Energy Technologies Institute
ETP	Energy Technology Pathways
FIRST	Nuclear Fission Research, Science and Technology Centre
FTE	full-time equivalent
GHG	greenhouse gases
GW	gigawatt
IAEA	International Atomic Energy Agency
IEA	International Energy Agency
LC	low carbon (an energy scenario)
LCICG	Low Carbon Innovation Coordination Group
MARKAL	MARKet ALlocation (an energy system model)
MWh	megawatt-hour
NUCLEAR	Nuclear Universities Consortium for Learning, Engagement And Research
NCIL	no clear international lead
NEA	Nuclear Energy Agency
NERC	Natural Environment Research Council
NIRAB	Nuclear Innovation and Research Advisory Board
NIRO	Nuclear Innovation and Research Office
NNL	National Nuclear Laboratory
NRCG	Nuclear Research Coordination Group
PWR	pressurised water reactor
R&D	research and development
RCUK	Research Councils UK
RD&D	research, development and demonstration
REF	reference (an energy scenario)

SMR	small modular reactor
STFC	Science and Technology Research Council
TINA	Technology Innovation Needs Assessment
TWh	terawatt-hour
UKERC	UK Energy Research Centre

1. Introduction

This document is one of a series of reports that sets out conclusions about UK research and training needs in the energy area. The focus of this report is nuclear fission. The primary audience is Research Councils UK (RCUK) which supports energy research in UK higher education institutions through the RCUK Energy Programme (RCEP).[1] However, other bodies involved in funding energy research and innovation, notably those involved in the UK's Low Carbon Innovation Carbon Group (LCICG)[2] may also find the content useful. The report is also being disseminated widely throughout the UK energy research and innovation community to encourage debate and raise awareness of the work conducted under the Fellowship.

The most important input to this report has been a session held at the 2nd Nuclear Universities Consortium for Learning, Engagement and Research (NUCLEAR) meeting at the University of Birmingham on the 19 September 2013. This meeting brought together academics from across the UK to interact, build common research communities, provide support to industry and government stakeholders and promote international activities. This meeting was attended by over 70 academics and other stakeholder representatives covering nuclear fission and fusion.

This subject of **Nuclear Fission** is one of three Prospectus areas[3] where a light-touch approach has been taken. This is because, in this case, the quantity and quality of recent research needs and roadmaps in this area were felt to be sufficient and that therefore the Fellowship did not need to run a full two-day workshop. The UK review of Nuclear Industrial Strategy[4] led by Government Chief Scientist Sir John Beddington, published in 2013, forms an important part of the evidence base for future research priorities, and the Fellowship saw no need to duplicate this work. The session therefore concentrated on training, connections and research support needs for the nuclear fission research area.

The Prospectus responds to a recommendation of the 2010 International Panel for the RCUK Review of Energy[5] that the research supported by the Research Councils should be more aligned with the UK's long-term energy policy goals. The key criteria used in developing this report have been the three pillars of energy policy – environment, affordability and security – coupled with potential contributions to UK growth and competitiveness.

The Fellowship team is using the EU/International Energy Agency (IEA) energy research and development (R&D) nomenclature[6] to map out the energy research landscape. This report covers Area IV, the nuclear fission sector.

This report is structured as follows. Sections 2-4 provide the wider context within which research and training challenges are identified. Section 2 focuses on the possible role of nuclear fission in future energy systems both globally and in the UK. Section 3 describes the current UK research landscape and capability levels. Section 4 reviews existing roadmaps and assessments of research and innovation needs.. Section 5 focuses on the ways in which the Research Councils operate, how the research they support is conducted and underlying needs for research infrastructure and data collection/curation. Many of the conclusions are generic in the sense that they may be applicable across the energy domain or even more widely. Section 6 addresses training provision. Section 7 addresses generic

[1] http://www.rcuk.ac.uk/research/xrcprogrammes/energy/Pages/home.aspx
[2] http://www.lowcarboninnovation.co.uk/
[3] The others are **Wind, Wave and Tide** and **Nuclear Fission**
[4] HM Government, **'Nuclear Industrial Strategy: The UK's Nuclear Future'**, 2013, https://www.gov.uk/government/collections/nuclear-industrial-strategy
[5] http://www.epsrc.ac.uk/SiteCollectionDocuments/Publications/reports/ReviewOfEnergy2010PanelReportFinal.pdf
[6] http://ec.europa.eu/research/energy/pdf/statistics_en.pdf

issues about the role of the Research Councils within the wider UK energy innovation system and EU/international engagement.

2. Current and future role of nuclear fission in the energy system

2.1 Global nuclear fission perspectives

Nuclear reactors have been used to supply power commercially since 1956. Nuclear fission reactors commonly supply base-load power to the energy system, as it is difficult to vary electricity output quickly and easily. In 2012, the installed capacity of nuclear power stations totalled 375 gigawatt (GW), providing about 5.7% of the world's primary energy and about 13% of electricity generated globally.[7] This is unevenly distributed between nations – the US, France and Japan together generated more than half the global total in 2010. Nuclear fission is a low-carbon energy source, and a review of life-cycle analyses for nuclear reactors found lifetime carbon emissions which were comparable to major renewable generation technologies.[8] However, due to public perception issues surrounding reactor safety and disposal of nuclear waste, nuclear power has had difficulty finding acceptance in many nations.

Nuclear fission reactors are split into three generations, relating to time of construction and operational features. Generation I reactors refer mostly to early, often prototypical reactors. Generation II reactors brought in the widespread commercialisation of nuclear power, and were built globally until the 1990s. Generation III reactors are evolutionary advances of Generation II designs, adding superior fuel and thermal efficiency, passive safety systems and longer operational lifetimes. Generation III reactors are the most modern designs available to be built commercially. Generation IV nuclear reactors refer to several theoretical future reactor designs, considered technically feasible but still requiring extensive R&D work to become commercially available. The set of these designs have the potential to produce smaller quantities of waste, utilise larger fractions of the available nuclear fuel and should provide greater operational safety. Generation IV reactors are not expected to be built for commercial purposes until at least the 2030s.

The Fukushima disaster caused by the Great East Japan Earthquake in March 2011 led to many countries scaling back or abandoning their nuclear power ambitions, with Germany pledging to close all its nuclear plants by 2022, and Japan currently considering its long-term nuclear policy. Other nations are however embarking on new nuclear build programmes, with China currently constructing 25 reactors, and new Generation III reactors planned or under construction in the US, UK, Finland and France.

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[7] IEA, 'Key World Energy Statistics 2012', https://www.iea.org/publications/freepublications/publication/kwes.pdf

[8] National Renewable Energy Laboratory, 'Life-cycle Assessment Harmonization', 2011, http://www.nrel.gov/analysis/sustain_lcah.html

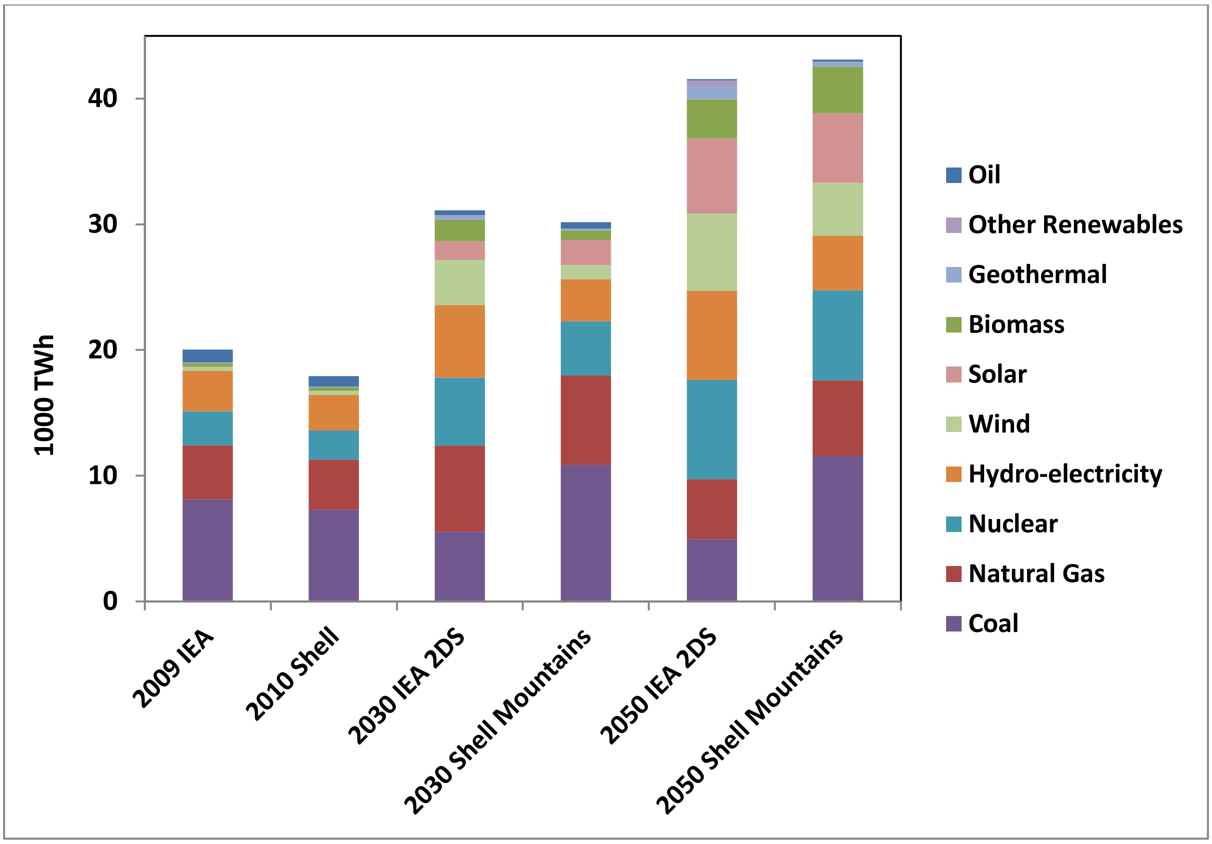

Figure 1: Global electricity production in 2030 and 2050 by type

A comparison of two scenarios modelling future global electricity capacity was made to elicit viewpoints on the deployment of nuclear power out to 2050. The two scenarios compared were the IEA's 2012 Energy Technology Perspectives (ETP) 2 degrees scenario (2DS),[9] which is a normative scenario, and the Mountains scenario from Shells New Lens Scenarios,[10] which is exploratory. In both of these scenarios, nuclear power increases as a percentage of the total global electricity mix by 2050, increasing from 13.5% to 19% in the 2DS scenario and from 12.8% to 19% in the Shell Mountains scenario.

2.2 UK nuclear fission perspectives

The UK has a long history of nuclear fission development and deployment. In 1956, the UK began operating the first commercial-scale nuclear reactor in the world, at Calder Hall. However, since then several older reactors have closed, and in 2013 the UK generated about one sixth of its electricity from nuclear fission, from 16 operational reactors. These consist of one Magnox reactor, 14 advanced gas-cooled (AGR) reactors and one pressurised water reactor (PWR). In 2012, the UK was the tenth largest producer of electricity from nuclear fission, producing approximately 62 terawatt-hours (TWh) from an installed capacity of 11GW. By 1997, the UK was generating 26% of its electricity from nuclear sources. Many of the current reactors are reaching the end of their operational lives, and in the absence of life extension orders by 2023 only the PWR reactor at Sizewell B will still be commercially generating electricity.

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[9] IEA, **'Energy Technology Perspectives 2012'**, http://www.iea.org/etp/

[10] Shell, **'New Lens Scenarios'**, 2013, http://www.shell.com/global/future-energy/scenarios/new-lens-scenarios.html

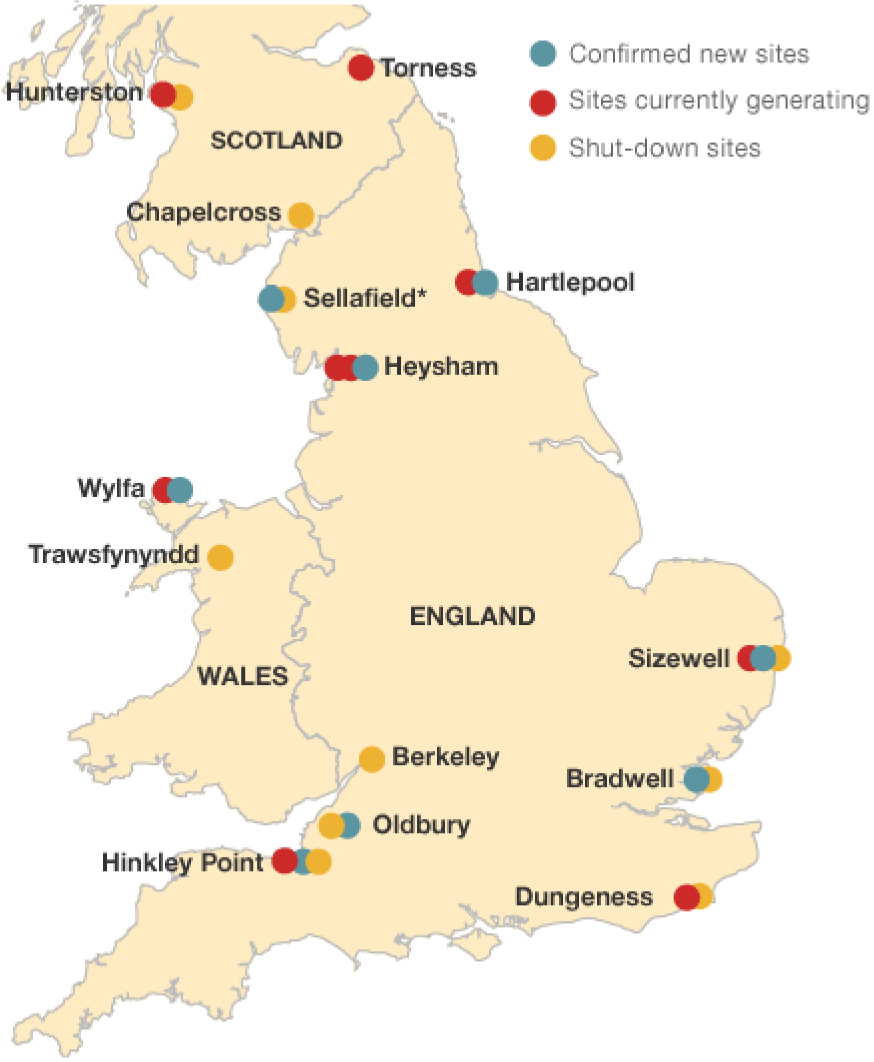

Figure 2: Existing and proposed sites for nuclear power stations in the UK. (Source: (BBC)/ (DECC))

There has been significant debate and discussion around the future of nuclear fission as part of the UK's future energy mix. Most UK energy scenarios that achieve an 80% greenhouse gas emissions reduction by 2050 show a large percentage of nuclear generation as an important part of the lowest-cost energy mix.

Two scenario sets were consulted to gain a picture of the UK's possible range of energy futures. The first was the revised UK Energy Research Centre (UKERC) Energy **2050** scenario set,[11] which used the UK MARKet ALlocation (MARKAL) model,[12] a bottom-up, technology-rich cost optimisation model. The two scenarios reviewed from this set were the reference (**REF)** scenario, which assumes that current policies extend into the future and a low-carbon (**LC)** scenario, which is compatible with the 2050 greenhouse gases (GHG) target. Current policies in **REF** include the assumption that the carbon price floor will rise to £30/tonne of CO_2 by 2020 and £70/tonne by 2030 in line with government intentions at the time. This provides a significant incentive for low carbon technologies even in the absence of other measures.

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[11] UKERC, **'Energy 2050 Scenarios: Update 2013',** http://www.ukerc.ac.uk/support/ES_RP_UpdateUKEnergy2050Scenarios

[12] UCL Energy Institute, **'UK MARKAL model',** http://www.ucl.ac.uk/silva/energy-models/models/uk-markal

The second scenario set was the Department of Energy and Climate Change (DECC) 2050 Pathways Calculator[13], which produces a scenario based on the consequences of technology deployment assumptions specified by the user. The two scenarios presented here are from the Ref Pathway, which assumes no significant low-carbon deployment beyond that dictated by current policy measures, and the Alpha pathway, which aims for an 80% CO_2 reduction in the UK using a balanced mix of technologies.

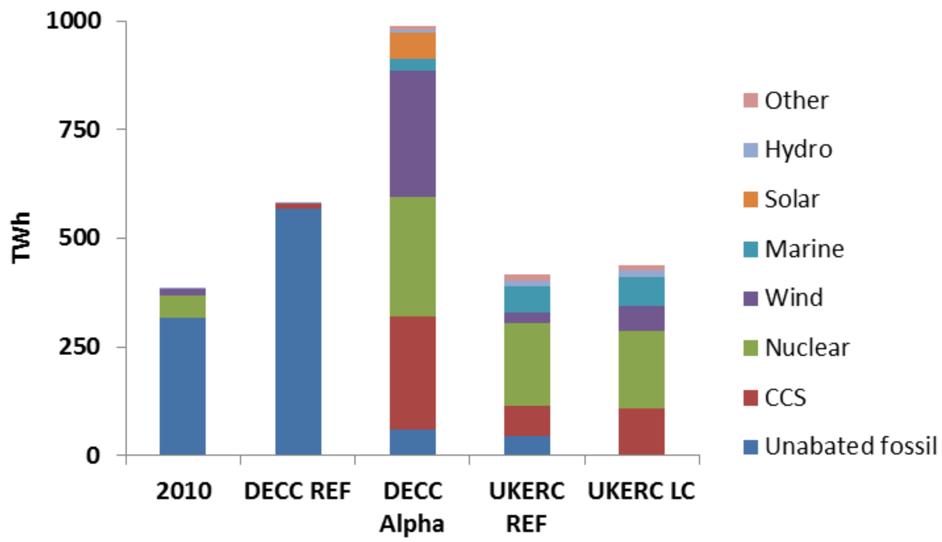

Figure 3: UK Electricity generation by type in 2050

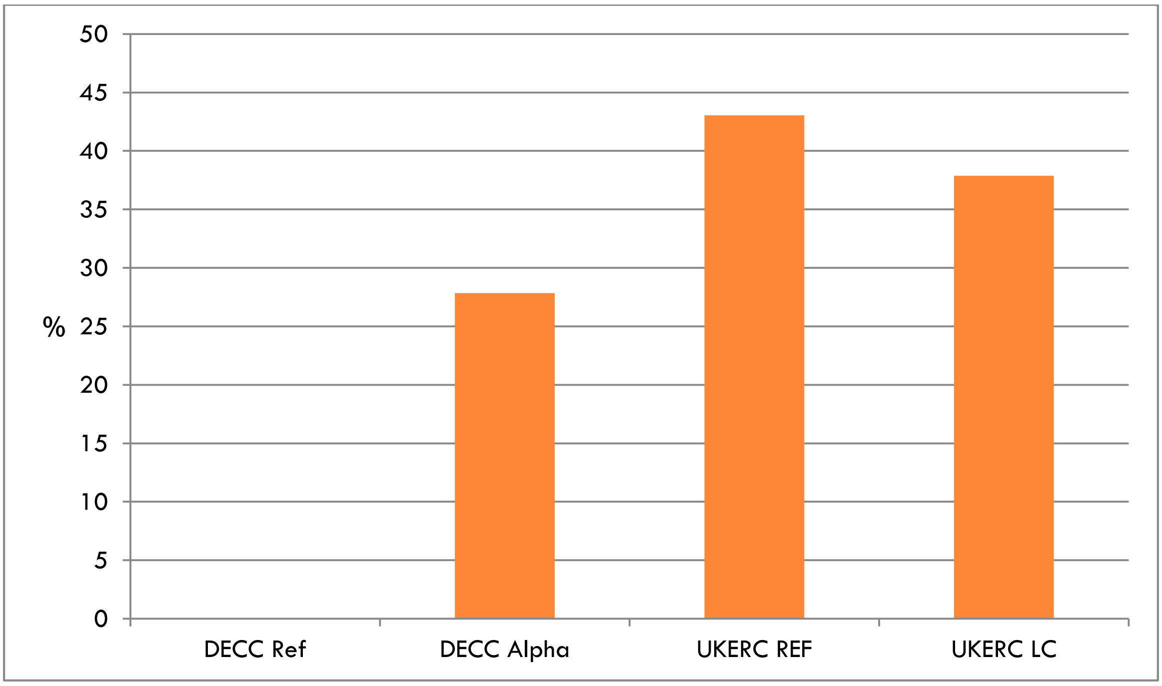

Figure 4: Percentage of total electricity generated by nuclear fission by 2050

As shown in Figure 3, nuclear power contributes the largest source of generated electricity in the UK in 2050 for both the central DECC Alpha and UKERC LC scenarios. The DECC Ref scenario assumes no new build of nuclear plant goes ahead, with the UK's existing plants being decommissioned by this time.

[13] DECC, **'2050 Pathways Calculator Analysis'**, https://www.gov.uk/2050-pathways-analysis

Unlike renewable energy, which tends to provide intermittent and variable output, nuclear power can provide base-load capability. This gives nuclear power an important potential role in a low-carbon energy mix, as the only other large-scale low-carbon base-load technologies are carbon capture and storage (CCS)-fitted fossil fuel plants. These scenarios project between 24-40GW of installed nuclear capacity by 2050, providing 250-400 terrawatt-hours (TWh) a year of electricity.

The UK government decided in 2008, after several years of public consultations, to permit up to eight new nuclear power stations to be built in England and Wales. Five sites have currently been earmarked for development, at Hinkley Point, Sizewell, Wylfa, Oldbury and Moorside. This would potentially add 16GW of nuclear generating capability by 2030, although these plans have been criticised by many commercial and policy stakeholders as extremely ambitious. The 2013 Energy Bill has introduced guaranteed strike prices for new low-carbon generation which many have seen as an implicit subsidy for nuclear generation. The current Scottish government has forbidden the construction of new plants in Scotland.

In October 2013, a consortium led by EDF Energy reached a deal with the government, still subject to contract, to build two new European Pressurised Water Reactors (EPRs) at Hinkley Point with a capacity of 3.2GW, with a guaranteed strike price of £92.50/megawatt-hour (MWh) for generated electricity. This strike price will fall to £89.50 if a similar set of EPR reactors at Sizewell are approved and brought forward by EDF. The other major commercial player in new-build plant in the UK is the Hitachi-owned Horizon venture, which is investigating building Japanese-developed Advanced Boiling Water Reactors (ABWR) at Wylfa in Wales. Horizon was brought by Hitachi after its founding owners E.ON and RWE pulled out of nuclear new build in the UK following the Fukushima disaster and Germany's decision to move away from nuclear power.

2.3 Nuclear energy goals and expectations

At the Fellowship strategy workshop **Energy strategies and energy research needs**, participants were invited to consider various key features of a future UK energy system. In the first session, they were asked to specify what technology mix they **wanted** to see in 2050 (aspiration) and what they **expected** to happen, given their knowledge of barriers, policy directions, technology limitations and other factors. In general, people's aspirations were aligned with a world in which a great deal of progress was made towards reaching climate goals. However, they 'expected' much slower progress to be made in deploying low carbon technologies in practice. Nuclear fission was considered to be a significant player in a low-carbon energy future, with participants **wanting** to see approximately 20% market share by 2050 and **expecting** a very similar amount. Although predictions were lower than for CCS and offshore wind, the other two 'big' low-carbon technologies, it was clear that participants foresaw nuclear fission providing a greater role in the UK's electricity mix in 2050 than at present.

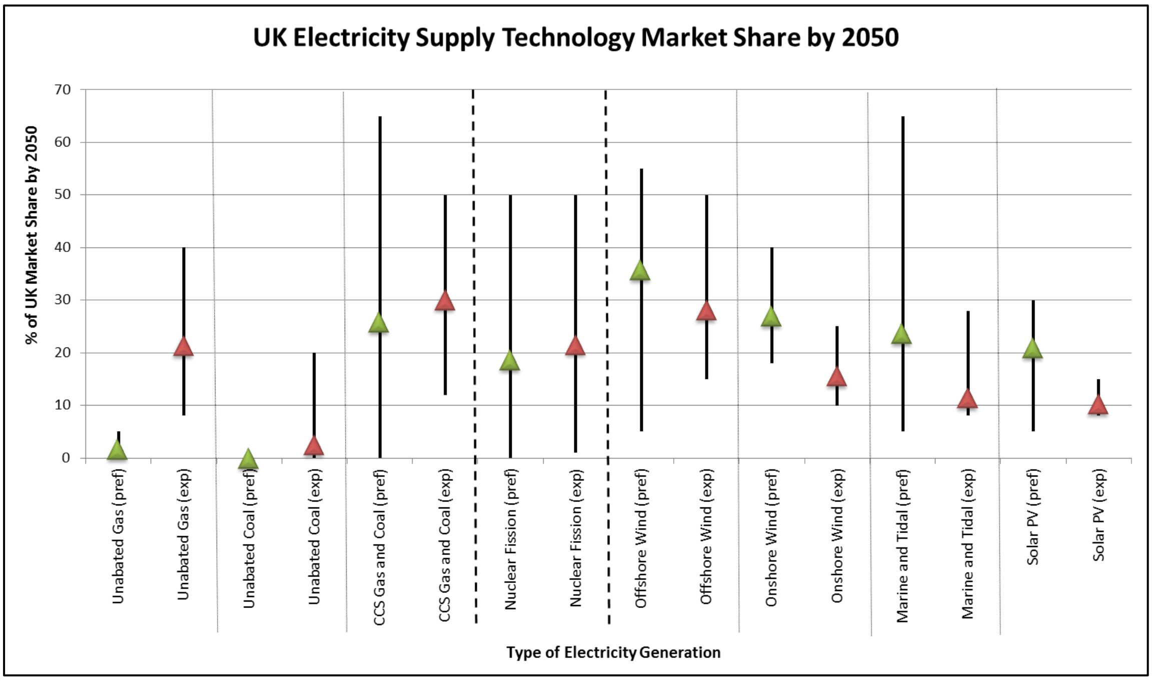

Figure 5: Preferred (green) and expected (red) ranges and mean average values for electricity supply technologies (RCUK Energy Strategy Fellowship Strategic Workshop 1)

3. UK Research Capabilities

3.1 Strategic Workshop

Figure 6, below, was the output of the second session of the strategy workshop **Energy strategies and energy research needs.** This figure plots subjective judgments as to how the UK's industrial capabilities in specific areas of energy research are mapped against 'relevance to UK energy futures' (environment, affordability, security, economic opportunity). Workshop participants were divided into five groups, and the figure below is an amalgamation of their outputs. Research areas to the left of the vertical axis represent areas where there is thought to be no clear international lead, or a clear lead has yet to be established. The sizes of the coloured circles represent a subjective judgment about the level of scientific capability in the UK.

Nuclear fission was seen by the workshop participants as moderately important to the UK's energy future. However, the UK was thought to possess limited industrial and scientific capability, ranking low in both. Although agreement around this was not particularly strong amongst the groups, it was felt the UK possessed relatively little experience of delivering nuclear power stations in recent years. One group also warned that the industrial skills and experience the UK had gained in delivering its first generation of nuclear power stations were gradually being lost. However, centres such as the Nuclear Fission Research, Science and Technology (FIRST) Centre for Doctoral Training (CDT) were considered to be playing an important role in attempting to halt this decline. Some groups believed that the UK did possess strengths in specific aspects of the nuclear industry, particularly nuclear decommissioning, fuel cycle and nuclear waste management. Furthermore, companies such as Rolls- Royce possess extensive experience of developing nuclear reactors. Further detail on these sessions can be found in the report of the strategic workshop.[14]

[14] RCUK Energy Strategy Fellowship: '**Energy Strategy Fellowship Report 2: Energy Strategies and Energy Research Needs.'** http://www3.imperial.ac.uk/rcukenergystrategy

Figure 6: The UK's current and future energy R&D portfolio

3.2 UKERC Research Landscape

The UKERC has published a Research Landscape on Nuclear Fission.[15] This defines the UK's main research requirements in this field , as focusing on the decommissioning and clean-up of existing sites, as well as on-going fuel cycle and infrastructure activities. This requires a close collaborative effort with the UK's nuclear industrial base. Due to the Government's desire for a new nuclear build programme, a major research priority is to ensure readiness for this in terms of reactor selection, licensing and development. Long-term energy policy requires the UK to keep abreast of new reactor developments and designs, and the UK should resume active participation in the international Generation IV research programme in 2014.

The UK's research capabilities are listed below. Overall, the UK has strong capabilities in fuel processing and decommissioning, but weak capabilities in reactor design and construction. The UK research capability in nuclear fission was allowed to decline substantially over the 1990s and early 2000s. Research spend on nuclear fission has been growing and accounted for approximately 11% of the UK's annual public sector energy RD&D spend in 2012, a total of £30.4 million. The increases in spend preceded the decision to pursue a new build programme. There are two CDTS operating in this sector, the Nuclear FIRST CDT at Manchester University and the Industrial CDT in nuclear engineering, split between Sheffield and Manchester. The Nuclear Champions Group is a £500k network which aims to 'facilitate the effective UK academic engagement in nuclear research programmes' An additional £16 million is awarded through this grant for the National Nuclear Users Facility (NNUF) for universities and companies carrying out research into nuclear technology.

Table 3: UK research capabilities in nuclear fission

High Capability	• Radionuclide Separation • Actinide Chemistry • Spent Fuel Handling • Fuel Reprocessing • Waste Encapsulation • Decommissioning Engineering • Waste Characterisation • Fuel-cycle Assessment and Evaluation • Fuel Manufacture • Materials Performance • Criticality and Safety Assessment • Nuclear Information Security
Medium Capability	• Enrichment Technology • Nuclear Data and Physics Code Development • Systems Engineering • Geological Disposal Engineering • Human and other Biota Risk Assessment
Low Capability	• Reactor Design • Reactor Construction • Thermal Hydraulics

4. Existing roadmaps and innovation needs assessments

The nuclear fission RD&D sector in the UK has been the subject of several recent comprehensive reviews. The Fellowship team did not wish to duplicate the work already carried out in this sector on research

[15] UK Energy Research Centre, **'Research Landscape: Nuclear Fission'**, http://ukerc.rl.ac.uk/Landscapes/Fission.pdf

needs and priorities, and therefore have carried out a 'light-touch' approach to nuclear fission, directly consulting the community only on research support, training and wider connections and linkages with other research areas.

4.1 UK Nuclear Industrial Strategy

In March 2013, the Government published its **Nuclear Industrial Strategy,**[16] the result of a wide-ranging yearlong investigation. This Strategy, comprising inputs from government, industrial and academic stakeholders, was commissioned as a response to a House of Lords Science and Technology Select Committee report in November 2011, which identified a number of shortcomings in UK nuclear R&D, including the lack of long-term roadmaps and a low level of funding relative to ambition. The Strategy includes a number of documents, including a set of R&D roadmaps, a review of the civil R&D landscape, a study on the economic benefit of improving nuclear supply chain capabilities and an industrial vision statement. The industrial strategy is an aspirational document – it sets out the steps required and challenges to be overcome to ensure the UK becomes a significant global player in nuclear fission development, but does so in a 'best-case' scenario.

The strategy sets out indicative roadmaps with milestones for 2020, 2030 and 2040 in several areas; the home market; innovation and R&D; international presence and investing in skills.

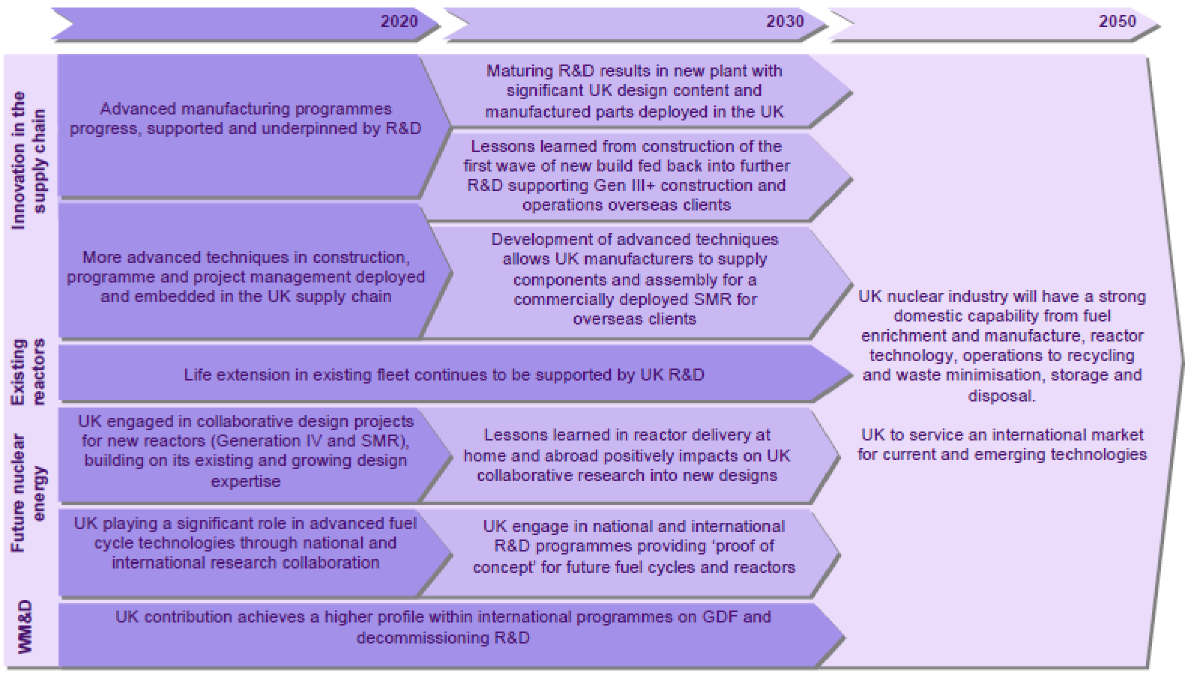

Figure 7: Indicative milestones for nuclear R&D in the UK (Nuclear Industrial Strategy)

Key actions identified to improve nuclear R&D and innovation efforts involve greater coordination of the research landscape, including the formation of two new bodies by Government:

- The **Nuclear Innovation and Research Advisory Board** (NIRAB), to ensure that public R&D programmes are aligned to support industrial and energy policy, and to maximise synergies through different aspects of the nuclear sector.

[16] HM Government, **'Nuclear Industrial Strategy: The UK's Nuclear Future'**, 2013, https://www.gov.uk/government/collections/nuclear-industrial-strategy

- The **Nuclear Innovation and Research Office** (NIRO), which will respond to recommendations from NIRAB and provide advice to Government organisations and industry on R&D and innovation opportunities. This will be hosted within the National Nuclear Laboratory (NNL).

Key actions also include keeping the level of public nuclear R&D expenditure under review, ensuring it identifies, directs and where possible accelerates commercial activities, focusing on new reactor designs and fuel cycles. The possibility of launching a small modular reactor (SMR) R&D programme is also being kept under review.

There is also a desire to raise the international profile of the UK nuclear industry and research capabilities, including more effective marketing of the UK's skills in waste management and decommissioning, enhancing strategic relationships with key nations in nuclear development and greater engagement with and impact in international fora, including the International Atomic Energy Agency (IAEA) and EU collaborative programmes.

4.2 Industry Vision Statement

The UK nuclear industry, together with government, produced a Vision Statement[17] in response to the Lords Select Committee report. This was designed to show the evolution of the UK nuclear supply chain over the next 40 years, divided into three phases: Phase 1, looking at operations over the next five years, Phase 2, looking at expanding global market share from 5-20 years' time, and Phase 3, developing and exploiting new technologies from 20-40 years' time. Industry plans to leverage experience gained from the UK's new nuclear build programme to access global markets and build up international involvement, with the overall aim being to capture a significant segment of a global market estimated to be worth nearly £1 trillion by 2025 given current investment plans. The Vision outlines four key enablers to achieve these goals:

1. The first wave of new UK nuclear power stations should be successfully delivered.
2. UK industry must strive to be competitive and make significant and growing contributions to domestic programme delivery across the entire nuclear sector.
3. Demonstrable progress should be made in safely managing historic facilities, including decommissioning, waste management and disposal.
4. Government must demonstrate that it recognises nuclear's long term importance to the UK, by working with industry to provide the required infrastructure solutions to underpin new build, identifying long-term strategic international relationships and by investing where necessary in education, skills and long-term R&D.

4.3 A Review of the Civil Nuclear Research and Development Landscape in the UK.

The Department for Business, Innovation and Skills (BIS) prepared a review of the civil nuclear fission landscape in the UK as part of the Industrial Strategy.[18] This report maps the institutional landscape of the UK's R&D capabilities, and discusses whether it is 'fit-for-purpose' for meeting the UK's policy goals and long-term ambitions. As stated above, the public budget for nuclear fission research totals around £30 million. Compared to research spends in France, Japan and the US, this level of expenditure remains low, and is heavily focused on decommissioning and maintaining present reactors. There is a comparatively low level of funding allocated to research into future generations of reactors than in these other nations.

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[17] HM Government, **Nuclear Industrial Vision Statement'**, 2013, https://www.gov.uk/government/collections/nuclear-industrial-strategy

[18] HM Government, **'A Review of the Civil Nuclear R&D Landscape in the UK'**, https://www.gov.uk/government/publications/civil-nuclear-research-and-development-landscape-in-the-uk-a-review

There are 1887 full-time equivalent (FTE) nuclear R&D personnel in the UK, 1260 in national laboratories, 394 in industry and 233 in UK universities. Figure 7 shows the distribution of academic staff across UK institutions. The review identifies concerns around the age profile of researchers in nuclear fission – whilst more young researchers are now entering the sector, the age profile is still skewed heavily towards older researchers, particularly in industry, and there is a worry that the UK will see a loss of talent in the next decade as older researchers retire and the demand for talented nuclear fission researcher becomes more competitive worldwide.

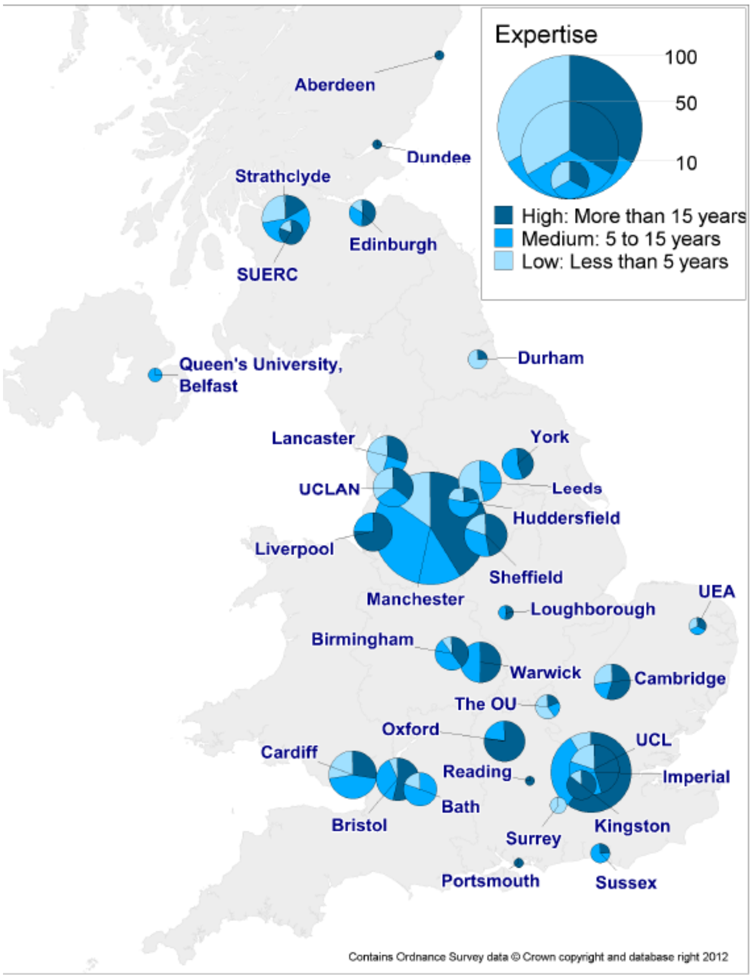

Figure 7: Nuclear academic personnel resource in the UK (Review of R&D landscape)

The nuclear research community is seen as relatively well-networked, with strong links between individual institutions and with private sector industry bodies. There is an RCUK Nuclear Champion with a specific aim of establishing collaborative networks, as well as the Nuclear Research Coordination Group (NRCG), an informal strategy group facilitated by the Engineering and Physical Sciences Research Council (EPSRC) to support networking and sharing of research priorities between research intensive nuclear industry players.

Nuclear fission requires strong international collaborative links due to the nature of the R&D process. While the UK has strong collaborative links with projects in EU nations as well as the US, Japan and South Korea, there is a lack of an overall clear UK strategy, and there are few bodies with the mandate to encourage coordination. In particular, the review found that there is no current overall strategy for the UK to engage with Euratom, or dedicated support to enable organisations to leverage EU funding.

4.3 Research Challenges

4.3.1 Nuclear Energy Research and Development Roadmap: Future Pathways

The Government's R&D Nuclear Roadmap[19] sets out three illustrative pathways to demonstrate the possible range of nuclear futures. These are:

- The **Baseline Pathway,** which assumes no new-build nuclear is constructed in the UK, and the existing fleet is operated and decommissioned to existing timelines.
- The **Open-Fuel Cycle Pathway,** involving the delivery of 16GW of new nuclear capacity by 2025, with the possibility of greater construction of up to 75GW by the middle of the 21st century.
- The **(Transition to) Closed Fuel-Cycle Pathway,** involving the delivery of 16GW of new nuclear capacity by 2025 as well as development of a new generation (generation IV) of reactors with the ability to recycle spent fuel into usable fuel rods.

Figure 8, below, shows the research areas needed to progress each pathway. It should be noted that even the baseline pathway, in which no new-build reactors are commissioned, still requires a significant programme of R&D activity to solve challenges around decommissioning and clean-up.

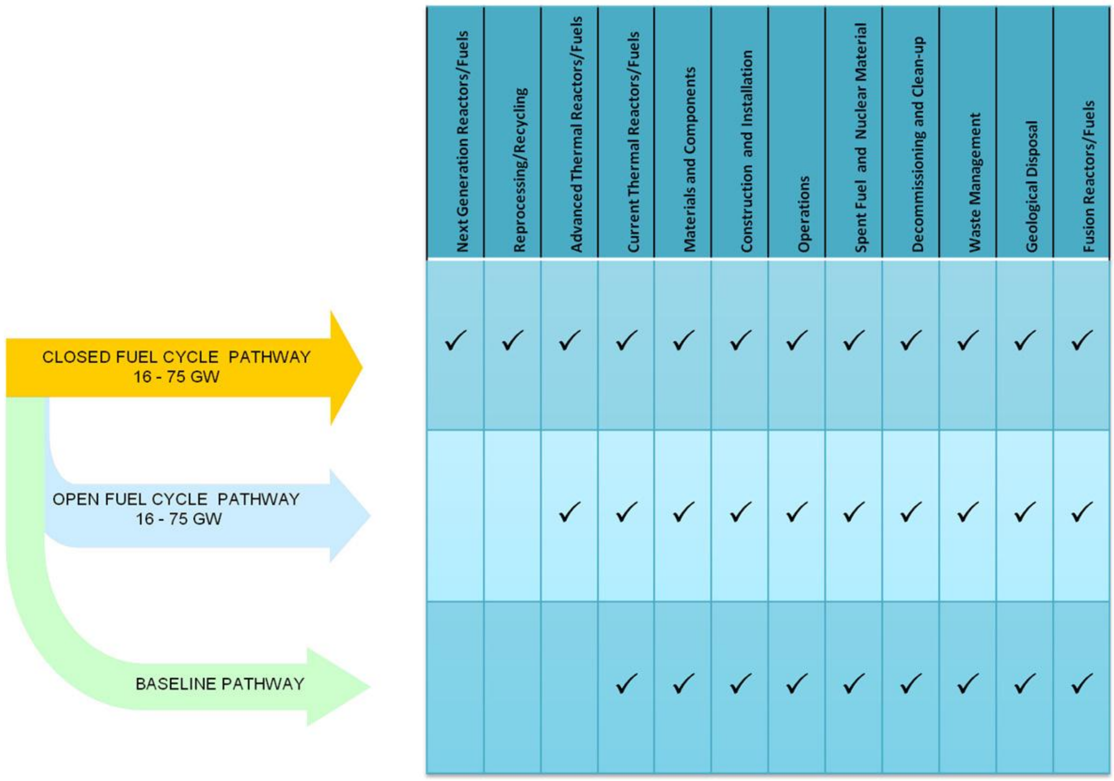

Figure 8: R&D areas required for the three indicative pathways (R&D roadmap)

In order to ensure flexibility and not to close off pathways pre-emptively, the roadmap identifies several decisions that will need to be taken over the next few years. These decisions are not intended to lock the UK into a particular path, but ensure that the capability exists for any pathway to be adopted, based on political desires.

[19] HM Government: 'Nuclear Energy Research and Development Roadmap: Future Pathways',

These decision points, and indicative dates by which the decision should be made, are:

- The UK to resume active participation in the Generation IV International Forum. (2014)
- Extend capability to independently and authoritatively evaluate and regulate additional Gen III/III+ and advanced thermal reactors. (2013)
- Join US Department of Energy (DOE) Small Modular Reactor (SMR) programme. (2013)
- Invest in UK fuel fabrication capability and infrastructure. (2014)
- Invest in spent fuel recycling capability through R&D using EU and national programme. (2013)
- Invest in integration of recycling R&D programme with next generation (including fast) reactors, fuel fabrication and disposal R&D programmes to create a complete fuel cycle capability. (2016)

The UK has now joined the DOE SMR programme.

4.3.2 Nuclear Fission Technology Innovation Needs Assessment

The LCICG Technology Innovation Needs Assessment (TINA) reports aim to identify and value the key innovation needs of specific low carbon technology families to inform the prioritisation of public sector investment in low carbon innovation. These assessments focus on the UK's energy innovation chain as a whole and not just RCUK's activities.

The TINA considers four indicative deployment scenarios for nuclear fission:

- Low: 16GW of new Generation III plant by 2050;
- Medium 1: 40GW of new Generation III plant by 2050;
- Medium 2: 40GW of new plant by 2050, with 80% of new reactors being Generation IV over an installed capacity of 30GW; and
- High: 75GW by 2050, with 80% of new reactors being Generation IV over an installed capacity of 30GW.

The TINA concludes that the UK is unlikely to be a market leader in nuclear fission technologies, as it has a relatively modest nuclear RD&D spend compared to globally-leading nations. There exist several major market failures in nuclear fission innovation, including high capital costs, a limited number of major nuclear vendors, lengthy decommissioning times and proliferation concerns. The TINA suggests that the UK can rely on other countries to drive innovation and overcome these barriers in many areas of R&D. Substantial opportunities are however available in specific areas, especially those in which the UK cannot easily rely on the expertise of other nations. These are;

- ***The Front End of the Fuel Cycle –*** the UK has valuable expertise in fuel enrichment, fabrication and conversion. This expertise could be lost without further investment, and will become more important if the UK decides to engage actively with the international Gen IV programme.
- ***Decommissioning –*** The UK requires a specific decommissioning capability due to its legacy nuclear sites. This capability could not be largely imported from overseas.
- ***Back End of the Fuel Cycle –*** The UK has a significant and unique spent fuel challenge, requiring significant domestic capability to overcome.

It is essential for the UK to retain world-leading regulatory and the ability to act as a well-informed and safe operator of new and existing nuclear plants. There is a potential £1.5-13bn net contribution to the UK economy assuming the UK can successfully contribute to the global nuclear market.

5. Research support

This section is based on a session held at the 2nd UK Nuclear Academic network meeting at the University of Birmingham on the 19 September 2013. The session was attended by over 30 nuclear academics, from a range of disciplines and different levels of seniority.

5.1 Ways of working

- Research Councils launch grant applications and renewals at different times to one another, with no consistency in timings or attempts to coordinate grant applications between them. A more consistent timetable, with complementary grants from different Research Councils timed to start and finish at similar times would assist academics greatly in allocating their resources and planning their long-term research strategy. This is especially important for those academics whose research lies on the edge between the domains of two Research Councils.
- The Science and Technology Facilities Council (STFC) lacks a responsive mode for grant applications. Academics in this area believe that STFC should begin accepting responsive mode applications. As a point of principle, there should be a responsive mode for all areas of research.

5.2 Long-term perspectives

- Nuclear research covers very long timescales. Generation IV fission plants and fusion power will likely not be commercially available until 2040-50, and the geological disposal of nuclear waste is similarly a long-term issue. Consistent research support and long-term strategies will be needed over the next few decades if the UK is to develop significant capability for a new generation of nuclear reactors.
- There is a public perception that nuclear fission is a proven technology, and therefore basic research is not needed. However, new generations of reactors take many decades to develop. It is vital to communicate to policymakers and the wider public that this is still a developing technology with many basic research questions still to answer, and that public support for nuclear R&D is still necessary.

5.3 Data, infrastructure and facilities

- Large sets of nuclear data were considered as very important. The Nuclear Energy Agency (NEA) databank is an important international databank, of which the UK is currently a member, but considered withdrawing due to funding cuts. Access to international databanks is inexpensive and important for research, and the Research Councils should ensure that funding in this area is maintained and increased where appropriate.

6. Training

- Participants generally felt that CDTs have been a useful initiative, producing a core group of well-trained PhDs, and a lot of flexibility in projects and skillsets. However, the issue was raised that CDTs were defined too narrowly, and there was a danger of losing the ability to do a PhD in niche areas. The idea was floated of linked CDTs, in which students spent some time with the CDT host university and some time working on a project in a different university. Proposals for nuclear CDTs are all multi-university, something that was felt to be very important.
- There is an issue for universities not hosting a CDT, as they can no longer attach PhD studentships to programme grants. Large programme grants were felt to allow PhD students to obtain valuable mentoring as well as giving important continuity in the programme field. However, it was also felt

that projects should strongly justify the need for PhD project students, including laying out the benefits to the students and the support available to them.

- Industrial Collaborative Awards in Science and Engineering (CASE) awards still exist and students are being supported via this mechanism. These students currently do not get the additional training and support benefits of their colleagues in a CDT cohort. If they could obtain these benefits as part of their CASE award, it would make these industrially-supported PhDs more appealing to prospective students.
- Overall, it was felt that different PhD project models bring different benefits, and one model should not be pursued to the exclusion of others.

7. Connections

7.1 Cross-Council linkages

- Skills are often multi-domain. For example, nuclear waste disposal, carbon capture and storage, and fracking all require geological expertise. This should be accounted for in cross-council working and joint programmes.
- There needs to be stronger links between EPSRC and the Economic and Social Research Council (ESRC) to look at social and economic issues in conjunction with technology R&D.

7.2 Linkages outside the Research Council sphere

- Research Council portfolios often do not represent the skills industry needs. The split between research responsibilities means that that people may not be getting the full set of skills they need for industrial projects. Research Council portfolios should be allocated with an eye to dovetailing with UK industrial needs.
- There will be a coordination group for nuclear – the NIRAB. This body will have strong links with the LCICG, and will certainly have an input into EU programmes, further helping to shape the direction of these projects.

7.3 International working

- Nuclear power is almost unique in the energy research sector due to the substantial security concerns surrounding R&D. There is a tension between the desire to engage with a wide range of international partners and these security concerns.
- There are issues with funding non-EU international students, due to government policies. This can result in very promising students not being able to come and study at UK universities.
- The Euratom treaty, establishing the European Atomic Energy Community, makes nuclear power distinct in the EU from other energy areas. In some areas, nuclear has very strong and old international links. A more active role should be played by central government in shaping EU programmes in nuclear to UK interests, including the distribution of draft proposals from the government to active researchers to solicit input, a practice adopted already by several EU member states.

7.4 Other issues

- There needs to be a robust research portfolio to cover a range of nuclear futures. Currently nuclear is regarded as a key component of the UK energy mix. However, this is a political stance and there is a danger with assuming that this position will continue in the long-term.

8. Conclusions and recommendations

The nuclear fission research sector in the UK is currently experiencing a period of growth and realignment to support the new-build programme and to explore further long-term opportunities relating to new reactor design and playing a larger part in the global market. This sector saw an extremely dramatic reduction in funding of over 90% from the 1980s to the present day, and has recently been focused on supporting operational and decommissioning efforts of the UK's reactor fleet. However, the sector has some ambitious plans for expansion to support new reactors and export opportunities, as can be seen in the **Industrial Strategy** and related documents.

The nuclear R&D sector has produced several substantive reviews and roadmaps over the past few years and has acted on their recommendations effectively, setting up coordination groups, closing gaps between research and policymakers, and putting into place long-term strategies and frameworks for maintaining and improving the UK's research and industrial capabilities in nuclear fission. This research area has produced significantly more analysis on its capabilities and shortcomings than any other energy research area the Fellowship has mapped, and is in a very strong position going forward.

Key points arising from the workshop discussion and review of roadmaps and research frameworks include:

- While national coordination in the sector has improved greatly in recent years, international collaboration does not take place according to an overarching framework or goal structure, and no single organisation or advisory group has responsibility. In particular, greater European engagement should be encouraged, helping UK researchers to gain a greater proportion of research resources and the UK to have a greater influence on the direction of European research.
- As in many other energy research areas, the adoption of CDTs has provoked a mixed response. Nuclear researchers seemed more positive towards CDTs than in other areas, due in part to the multi-university structure of nuclear fission CDTs. However, it was felt that CDTs needed to be less narrowly focused to allow more niche research areas to be included, and that PhD students attached to large programme grants would add value both for the student and for the grant.
- Nuclear research tends to take place over very long timescales, and research into a new generation of reactors will be a very long-term goal. Policymakers and the Research Councils will need to take this into account if the ambitious goals outlined in the **Industrial Strategy** are to be accomplished. A research portfolio robust against political uncertainty and covering a range of UK nuclear futures should be considered.
- Access to international databanks and facilities is very important in this sector. Care should be taken to ensure that UK researchers can access these important international resources.
- Skills in the nuclear sector are often multi-domain, and incorporate a range of disciplines. This needs to be fully accounted for when considering cross-council projects and overarching joint programmes. Skills and training programmes should be benchmarked against the skills UK industry requires in order to ensure that researchers can work on industrial projects where necessary.

Annex A: Process for developing the prospectus

This Energy Research and Training Prospectus Report has been developed under the auspices of the RCUK Energy Strategy Fellowship which was established in April 2013. Fellowship activities leading the production of the Prospectus have gone through three phases.

Phase I (Spring – Summer 2012), **the scoping phase,** involved a comprehensive review of relevant energy roadmaps, pathways and scenario exercises in order to provide a framework for possible UK energy futures. Extensive consultation with stakeholders across the energy landscape was carried out in order to encourage buy-in and establish clearly the boundaries and links between the RCUK Prospectus and other products related more to deployment. One conclusion arising from the consultations was that linkage should be sought across the energy research domain and that consequently related topics linked by underlying research skills should be covered in single workshops during Phase II.

Phase II (Autumn 2012 – summer 2013), **the evidence-gathering phase,** relied heavily on workshops bringing the research community and stakeholders together round specific topics. Three 'strategic' workshops on **Energy Strategies and Energy Research Needs, The Role of Social Science, Environmental Science and Economics**, and **The Research Councils and the Energy Innovation Landscape** were held October-December 2012. Six expert residential workshops on **Fossil Fuels and CCS, Energy in the Home and Workplace, Energy Infrastructure, Bioenergy, Transport Energy** and **Electrochemical Energy Technologies** were held January - June 2013. In addition, 'light-touch' activities were conducted in respect of: **Industrial Energy; Wind, Wave and Tide**; and **Nuclear Fission.** A final strategic level 'synthesis' workshop was held in July 2013. During Phase II, reports on each of these workshops were prepared and web-published following comments from participants.

During Phase III (summer - autumn 2013), **the synthesis stage,** the workshops reports were 'mined' and combined with contextual information to produce the Prospects Reports which were put out for peer review. The Prospectus, including a hard-copy Synthesis Report, was launched in November 2013.

Annex B: List of prospectus reports

No 1	Investing in a brighter energy future: energy research and training prospectus
No 2	Industrial energy demand
No 3	Energy in the home and workplace
No 4	Transport energy
No 5	Fossil fuels and carbon capture and storage
No 6	Electrochemical energy technologies
No 7	Wind, wave and tidal energy
No 8	Bioenergy
No 9	Nuclear fission
No 10	Energy infrastructure