February 2012

UK Nuclear Fission Technology Roadmap

Preliminary Report

This report has been prepared by the UK National Nuclear Laboratory (NNL) on behalf of the project team consortium. Input has been provided by the Steering and Expert Groups.

The views are not the official point of view of any organisation or individual and do not constitute Government policy. The development of this report was sponsored by the following organisations:

ERP Energy Research Partnership

National Nuclear Laboratory

EPSRC Pioneering research and skills

NDA Nuclear Decommissioning Authority

energy technologies institute

Key Messages

Considerable effort has already been, and continues to be, put into opening the way for new nuclear power stations in the UK to replace existing capacity by 2025. However, many energy scenarios for a secure, low carbon energy system indicate that nuclear power may have to play a much greater role by 2050. Delivering such an expanded fleet is not a matter of doing more of the same, but requires a long-term strategic approach focused on ensuring a secure supply of fuel and managing the additional waste arisings as well as maximising opportunities for the UK supply chain. Given the long lead times for developing many of the technologies that may be needed, actions need to be taken now to avoid closing off options unnecessarily, which might prove costly to rectify in the future. This preliminary report highlights the key issues and analysis that will be needed to inform the strategic decisions on which a Research and Development (R&D) roadmap can be based.

The UK has world-class R&D capabilities in key areas across the nuclear fuel cycle. Historically the UK has developed advanced reactor systems and associated fuel cycles and retains considerable knowledge. In addition, the UK has significant expertise in decommissioning, safety management, regulatory frameworks and advanced manufacturing. Overall, the UK should be well placed to take early advantage of the growing global market for nuclear power. The UK's civil nuclear sector has contributed approximately £3.3 billion to Gross Domestic Product (GDP) and is a major exporter of technology and skills, with UK companies actively engaged in collaborative projects with overseas bodies. A recent submission to the House of Lords Select Committee Inquiry on Science and Technology on Nuclear Research and Development Capabilities highlighted £1.7 trillion of investment worldwide in new nuclear technologies. Any new build programme in the UK could greatly enhance these opportunities. However, the choice of pathway, particularly for expansion beyond 2025, will affect these opportunities. It is therefore vital that pathways and opportunities are identified and analysed in detail so that the UK is in a position to make the appropriate supportive investment to keep options open and maximise the long-term value to UK plc.

This high-level analysis of two possible nuclear new build scenarios sets out some of the key issues and decisions that will need to be made for developing a long-term nuclear programme and R&D roadmap. Industry, academia, regulators and other key stakeholders were consulted widely to compare two plausible scenarios for nuclear expansion to 2050 and beyond – a 16 GW Replacement Scenario and a 40 GW Expansion Scenario (see Table 1) – to understand what this means in terms of research and technology development and the timelines for required actions. These scenarios represent two realistic options for nuclear deployment in the UK. Other scenarios between these two were included in the early stages of the project but the detailed work which forms this report was confined to the specified Replacement and Expansion Scenarios. They were purposefully chosen to explore the differences between an open and closed fuel cycle in terms of technology and R&D requirements: not to advocate that any particular scenario be adopted. Consideration was given to the facilities, infrastructure and skills that will be needed to maintain and develop the UK's world class expertise and capabilities from a technology standpoint: not from the point of view of business justification; which would require much more detailed analysis outside of the scope of this project.

Scenario	Electrical Generation [1]	Fuel Cycle	Reactor Generation & Technology
Replacement Scenario	16 GW to 2025	Open fuel cycle	Generation III reactors - Historic plutonium recycled in Generation III reactors.
Expansion Scenario	16 GW to 2025 and then build up to 40 GW in 2050	Closed fuel cycle	Generation III with Generation IV fast reactors from 2040 (the earliest assumed date for commercial deployment of fast reactors) - Historic plutonium recycled in Generation III reactors. - Spent fuel from Generation III reactors recycled to fast reactors.

Table 1: Nuclear new build scenarios selected for roadmapping

[1] Unless stated otherwise, throughout this report all references to capacity are in GW of installed electrical generation and do not refer to thermal output.

The 16 GW Replacement Scenario (see Table 1) has ongoing technical challenges and priorities associated with its implementation. Much has already been done and UK companies are already preparing to feed into the supply chain; for example, the Nuclear Industry Association (NIA) SC@nuclear[2] programme. This analysis highlights some of the key challenges extant in the 16 GW Replacement Scenario; which will also need to be addressed for any expansion of the UK's nuclear programme, specifically:

- Ensuring maximum take up of UK and overseas opportunities by the UK supply chain and in particular by UK manufacturing.
- Possible vulnerability to long-term uranium supply issues depending on overall global expansion.
- Ensuring sufficient numbers and breadth of skills within the regulators specifically and the sector generally.
- Evaluation of the current stock of UK plutonium.
- R&D to underpin licensing of MOX fuel in the Generation III reactors to be built, including R&D necessary to assure the route for production of qualified fuel from the UK's plutonium feedstock.
- Assessment of the technical implications of increased volumes of wasteforms and the requirement to deal with significant quantities of spent Uranium Dioxide (UO_2) and spent MOX fuel in a Geological Disposal Facility (GDF).

The 40 GW Expansion Scenario (see Table 1) has significantly different implications from a 16 GW scenario for a UK Nuclear Fission Technology Roadmap in terms of:

- Possible vulnerability to long-term uranium supply issues depending on overall global expansion which would drive a requirement for consideration of alternative fuel cycles, such as plutonium based Generation IV fast reactors, and/or thorium fuel cycles.
- Increased challenges of spent fuel management, volumes, long-term storage and disposal.
- The availability of Generation IV fast reactor technology within the mix and the requirement for reprocessing spent fuel from Generation III reactors.
- Significant R&D to underpin the development and deployment of future fuel cycle and Generation IV fast reactor systems, including involvement within international collaborative arrangements.
- Further opportunities for the UK supply chain, both in the UK and internationally.
- Requirement for early investment in assets essential for research, technology development and demonstration given the long lead times.
- Ensuring appropriate skills are available for construction and operation of new reactors, both Generation III and IV.
- Timely identification of additional sites and/or extensions to existing licensed site boundaries.

For open fuel cycle scenarios, increasing from 16 GW to 40 GW results in a significantly greater (x 2.5) level of spent fuel arisings. Given that the pathway to the UK's GDF is expected to be taken forward in the near future it is important that issues of long-term storage of spent fuel and any implications for the GDF are analysed early. Detailed analysis of the differences between open and closed fuel cycles should also help inform future roadmap developments in the UK context in terms of waste management and disposal and issues relating to the utilisation of fissile resource.

There are major opportunities for UK companies to become part of the global supply chain if they are given the support to gain early qualified supplier status. Enlarging the Generation III Light Water Reactor (LWR) fleet beyond the currently envisaged 16 GW will take 20-30 years and the reactors deployed will have at least a 60 year operating life. Investment in high-end manufacturing will pioneer the introduction of modern state-of-the-art manufacturing technologies into LWR plant fabrication and construction and enable the UK supply chain to reach the forefront of new nuclear manufacturing technology. Extension of the technology to address the requirements of Generation IV systems will provide the supply chain with advanced capabilities that could feedback to provide beneficial long-term support for LWRs and hence provide further innovation opportunities for UK companies.

To ensure that the necessary skills are available to build and operate the required facilities, the UK needs a skills delivery pipeline starting now that covers both the 16 GW and 40 GW scenarios. Any delays or gaps in delivering a coordinated programme will lead to a drop in capacity of jobs and skills, requiring additional training interventions to recover this capability and possibly a reliance on importing transitory skills from abroad to fill the gaps. Recovering these skills will lead to unnecessary costs and delays to a future build programme.

Several technologies are under development internationally for Generation IV systems offering the potential for improved sustainability, economics, proliferation resistance, safety and reliability. Each involves significant technological development and industrialisation through demonstration before commercial deployment. Participating in these international initiatives opens the opportunity for the UK's R&D capability and supply chain to develop new technologies, such as fuel and component manufacture, and gain early advantage and position the UK as a centre of excellence for aspects of advanced nuclear technology. The commercial opportunities from UK participation in international programmes need detailed assessment, in consultation with industry, the National Nuclear Laboratory (NNL) and academia.

Given the long lead times for the development of many of the technologies, early investment is required in targeted R&D programmes and projects and in detailed further analysis of the challenges faced in any scenario, such that future decisions can be appropriately underpinned. This early investment is also required to sustain the UK's world class capability in fuel technology development and reprocessing technology. This in turn also creates a unique opportunity for the UK to influence the international development of new fuel cycles and to enable the manufacturing supply chain to gain an early lead in next generation technology.

[2] Nuclear Industry Association, Nuclear Supply Chain Development Programme (SC@nuclear)

The analysis of technology pathways in this report has concentrated mainly on large scale Generation III LWR and Generation IV fast reactor technology. However it also highlights that given global interest, new LWR technology in the form of Small Modular Reactors (SMRs) could enter the commercial landscape over the next 30 years. Here the UK already has supply chain expertise and capability and has made private sector investment. It is vital these opportunities are properly understood so that targeted support can be provided and underpinning R&D requirements specified.

Implementing and Sustaining a UK Nuclear Fission Technology Roadmap

Delivering an expanded nuclear scenario, beyond the proposed 16 GW, could require a distinctly different and integrated approach led by an understanding of the fuel cycle and waste management implications, rather than by the choice of reactor alone. A long-term strategy for nuclear energy, and its associated industry infrastructure, requires a properly developed comprehensive roadmap that highlights the decisions to be made on a number of key areas and how soon these decisions need to be made to avoid foreclosing options. Such choices also open up a range of opportunities to develop the UK supply chain. This report makes no decisions or recommendations for a particular pathway or technology choice. All create significant yet differing opportunities which need to be analysed. It is expected that this analysis will feed into the nuclear Technology Innovation Needs Assessment (TINA) which is being undertaken by the Department of Energy and Climate Change (DECC).

Developing the strategy requires a focal point in Government that can provide an oversight to the UK's nuclear aspirations and provide a cohesive and coordinated approach. It should be supported by a body made up of Government, regulators, industry, NNL, NDA and academia that can provide oversight of the whole UK nuclear R&D landscape and own, inform and lead detailed assessments of the key areas of a roadmap, to ensure opportunities to exploit UK expertise are maximised. Key national assets, such as the NNL and the Nuclear Advanced Manufacturing Research Centre (NAMRC), could be utilised and capitalised upon to help realise the global opportunities associated with new nuclear build programmes.

This coordinating body would also direct a strategic approach to the UK's involvement in international collaborations and research programmes that are of interest to the UK, such as the European Atomic Energy Community (Euratom) programme and the Generation IV International Forum (GIF), either directly or through Euratom, or other bilateral/multilateral collaborative programmes.

Next Steps

This strategic outline has highlighted significant issues and consequences that need to be addressed not only for the 16 GW scenario, but for any future expansion of nuclear capacity. The analysis for this report highlights that any delays risk closing off options for future development and missing valuable opportunities for UK industry to capitalise on the global market.

Recommendation 1: Further detailed assessments are needed to understand the issues and to realise the potential opportunities for UK industry.

Recommendation 2: The UK Government needs to develop a clearly defined long-term nuclear energy and industrial strategy and an R&D Roadmap for the nuclear sector.

Recommendation 3: An R&D co-ordinating body should be formed that includes Government, industry, NNL, NDA, regulators, academia and research funders, to own, develop and advise Government on a long-term nuclear R&D strategy and roadmap, in order to underpin realisation of the commercial opportunities and to direct the underpinning programme of R&D, in part through international collaboration.

The following table highlights the critical decisions and assessments that the UK should address within the next 5 years.

No.	Activity	Outcome
D1	Evaluation of the UK's stockpile of separated plutonium for use as a fuel in thermal MOX reactors.	Give assurance as to the suitability of the plutonium for use as fuel.
D2	Commitment to a national R&D programme to support the Generation III new build fuel cycle.	Realise UK business opportunity from delivering associated R&D programme and growing Generation III technology capability. Secure UK Generation III technology facilities, capabilities and skills.
D3	Assessment of spent fuel and waste arisings from possible generation scenarios. Detailed evaluation of global supply of uranium and fissile material for fuel and assessment of implications for future UK capacity and various technology pathways over lifetime of programme. Evaluation of the 40 GW closed fuel cycle scenario challenges in technology, siting, spent fuel disposal, fissile material resource (uranium ore, plutonium and reprocessed uranium) and hence drivers for Generation IV fast reactors. Decision on a national R&D programme to support the Generation III/Generation IV sustainable nuclear expansion.	Ensure appropriate provision is made during development of the GDF. Provide understanding of security of fuel supply as basis for making decisions about future technology pathways. Keep Generation IV fast reactor and closed fuel cycle options open. Secure UK Generation IV technology facilities, capabilities and skills.
D4	Establish collaboration agreements for international Generation IV fast reactor and associated fuel cycle programmes. The UK could provide valuable underpinning fuel cycle R&D, giving facility and resource access to develop advanced systems.	Gain experience and understanding of Generation IV fast reactor and associated fuel cycle technology capability to keep option open. Realise UK business opportunity from delivering associated R&D programme.

Should the current nuclear programme be expanded beyond 2025 then the following action will be required:

No.	Date	Activity	Outcome
D5	2015 - 2020	Decision to permit second tranche of Generation III reactors, based on the success of first new build projects and the scale of deployment of other low carbon technologies.	Ensure continuity in construction workforce and supply chain between build programmes.
D6	2019	Evaluation of the need for reprocessing Generation III LWR spent fuel.	Keep closed cycle option open for LWR fuel.
D7	2024	Evaluation of the need for reprocessing Generation III MOX spent fuel.	Keep closed cycle option open for MOX fuel and enables sufficient plutonium for first Generation IV fast reactor fleet.
D8	2030	Commence permitting process for first tranche of Generation IV fast reactor fleet.	Enable first Generation IV fast reactor on grid by 2040.

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Analysis for this report involved significant interaction with industry, academia, the regulators and other key stakeholders. Substantial underpinning information and detail has been retained but could be made available for further development of this Roadmap.

Introduction

Without a detailed understanding of the opportunities and issues and a clear plan for maintaining and developing nuclear R&D facilities, capabilities and skills, the UK will be unable to sustain any significant increase in nuclear contribution to the low carbon energy portfolio beyond 2025. Actions, if taken, can address this and help sustain the skills necessary to deliver it and secure the significant business advantage of being early to market in Europe. Any delays risk closing off options for future development and missing valuable opportunities for UK industry to capitalise on the global market.

The new build programme could greatly enhance the UK's nuclear industry, developing its supply chain and utilising its R&D capabilities, which in turn will put it in a position to gain a share in the global nuclear renaissance. The UK nuclear energy industry infrastructure will need to expand rapidly to sustain the level of new build needed to deliver the nuclear contribution to the transition to a low carbon economy through to 2050 and beyond. The UK will require sustainable assets and processes, supply chain capability, research and development programmes, and a technology innovation and skills base to deliver the new build programme. This requires a clearly articulated vision and strategic direction.

This report sets out some of the issues that need to be addressed to keep options open for any further development of the nuclear contribution to a diverse, safe, secure and affordable energy supply portfolio to 2050 and beyond; and to maximise the UK's take-up of the potential business opportunities offered by the growing world-wide nuclear market. Further detailed analysis of most of the issues and opportunities highlighted will be required on an early timescale to inform decisions and intervention points.

The Need for a Roadmap

A number of organisations have recommended a roadmap to enable the UK to inform the strategic direction for its nuclear industry and identify the R&D necessary to support it. These organisations include the Energy Research Partnership (ERP), the Royal Society, the House of Lords Select Committee on Science and Technology, the Engineering and Physical Sciences Research Council (EPSRC) and the National Nuclear Laboratory (NNL). Such a roadmap is essential to ensure actions by key players (Government, industry, NNL, academia and regulators) are aligned across both the public and private sector and to identify barriers that will need to be addressed to enable systems to be commercially deployed. A very modest initial investment from a project consortium of ERP, NNL, Nuclear Decommissioning Authority (NDA), EPSRC and Energy Technologies Institute (ETI) (see Appendix 1) enabled this strategic analysis to be developed. A series of Expert Groups were convened under the direction of a high level Steering Group to highlight the key issues and analysis that will be needed to inform the strategic decisions on which an R&D roadmap can be further developed. For details of membership of the Steering and Expert Groups and the process for development of the Roadmap see Appendices 2 and 3.

The project did not include determination of the costs of the various options: detailed analysis of the economics will be required in the recommended further work. The report also does not include analysis of the public investment in R&D that will be required; it rather seeks to highlight the issues and the importance of being sufficiently aware of options for detailed review. This economic and value for money analysis is expected to be part of subsequent work. The report does not attempt to discuss the more fundamental arguments for or against nuclear energy. It is recognised that public acceptability of energy technologies is a key factor in determining their future use.

While this analysis was being undertaken, a number of key reports have been published, for example, the DECC consultation response on the long-term management of UK-owned separated civil plutonium (Dec 2011) and the NDA Oxide Fuels Credible Options (Nov 2011). The proposals contained in this specific report are largely consistent with these latest announcements, although some of the inputs and analysis pre-date them.

Given that fusion energy is not predicted to have an impact on the energy portfolio until after 2050,[3] and therefore will not be able to contribute to meeting the UK's 2050 emission reduction targets, this analysis has not considered what fusion energy R&D capabilities may be required over this period. The UK's fusion R&D endeavours are an integral part of international collaborations in the field and overseen by a Research Councils UK (RCUK) Fusion Advisory Board. A roadmap for fusion has been requested by the European Commission (EC) to help guide the actions and investments required at the European level to support the further development of fusion technology post the International Thermonuclear Experimental Reactor (ITER) and on towards possible commercialisation in the latter half of the century. Additionally, the synergies between fission and fusion in key areas of development are understood and already part of a drive to build bridges between the two communities of scientists and engineers at the research level.

[3] House of Lords (2011), Nuclear Research and Development Capabilities. House of Lords. Select Committee on Science and Technology.

Global Context

At present, 433 reactors are operating worldwide, totalling 369 GW capacity and delivering 13.8% of electricity.[4] Sixty two reactors are being built, primarily in China and Russia, with a further 156 (173 GW) on order or planned and 343 reactors proposed, potentially delivering an additional 392 GW.[5] The World Nuclear Association (WNA) estimate that - with a full international policy commitment to nuclear power as part of a carbon emission reduction strategy - the global nuclear generation capacity by 2060 could rise to between 1,140 GW and 3,688 GW, with the potential to expand to between 2,000 GW and 11,000 GW by 2100 (Figure 1).[6]

Even post Fukushima, nuclear power remains an energy option on the agenda globally (the so-called 'nuclear renaissance'), with new construction programmes underway in USA, China, Russia, India and the UK. A recent estimate suggests a potential worldwide investment of £1.7 trillion in new nuclear technologies.[7]

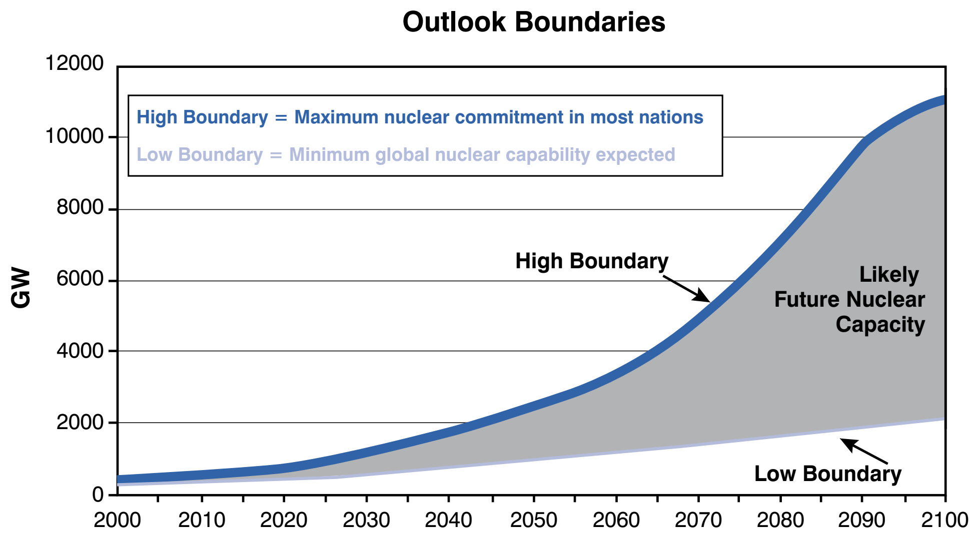


Figure 1: Potential future global nuclear generation (adapted with permission from WNA Nuclear Century Outlook)[6]

The UK Technology Strategy Board (TSB) has estimated that the global nuclear fission market is worth about £600 billion for new nuclear build and £250 billion for decommissioning, waste treatment and disposal over the next 20 years.[8] The TSB review identified considerable opportunities for UK businesses in the supply chain to benefit from the new build programme, building mostly on the UK's strengths in areas such as non-destructive testing (NDT), condition monitoring, decommissioning, waste disposal, and advanced manufacturing and materials. For example, the review estimated the size of the market for non-destructive evaluation (NDE) and NDT to be £10 million for each reactor for construction, and £100s of millions through the lifetime of a plant.[9]

The UK is seen as part of the first wave of new builds in Western Europe; the success of nuclear new builds in the UK market has the potential to open up other nuclear markets and global nuclear supply chains. The logic being applied here is that the UK regulated market has very high standards. Where firms can meet the quality and safety standards within the UK market successfully this can act as a sign of quality for future projects within Europe and globally.

'Targeted R&D will allow the UK to penetrate and exploit the market created by global nuclear expansion as well as enabling deployment in the UK'.

National Nuclear Laboratory

'If the UK becomes one of the global early movers in new build UK companies will have considerable global market potential. This will secure highly skilled jobs in the UK'.

Cogent

[4] World Nuclear Association, (Dec 2011) World Nuclear Power Reactors and Uranium Requirements.

[5] Ibid.

[6] World Nuclear Association (2010) Nuclear Century Outlook.

[7] House of Lords (2011), Science and Technology Select Committee, Nuclear Research and Development Capabilities, Oral and Written Evidence, Memorandum by Rolls Royce.

[8] TSB (2010), A Review of the UK 's Nuclear R&D Capability. TSB/Dalton/NNL/Battelle.

[9] Ibid.

UK Capability

The UK has a strong historic track record in nuclear R&D; having been one of the first nuclear countries and one of very few countries that has closed the complete fuel cycle. It has been involved in the development of a wide spectrum of technologies and is recognised as a world leader in areas such as regulatory frameworks, safety management, advanced manufacturing capability, and has been a leader in advanced reactor designs and associated fuel cycles. Despite the focus shifting primarily to decommissioning end of life nuclear plants in recent years, the UK has retained strengths in nuclear R&D capabilities and associated expertise across some areas. These have been shaped by historic R&D programmes and include advanced fuel development, spent fuel management, waste management, decommissioning, and early generation reactor technology. This breadth of knowledge acquired across the whole fuel cycle is considered by many to be the UK's unique selling point.

The potential commercial opportunities that nuclear R&D and associated expertise presents for the UK can be split into four overlapping areas:

1. Support to develop the UK supply chain for the current new build programme.
2. UK involvement in future international technology development.
3. Delivery of competence to support development of future technology options and provide advice on nuclear issues (e.g. Fukushima).
4. Decommissioning and clean-up.

The UK's civil nuclear sector has contributed approximately £3.3 billion to GDP.[10] The estimated investment for the planned 16 GW new nuclear capacity currently stands at around £50 billion and is estimated to create 30,000 jobs by 2025.[11] The UK supply chain has a strong capability in most of the required areas and could supply at least 70% of the total requirements for such a programme.[12] This capability is currently being used to support existing nuclear power and fuel cycle plants, and also in decommissioning and waste management activities. In addition, it is being applied to non-nuclear projects and the construction activities where much of the skills, plant and equipment are similar to those of a nuclear power plant.

The UK's nuclear industry is also a major exporter of technology and skills and UK companies are actively engaged in collaborative projects with overseas bodies. Several major UK engineering companies and consultancies also have the global presence to exploit the ensuing global nuclear renaissance. The combined civil and defence nuclear sectors earn the UK approximately £700 million a year from overseas business.[13] UK companies are playing an increasingly important role as owner, operator, engineer, consultant, contractor, supplier and investor in the global nuclear energy industry.

There is a concerted effort through the NAMRC to develop technology and align UK manufacturers to support the Generation III new build. This effort is needed to optimise the construction and involvement of LWRs in England and Wales and will allow UK companies and consultancies to gain a prominent position in the global LWR systems and services market.

The UK is currently involved in a number of international research programmes including the European Atomic Energy Community (Euratom) programme and through Euratom, the Generation IV Forum (GIF). However, this is mainly through individual researcher involvement as opposed to a more co-ordinated approach. The NDA has developed relationships with other countries on decommissioning and waste management to share experience and good practices and the Office for Nuclear Regulation (ONR) is also involved in international activities.

The UK has some excellent research facilities. These could provide value to the nuclear sector and to the research community and, in particular, its contribution to training the next generation of experts. It would also increase the attractiveness of the UK as a location for international research collaboration.

'The UK supply chain has a strong capability in most of the areas required to support a new nuclear build programme, and UK industry could supply around 70% of the total requirements for such a programme. Furthermore, it is estimated that with some investment in facilities and the training of new personnel, this capability could be increased to a little over 80%'.

Nuclear Industry Association

[10] Northwest Regional Development Agency (2006), Northwest Nuclear: A Strategic Approach to the Nuclear Sector in the Region.
[11] Department of Energy & Climate Change (2011), Nuclear Key Facts.
[12] NIA (2008), The UK Capability to Deliver a New Nuclear Build Programme.
[13] Northwest Regional Development Agency (2006), Northwest Nuclear: A Strategic Approach to the Nuclear Sector in the Region.

Replacement and Expansion Scenarios

Nuclear energy currently supplies 16% of the UK's electricity (~11 GW capacity), but will decrease over the next decade and a half, as all but one of the UK's nuclear reactors are closed down and decommissioned.[14] Current industry plans will see a new build programme to replace this capacity using Generation III LWR reactors, which are expected to deliver up to 16 GW of capacity by 2025.[15] The scenarios analysed[16] in this report are aimed at exploring the implications of expanding the fleet beyond 2025 and the potential benefits to the UK nuclear industry.

Many energy scenarios for a secure, low-carbon energy system indicate that considerably greater nuclear capacity may be needed by 2050 (see Table 2). How much capacity will depend on a number of factors, including the cost and scale of deployment of other low-carbon supply technologies, overall demand for electricity and the success of the current new nuclear build programme. Based on this energy modelling, two scenarios for nuclear capacity up to 2050 were chosen for analysis: 16 GW, based on the current plans and 40 GW of expansion. Figure 2 and Figure 3 illustrate what this will mean in terms of generating output. Some models suggest higher capacity may be needed but it was decided that both of the options chosen were realistic and feasible.

Several pathways for achieving the 40 GW scenario are possible, such as a once-through open fuel cycle or a closed system where spent fuel and other wastes are reprocessed into new fuel and burnt in a Generation IV fast reactor. For further details see Appendix 4. Many other pathways exist including the use of alternative fuels, such as thorium. Each pathway has significant differences in the amount and type of waste produced, the overall demand for fuel and the infrastructure, R&D and skills that will be needed to deploy them.

The choice of pathway and which technologies are developed in the UK, will also affect the opportunities for the UK supply chain, not only to the domestic market but also to benefit from the growing global market in nuclear power. As this analysis highlights, decisions about which technology option is deployed in the UK should be based on assessments of a number of key issues highlighted by this report.

Based on the two scenarios, 16 GW and 40 GW, Table 3 outlines the six main technology pathways. Two bounding scenarios for new build were considered in detail (Scenario 3 'Replacement' and Scenario 6 'Expansion'); the 16 GW open fuel cycle with recycling of historic plutonium reflects current proposals, while the 40 GW closed fuel cycle with development of Generation IV fast reactors was chosen to explore the implications of a significant increase in nuclear power generation and what would be required to keep this option open. Modelling work was undertaken to understand the fuel demand and waste arisings for each pathway. From this the technologies that would be needed were identified, when they would need to be operational and the R&D required to deliver them.

Parsons Brinckerhoff,[17] 2009	2050 require min 16 GW – max 25 GW Build rate: Max 1.5 GW/yr, expected 1.2 GW/yr
UKERC Carbon Ambition Scenario[18], 2009	2000 = 12 GW 2035 = 9 GW 2050 = 29 GW
UKERC range for all scenarios[19]	2035 = 9–30 GW 2050 = 12–38 GW
MacKay[20] Plan C	Up to 70 GW by 2050 (note: supply/not capacity) First built in 2018, add 2.2 GW per year
Committee on Climate Change[21] , 2008	Limit on nuclear and CCS expansion of 3 GW/yr up to 2030 and 5 GW/yr after 2030
Royal Academy of Engineering[22] , 2010	30 nuclear power plants likely to be required by 2050
HM Government[23], 2010 2050 Pathways Analysis	Level 1 = No new build Level 2 ('Ambitious, reasonable') = 39 GW in 2050 Level 3 ('Very ambitious') = 90 GW in 2050 Level 4 ('Extreme upper end') = 146 GW in 2050
HM Government[24], 2011 The Carbon Plan	Core scenario = 33 GW in 2050 Other scenarios range from 16–75 GW in 2050

Table 2: Potential scale of deployment of nuclear power in 2050 from various UK energy scenarios

[14] World Nuclear Association, Nuclear Power in the UK.

[15] Department of Energy & Climate Change (2011), Nuclear Key Facts.

[16] Modelling of the scenario fuel cycles with the NNL ORION fuel cycle modelling tool provided the underpinning analysis for evaluation in the roadmapping process.

[17] Parsons Brinckerhoff (2009) Powering the Future: Mapping our low-carbon path to 2050.

[18] UKERC (2009), Making the transition to a secure and low-carbon energy system.

[19] ibid

[20] MacKay (2009), Plan C, Supplement to Sustainable Energy – Without the Hot Air.

[21] CCC (2008), Building a low-carbon economy.

[22] RAEng (2010), Generating the Future: UK energy systems fit for 2050.

[23] HM Government (2010), 2050 Pathways Analysis.

[24] HM Government (2011), The Carbon Plan: Delivering our low carbon future.

Scenario	Electrical Generation	Fuel Cycle	Reactor Generation	Technology Description	Roadmap Scenarios
1	No new build	N/A	N/A	- Baseline used for scenario analysis in this report.	
2	16 GW construction to 2025	Open	Generation III	- No recycling of historic plutonium – current situation.	
3	16 GW construction to 2025	Open	Generation III	- Recycle of historic plutonium to produce fuel for Generation III reactors.	Replacement
4	16 GW construction to 2025 and then build up to 40 GW to 2050	Open	Generation III	- Assume historic plutonium is recycled (i.e. Scenario 3 for first 16 GW). - Dispose of spent fuel in GDF – no further reprocessing.	
5	16 GW construction to 2025 and then build up to 40 GW to 2050	Closed	Generation III	- Use historic plutonium as MOX fuel for Generation III reactors. - Reprocess spent fuel from new build Generation III reactors (uranium) to produce new fuel for reactors.	
6	16 GW construction to 2025 and then build up to 40 GW to 2050	Closed	Generation III & Generation IV	- Generation III with Generation IV fast reactors from 2040 (the earliest assumed date for commercial deployment of fast reactors). - Use historic plutonium as MOX fuel for Generation III reactors. - Reprocess spent fuel from new build Gen III reactors (inc. plutonium and uranium) to produce fuel for Generation IV fast reactors.	Expansion

Table 3: Nuclear scenarios considered for roadmapping

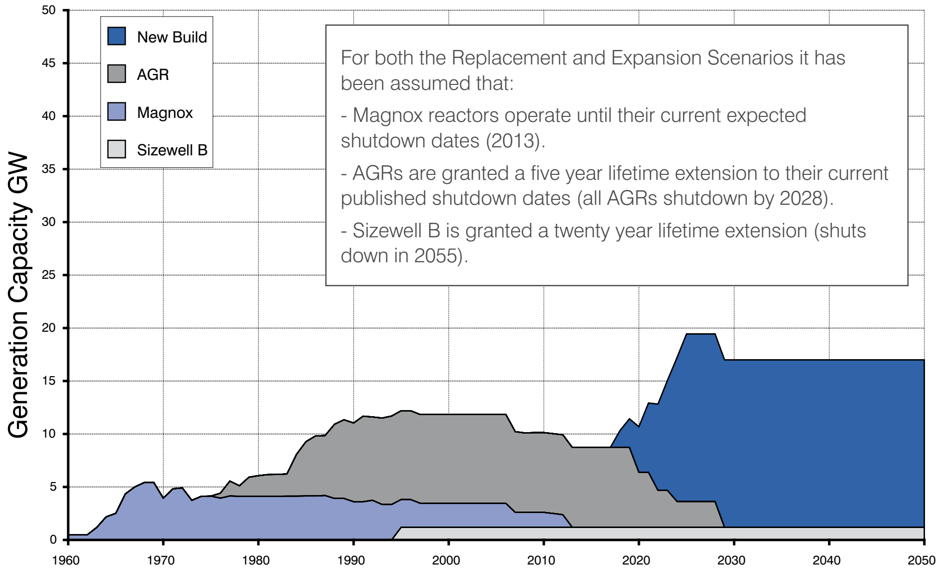


Figure 2: Replacement Scenario - installed nuclear electrical generation capacity per year to 2050

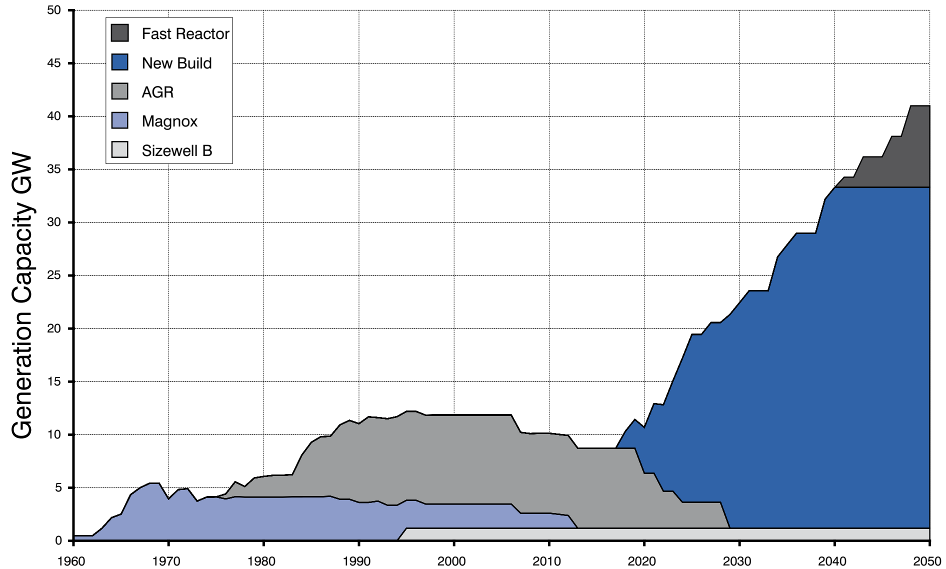


Figure 3: Expansion Scenario - installed nuclear electrical generation capacity per year to 2050

Implications of the Scenarios

As has been highlighted in previous sections, in preparing a long-term strategy for nuclear generation and development of the nuclear industry, a number of decisions will need to be made that should be based on detailed analysis of key issues. This report maps two scenarios and the following section explores some of the issues and considers their implications and the timeframes within which they should be addressed.

Uranium Supply

There is some uncertainty about the global supply and cost of uranium over the long timescales that it might be required, as availability will be affected by the scale of deployment and the choice of technologies, both in the UK and internationally. It is widely agreed, internationally, that sufficient uranium ore reserves are already identified to satisfy global demand from a moderate expansion of nuclear generation. Higher growth would drive up costs as lower grade ore is mined. While the overall cost of obtaining uranium ore is only a small part of the cost of generation, ensuring a secure, reliable supply could become a significant issue, particularly for a larger nuclear fleet. One projection indicates that the demand for uranium, from the expected growth in new nuclear LWRs globally, would exceed identified reserves in about 2060 and exceed estimated (as yet undiscovered) reserves by 2100.[25] Figure 4 illustrates the demand for uranium ore in both the 16 GW Replacement and 40 GW Expansion Scenarios.

With such uncertainty, a detailed evaluation is needed of the availability of fuel required to supply any nuclear programme, given that any new fleet of reactors is likely to be operational for at least 60 years. With better data and an improved understanding, an assessment can be made as to whether other options for assuring fuel supply will be required. These need to be considered alongside analysis of the waste arisings, the fuel cycle and the use of plutonium. This is primarily a Government decision as it will require policy intervention to implement.

For a 16 GW scenario the availability of uranium is unlikely to present a serious problem. It was assumed that part of the fissile material for fuel will come from utilising the UK's historic stock of plutonium as MOX fuel.

If it was determined that the global developments might increase the demand for uranium such that it presents an issue for future UK nuclear operations then one option would be to close the fuel cycle, as explored in the 40 GW Expansion Scenario. Fuel for the Generation IV fast reactor could be produced by reprocessing spent fuel from the Generation III reactors. Developing a sustainable supply of fissile material through a closed fuel cycle would greatly reduce the demand for uranium ore. Figure 5 illustrates the effect of closing the fuel cycle on the demand for uranium ore from a 40 GW fleet.

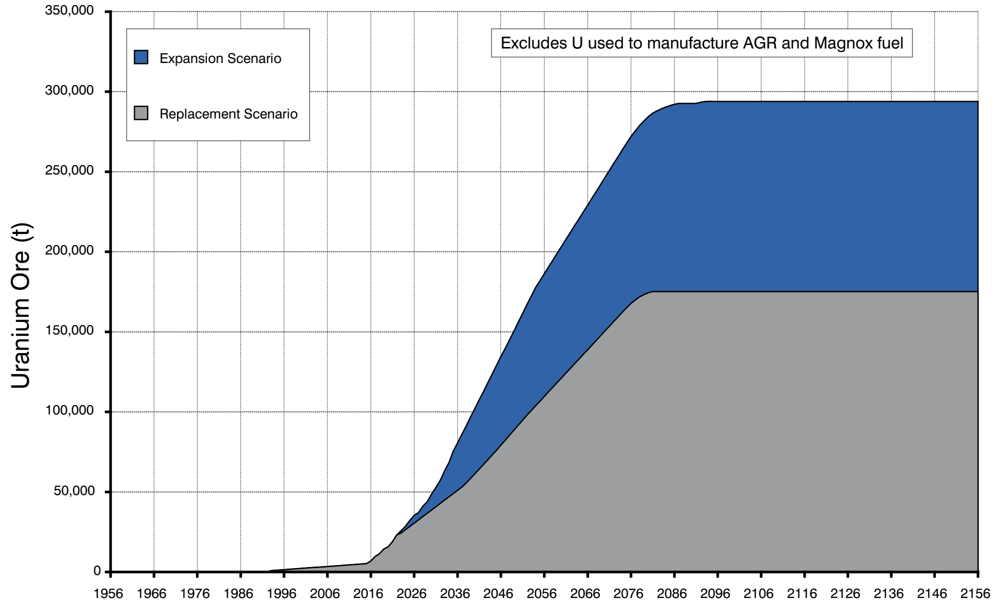


Figure 4 Uranium ore demand for Replacement and Expansion Scenarios

'Commercial deployment of fast reactors with a closed fuel cycle by 2050 would maintain the uranium demand within the estimated reserves indefinitely (although there are some fairly major assumptions about stabilisation of growth in world population and energy demand). Such is the fineness of the balance that a decade delay in implementing fast reactors could result in uranium shortages towards the end of the century'.

AMEC submission to House of Lords Select Committee on Science and Technology

[25] House of Lords (2011), Science and Technology Select Committee, Nuclear Research and Development Capabilities, Oral and Written Evidence, Memorandum by Amec (NRD 41).

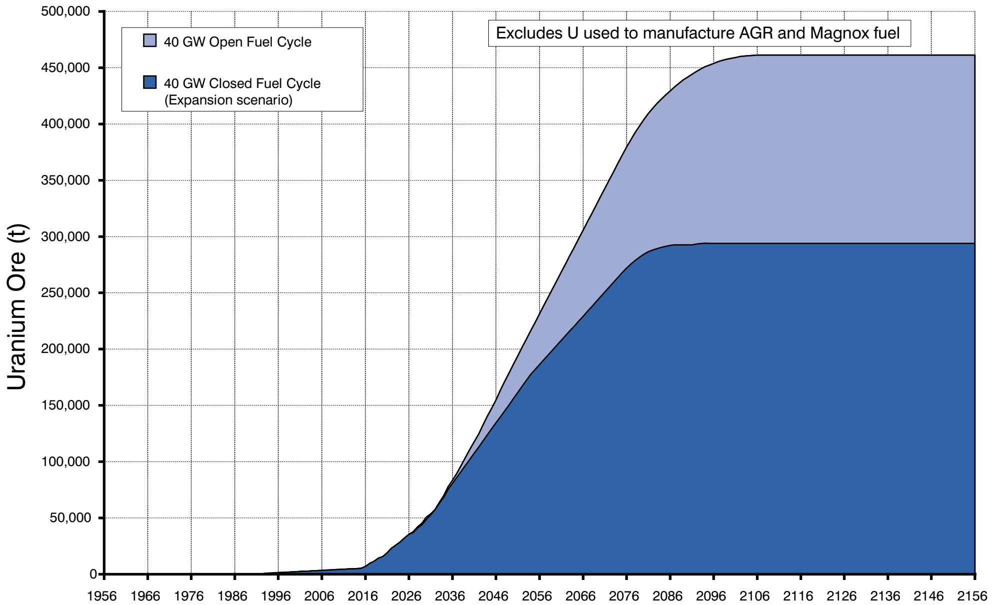


Figure 5 Uranium ore demand for 40 GW open fuel cycle (Scenario 4) and 40 GW closed fuel cycle (Expansion Scenario)

Waste Arisings and Fuel Cycle

Modelling work for both the 16 GW Replacement and 40 GW Expansion Scenarios set out the types of waste material produced. As might be expected, the level of spent fuel arisings from a 40 GW once-through open fuel cycle scenario is significantly greater (x 2.5) than for 16 GW open cycle (Figure 6). Increasing the volume of waste from an expanded nuclear programme would have to be accounted for in the design of the Geological Disposal Facility (GDF) and any long-term storage strategy for spent fuel. Closing the fuel cycle, as set out in the 40 GW Expansion Scenario, would change the types of waste produced, reducing the amount of spent fuel produced from the Generation III reactors and producing more Higher Activity Waste (HAW)[26] from the reprocessing. Detailed analysis is required to understand the waste arisings from an expanded nuclear fleet, the implications of closing the fuel cycle and from final closure of any programme. Early assessment is needed of the implications for management of spent fuel from both scenarios, especially the Expansion Scenario, to ensure appropriate provision is made as the GDF is progressed in the coming decade.[27]

In the 16 GW Replacement Scenario spent fuel from new build plants is of a type that is already well understood in the UK today. It is well characterised, widely used internationally and suitable for long-term dry storage. Assessment of the long-term storage of spent Generation III fuel, either on-site or in a centralised store, must also be part of the consideration of future fuel cycle options.

In an expanded 40 GW scenario if the back end of the fuel cycle is a prime driver for the technology requirements then reprocessing technology may be needed, in which case an active pilot plant will need to be demonstrated around 2020–2030. Appropriate investment would be needed in the infrastructure, R&D and the skills base to keep this option open. In order to retain the UK's current expertise in recycling technologies an active programme would need to be in place in the next few years to maintain and refresh capabilities.

If the fuel cycle is closed using Generation IV fast reactors there is potential to provide a sustainable fuel supply for future nuclear programmes. As the Generation III reactors are closed they could be replaced by Generation IV fast reactors. However, if it was decided to close the nuclear programme after the first round of fast reactors then a strategy would need to be in place to ensure separated plutonium and spent fuel is eventually minimised through use of the fast reactor as a burner. Consideration is needed of the very long-term waste management issues well beyond 2050.

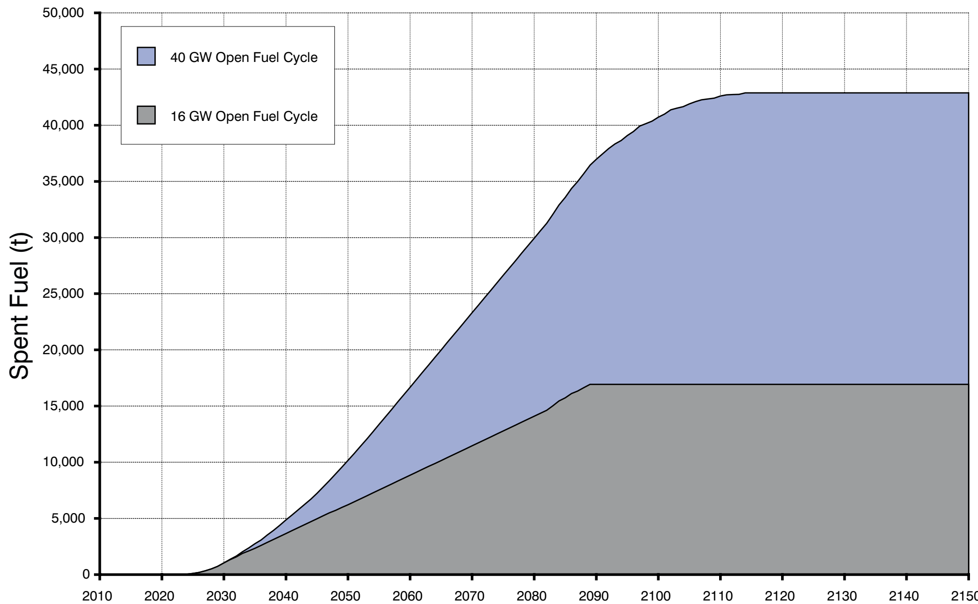


Figure 6 Comparison of spent fuel arisings from 16 GW and 40 GW open cycle nuclear fleets

[26] HAW includes HLW, ILW and some LLW unsuitable for prompt disposal at the LLW repository.

[27] DECC (2011), Management of Wastes from New Nuclear Build: Implications of the Generic Disposal System Safety Case for Assessment of Waste Disposability.

Plutonium Management

In the 16 GW Replacement Scenario the use of reprocessed plutonium could meet a significant proportion of the UK's fuel demand and provide an effective and technically proven management strategy for the stockpile. A new MOX fabrication facility would need to be constructed in the UK and any reactor that uses the MOX fuel would need to be suitably licensed. The existing AP1000 and European Pressurised Reactor (EPR) Justification does not cover MOX as a fuel so, if the UK nuclear new build utilities wanted to burn MOX fuel in reactors a new Justification exercise would have to be undertaken, which could take a number of years. The GDF regulatory regime is appropriate however, for disposal of MOX although further consideration would be required to support this aspect.

Investment in an operational recycling facility and the infrastructure to reuse the UK's stockpile of separated plutonium would allow the UK to continue providing national and international reuse services.

In the 40 GW Expansion Scenario the Generation IV fast reactors require plutonium for start-up, but are also able to utilise it efficiently as a fuel. The operation of both the Generation III reactors and the fast reactors can be adjusted so as to optimise the amount of fissile material that can be recovered and reused. This can allow either the development of a long-term sustainable fuel supply or, if the nuclear fission programme is to be phased out, burning up of the harder to manage materials.

Government intervention and policy on reprocessed uranium and plutonium recycle needs to be clear and consistent as it will have an impact for many decades ahead. A key issue for both scenarios is the reuse of plutonium; a new MOX plant to produce fuel for UK reactors requires Justification from the Secretary of State and thus requires an appropriate policy framework to be in place. The timing for such considerations depends upon the pace of new build development, technology development and utility demand. Government and NDA are currently developing the approach.

If plutonium was not utilised as a fuel, either as MOX in the Generation III reactors or in the fast reactors, disposal to a GDF in the UK would require an approved waste-form for the plutonium to be developed and the construction and operation of a plant in which to make it. The GDF could be made suitable to receive the plutonium waste.

Reactor Options

In the 16 GW Replacement Scenario analysed for this report the reactor choice is based on current proposals of either EPR or AP1000, but with some adapted to use MOX fuel. For the 40 GW Expansion Scenario, Generation III reactors are deployed to 2040 before switching to a Generation IV sodium-cooled fast reactor; the earliest assumed date for their commercial deployment. This is not the only fast reactor design available for consideration, but it presents a credible technology option, given the current international focus, experience of prototypes worldwide and the UK's historic expertise. For further details of nuclear reactor systems see Appendix 5.

If the UK is to deploy fast reactors as part of the energy mix before 2050, it needs to demonstrate the technology at least 15 years before industrial deployment (i.e. around 2025 to start demonstration operations and conduct the necessary R&D on the overall fuel cycle to be online in 2040). Prior to the demonstration projects, investment is required in underpinning R&D. A credible option would be for the UK to work with France on a collaborative (European) programme and the USA on an international programme, such as Generation IV. The UK could contribute to the development of the reactor fuel cycle with its expertise in fuel manufacturing and advanced reprocessing technology. A decision to be engaged should be made within the next three years to ensure engagement and retain UK expertise.

If it was decided not to collaborate and to buy in a fast reactor from an overseas supplier, the UK could still develop an indigenous capability in key fuel cycle areas such as fuel fabrication, recycling, waste management, and regulations.

An alternative option is to completely rely on fuel and recycling services based outside the UK.

These various options need to be examined at a strategic level, as they will require capability to regulate and licence the technologies and will have implications for the R&D and the degree to which UK industry may benefit from opportunities in the long-term international market.

Build Programme

The UK nuclear industry needs to demonstrate in the early years of the new build programme that the fleet can deliver full power and the promised performance to a high standard of safety. Achieving either scenario, particularly an expanded programme, will depend on this confidence and certainty of the industry to deliver. The rate of reactor build could become a limiting factor in the event of a dramatic nuclear expansion in the UK, with significant demand placed on resources, including the construction teams and scientific and engineering expertise in the UK. Plans to expand the fleet further will need to be in place well before 2025 if the benefits of a continuous build plan are to be realised.

Siting

In the event of a notable expansion of nuclear capacity (greater than 25 GW), an extension to the existing site boundaries or a greater number of sites than those already identified may be required. An assessment is therefore required of the potential to extend the boundary fences of existing sites and to identify possible future sites.

Alternative Reactor Designs

Global interest is also growing in new Generation III LWR technology in the form of Small Modular Reactors (SMRs), which could be deployed over the coming three decades. Here the UK may have the capability to play a significant role. It is vital these opportunities are properly understood so that targeted support can be provided and underpinning R&D requirements specified.

Other reactor systems are also in development and may become commercially viable for deployment. These include GE-Hitachi's Power Reactor Innovative Small Module (PRISM) reactor and other Generation IV systems, such as the Very High Temperature reactors (which could also provide process heat and hydrogen) and other designs of fast and fast breeder reactors. In order for these to be deployed in the UK, sufficient capability will need to be available to regulate them and deliver the necessary fuel cycle system support. Delivering this capability will require maintaining an R&D base that can provide the expertise and capacity.

Research and Development

As this analysis has shown, which pathway is chosen has significantly different technology requirements and opportunities for development by UK industry. R&D is required to support these different options, but given the long-lead times on many of these technologies, keeping these options open requires investing in R&D many years in advance. To ensure that these investments are coordinated and aligned across the public and private sectors a strategy is needed for the development of the nuclear sector on which a detailed roadmap for R&D is based. A detailed assessment is required of the R&D requirements to support the possible energy pathways and to the development of the supply chain. From a UK perspective the opportunities for nuclear R&D are to:

- Use the UK's early position in the nuclear renaissance to rejuvenate its nuclear industry and gain a share of the export growth in nuclear.
- Maintain its ability to be a responsible host of current and planned power reactors from a safety, environmental, security and non-proliferation perspective.
- Gain the benefit from on-going LWR developments.
- Develop a position in the international fast reactor and fuel cycle technology programmes.
- Mitigate technical risks associated with the reactors and fuel cycle in the future.
- Enable the UK to make informed decisions on future nuclear energy strategy and policy.
- Enable the UK future strategies to be flexible by providing appropriate levels of capabilities, expertise and facilities.

The existing fleet and a replacement new build programme require long-term R&D capabilities and associated expertise to enable:[28]

- The safe running of the current fleet and life extension options.
- The safe operation of the new Generation III fleet for 60 years or more.
- Deployment of advanced Generation III fuel manufacturing and associated technologies.
- Decommissioning and waste management of legacy and new build waste, including spent fuel.
- Continuation of the UK's reprocessing commitments up to 2018.
- Implementation of the UK's geological disposal plans.

Depending on the outcome of current considerations, R&D capabilities and associated expertise associated with implementation of a plutonium reuse strategy may also be required.

A new build programme for the 40 GW Expansion Scenario additionally requires the long-term R&D capabilities and associated expertise to enable options for:

- A Generation IV fast reactor programme.
- An advanced reprocessing programme for uranium and plutonium.
- Deployment of advanced Generation IV fast reactor fuel manufacturing and associated technologies.

If this option is to be kept open then demonstration facilities will be required in advance of commercial deployment, which will need to be preceded by underpinning R&D. The roadmapping exercise in this report indicates that this investment should start as soon as possible.

Developing the strategy requires a focal point in Government that can provide an oversight to the UK's nuclear aspirations and provide a cohesive and coordinated approach. It should be supported by a body made up of Government, industry, regulators, NNL, NDA and academia and provide oversight of the whole UK nuclear R&D landscape and own, inform and lead detailed assessments of the key areas of an R&D roadmap, to ensure opportunities to exploit UK expertise are maximised. Key national assets, such as the NNL and the NAMRC, could be utilised and capitalised upon to help realise the global opportunities associated with new nuclear build programmes.

This coordinating body would also direct a strategic approach to the UK's involvement in international collaborations and research programmes that are of interest to the UK, such as the European Atomic Energy Community (Euratom) programme and the Generation IV International Forum (GIF), either directly or through Euratom, or other bilateral/multilateral collaborative programmes.

UK R&D facilities could provide significant assistance to international developers planning to build nuclear plants in the UK, including detailed, site-specific investigations to underpin the claims made in the safety cases for these reactors.

[28] House of Lords (2011), Nuclear Research and Development Capabilities. House of Lords. Select Committee on Science and Technology.

International Collaboration

The scale and cost of developing a Generation IV fast reactor and fuel cycle will mean that it will be most effectively developed through a cooperative programme. Over the 2010-2020 period, European funding needs for the R&D effort (including deployment) are estimated at €11 billion.[29]

If the UK is to keep the option open for a fast reactor in the future, international collaborations on advanced fuel reactor and fuel cycle R&D, particularly with France and USA, would be an efficient way to share the costs and would provide leverage for UK investment. Collaboration would enable the UK to act as intelligent customer (e.g. by gaining access to underpinning intellectual property to be able to operate) when buying new plants and provide opportunities to understand its operation and regulation, including opportunities to train regulators, if required. A decision in the next three years would help retain and develop UK expert capability to ensure safety compliance in future nuclear activities.

From a commercial perspective, engagement in such technology development would allow UK industry to exploit commercial opportunities in niche areas in the international market.

Skills and Regulation

Nuclear specialists, including highly qualified scientists and engineers will be needed by the utilities, supply chain, regulators, Government and other stakeholders. An active R&D programme is valuable for developing a domestic skills base that can help ensure the safe operation and maintenance of a nuclear energy programme, but also to maintain and develop the expertise that will allow the UK to make decisions about deployment of future reactor and fuel systems. Such a research base would also help develop the skills pipeline that will be needed by the nuclear sector.

An important part of this demand will come from the regulators, in order to understand the technologies being deployed and potentially to be able to influence their development. The demand is significant; ONR currently has 77 projected nuclear safety inspector vacancies within its current three-year workforce plan. Based on intelligence from the industry they estimate that, for new build alone, a further 80 inspectors could be needed by 2017/18, and then a further 35 by 2020/21. Additional demand will come from the Environment Agency. Any expansion of the nuclear programme or deployment will require timely consideration of the skills requirement to ensure the regulators have the appropriate capability.

If the UK is to capitalise on its expertise and experience from past R&D programmes then decisions need to be made promptly. Many of the experts in the key areas, who are regarded as national and international experts, are close to retirement. This leaves a limited window of opportunity for the UK to draw on this expertise to train new people. Any delays in addressing this will mean that the UK will become increasingly dependent on overseas training programmes to deliver its capability.

Once the requirements for the Generation IV technical, construction and operational workforce are sufficiently defined, a further study should be undertaken (building on the Cogent ‘Renaissance 2’ report[30]) to evaluate the requirements in detail.

International collaborations could provide access to relevant technologies that may be needed over the next four decades and consideration should be given to the potential for gaining experience and expertise from participating in them. Collaboration would also provide an opportunity for training regulators and help harmonise international regulation to de-risk licensing. Engagement by the ONR would help regulators to prepare and identify the R&D required for the development of operators and regulators.

Skilled crafts-people will be needed for the construction and manufacture of the new build programme and its on-going maintenance. Delivering these skills requires a strategy to be in place to ensure that the appropriate skills are available through the duration of the new build programme. If the UK is to keep the option open for an extension to the current nuclear programme, timely decisions need to be made to ensure the skills delivery pipeline is in place beyond the 16 GW replacement programme. Any delays or gaps in delivering a coordinated programme will lead to a drop in capacity of jobs and skills requiring additional training interventions to recover this capability and possibly a reliance on importing transitory skills from abroad to fill the gaps.

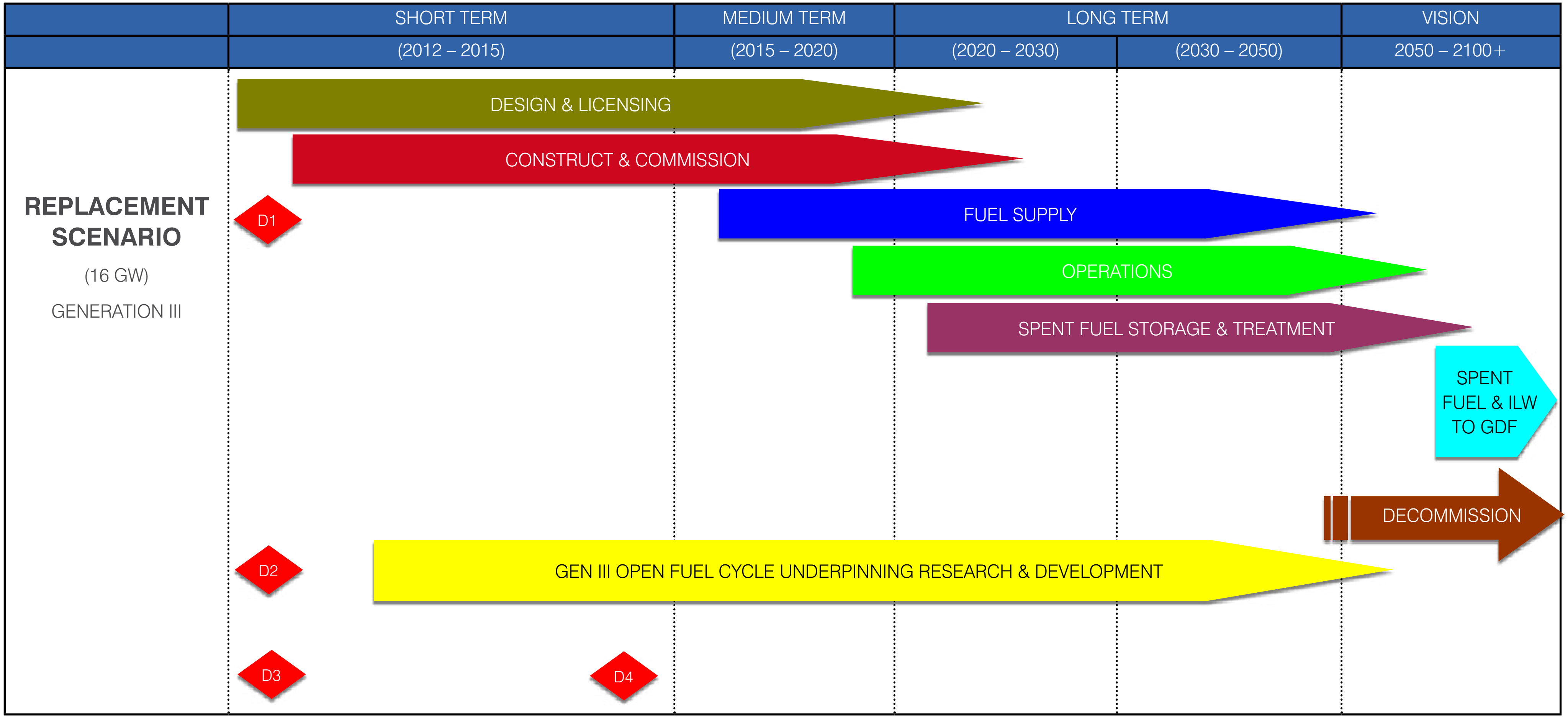
The demand for skills requires careful planning due to the significant ‘volume’ of people required across a range of skills and occupations. This will be compounded by nuclear awareness and safety training requirements associated with working under a regulated nuclear site license from the outset of construction. The first new builds could provide on the job training, which could be a valuable part of delivering the supply of graduates and apprentices of sufficient quality and with the capability of acquiring the right ‘behaviours’. Coupled with an appropriate accreditation process, this could provide an efficient route to employers. Such proposals are being explored by Cogent and the National Skills Academy for Nuclear, along with the NAMRC and Semta for manufacturing.

[29] SNETP (2011), EU Multi-annual Financial Framework 2014-2020: Aligning nuclear fission R&D budgets to reach SET-Plan targets - Position Paper.

[30] Cogent (2010), Renaissance Nuclear Skills Series, Next Generation: Skills for New Build Nuclear.

High-Level Summary Roadmap

The high-level summary Replacement and Expansion Scenario Roadmap emphasises the sequence of events and the key decision points associated with both of the nuclear scenarios.



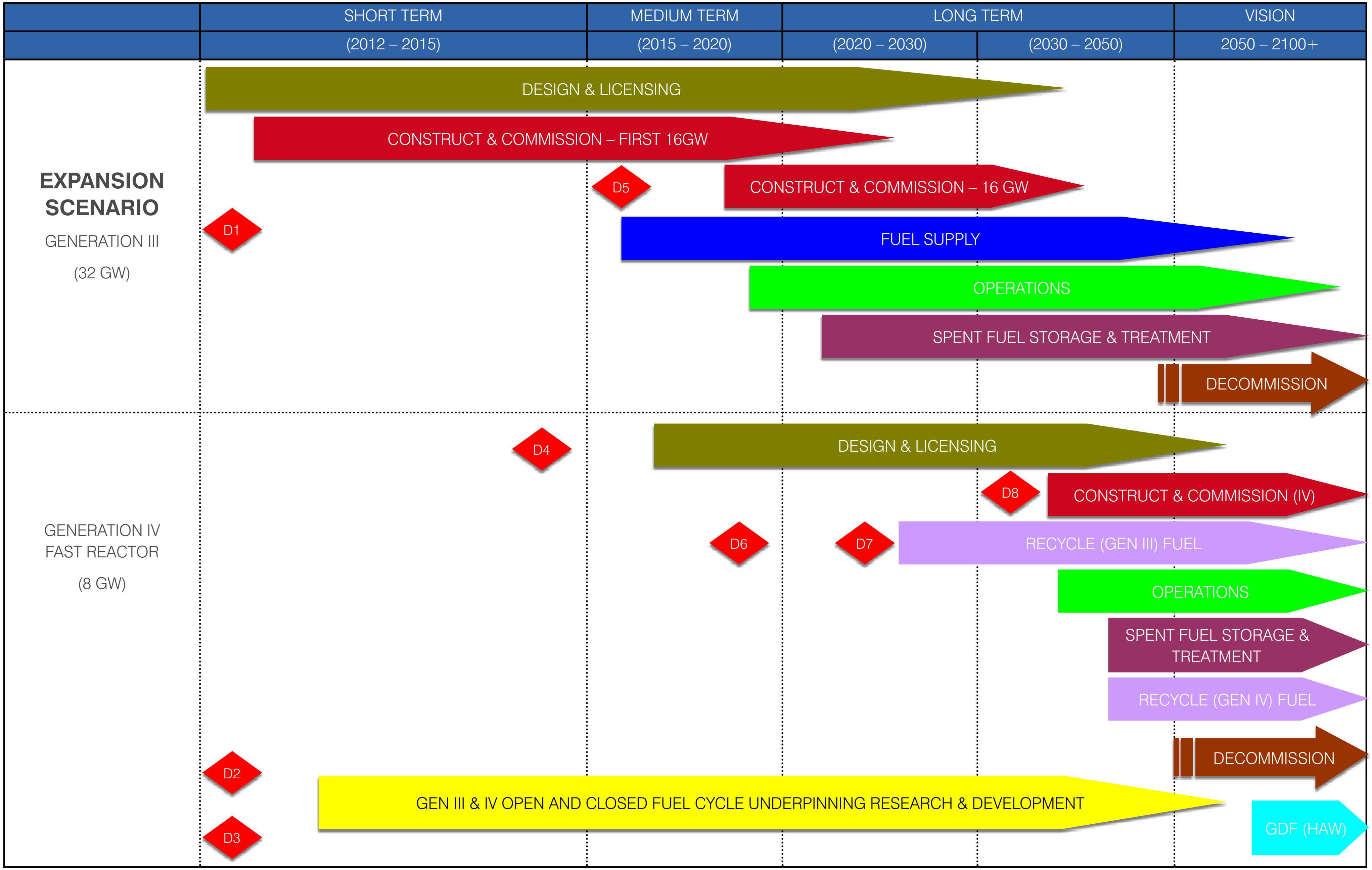

SHORT TERM
MEDIUM TERM
LONG TERM
VISION
(2012 – 2015)
(2015 – 2020)
(2020 – 2030)
(2030 – 2050)
2050 – 2100+
EXPANSION SCENARIO
GENERATION III
(32 GW)
DESIGN & LICENSING
CONSTRUCT & COMMISSION – FIRST 16GW
D5
CONSTRUCT & COMMISSION – 16 GW
D1
FUEL SUPPLY
OPERATIONS
SPENT FUEL STORAGE & TREATMENT
DECOMMISSION
GENERATION IV
FAST REACTOR
(8 GW)
D4
DESIGN & LICENSING
D8
CONSTRUCT & COMMISSION (IV)
D6
D7
RECYCLE (GEN III) FUEL
OPERATIONS
SPENT FUEL STORAGE & TREATMENT
RECYCLE (GEN IV) FUEL
DECOMMISSION
D2
GEN III & IV OPEN AND CLOSED FUEL CYCLE UNDERPINNING RESEARCH & DEVELOPMENT
GDF (HAW)
D3

Table 4 shows the critical decisions that the UK Government will need to address to deliver the 16 GW Replacement and 40 GW Expansion Scenarios.

No.	Date	Activity	Outcome
D1	2012 - 2013	Evaluation of the UK's stockpile of separated plutonium for use as a fuel in thermal MOX reactors.	Give assurance as to the suitability of the plutonium for use as fuel.
D2	2012	Commitment to a national R&D programme to support the Generation III new build fuel cycle.	Realise UK business opportunity from delivering associated R&D programme and growing Generation III technology capability. Secure UK Generation III technology facilities, capabilities and skills.
D3	2012	Assessment of spent fuel and waste arisings from possible generation scenarios. Detailed evaluation of global supply of uranium and fissile material for fuel and assessment of implications for future UK capacity and various technology pathways over lifetime of programme. Evaluation of the 40 GW closed fuel cycle scenario challenges in technology, siting, spent fuel disposal, fissile material resource (uranium ore, plutonium and reprocessed uranium) and hence drivers for Generation IV fast reactors. Decision on a national R&D programme to support the Generation III/Generation IV sustainable nuclear expansion.	Ensure appropriate provision is made during development of the GDF. Provide understanding of security of fuel supply as basis for making decisions about future technology pathways. Keep Generation IV fast reactor and closed fuel cycle options open. Secure UK Generation IV technology facilities, capabilities and skills.
D4	2015	Establish collaboration agreements for international Generation IV fast reactor and associated fuel cycle programmes. The UK could provide valuable underpinning fuel cycle R&D, giving facility and resource access to develop advanced systems.	Gain experience and understanding of Generation IV fast reactor and associated fuel cycle technology capability to keep option open. Realise UK business opportunity from delivering associated R&D programme.
D5	2015 - 2020	Decision to permit second tranche of Generation III reactors, based on the success of first new build projects and the scale of deployment of other low carbon technologies.	Ensure continuity in construction workforce and supply chain between build programmes.
D6	2019	Evaluation of the need for reprocessing Generation III LWR spent fuel.	Keep closed cycle option open for LWR fuel.
D7	2024	Evaluation of the need for reprocessing Generation III MOX spent fuel.	Keep closed cycle option open for MOX fuel and enables sufficient plutonium for first Generation IV fast reactor fleet.
D8	2030	Commence permitting process for first tranche of Generation IV fast reactor fleet.	Enable first Generation IV fast reactor on grid by 2040.

Table 4: Critical decisions and outcomes

Overview of the Technology Roadmap

The figure below summarises the assets, technologies and capabilities, enablers and the opportunity areas identified from the Technology Roadmap on the subsequent pages and shows these together with overarching trends and drivers which were derived during the development of the Roadmap.

TRENDS AND DRIVERS

Government Strategy – UK Nuclear R&D Capability: will determine industry future

Plutonium Management Policy Decision: will determine plutonium reuse strategy

Meeting Office for Nuclear Development (OND) objectives for new nuclear build will require:

- Programme acceleration
- Realisation of opportunities from world-wide nuclear renaissance
- Meeting new nuclear skills requirements
- Development of a globally competitive UK supply chain

Global supply and demand for uranium will drive need for attaining a sustainable fuel cycle

Delivering an affordable solution will require:

- Reducing uncertainty in generation costs
- Driving down whole-life fuel cycle costs

ASSETS

Replacement Scenario:

16 GW installed by 2025 (Generation III technology)

- R&D Facilities for Generation III
  - o NNL
  - o NAMRC
  - o Vendor/Utility
  - o Regulator
- Generation III UO_2 Fuel Fabrication Facility
- Generation III MOX Fuel Fabrication Facility
- Generation III Irradiated Fuel Storage & Treatment Facilities

- **Geological Disposal Facility (Irradiated Fuel and ILW)**

Expansion Scenario:

40 GW installed by 2050 (Generation III and IV technology)
- 32 GW Generation III reactors installed by 2040
- 8 GW Generation IV fast reactors between 2040 and 2050

Further assets required, in addition to those listed on the Replacement Scenario:

- Reprocessing of LWR Uranium Spent Fuel
- Demo Prototype Gen IV Fast Reactor
- R&D Final Demo (Hot Cells)/Pilot Plant for Advanced LWR and MOX Aqueous Reprocessing
- LWR and MOX Fuel Advanced Aqueous Reprocessing Facility[31]
- Advanced Reprocessing Pyro[32] Head End Demo
- Fast Reactor Fuel Manufacturing Facility
- Fast Reactor Fuel Reprocessing Facility
- Pyro Head End to Fast Reactor Reprocessing Facility
- Generation III Irradiated Fuel Storage Facilities
- Generation IV Irradiated Fuel Storage Facilities

- **Geological Disposal Facility (Higher Activity Waste (HAW))**

For clarity on the Roadmap diagrams, storage and/or treatment of wastes (other than irradiated fuel) is not shown.

Opportunity areas are shown as ★ in the overall Roadmap (and also in this figure, with further detail). Decision points from Table 4 are shown in the Roadmap as follows: ◆.

[31] Advanced aqueous reprocessing of Generation III fuel.

[32] Pyrochemical reprocessing of Generation IV fuel.

TECHNOLOGIES & CAPABILITIES

- Gen II Supply Chain Capabilities
- Gen III Supply Chain Capabilities ★
- Technology and Capability for Gen III ★
- Technology and Capability for Gen III with MOX ★
- Technology and Capability for Gen IV (inc. the associated Fuel Cycle) ★

ENABLERS

- Establish Policy Framework (Co-ordinating Body)
- Define R&D Programmes for Gen III and Gen IV and the associated Fuel Cycle
- Maintain Gen III Capability including MOX
- Develop Gen IV Capability
- International R&D Collaboration - ★
  - o Advanced Gen III fuels
  - o Long-term fuel storage (Gen III)
  - o Gen IV FR fuels
  - o Gen IV FR design
  - o Geological Disposal
  - o Advanced Reprocessing (Aqueous and Pyro)
- Skills Transfer from Decommissioning Market
- Increase Regulatory Inspection Resources
- Regulatory Licensing of Gen III MOX
- Regulatory Licensing of Gen IV

TECHNOLOGY ROADMAP

The Roadmap in the analysis of the 16 GW Replacement and 40 GW Expansion Scenarios were developed progressively through a series of Expert Group workshops: Supply Chain, Skills, Technology and R&D, Stakeholder and Regulations.

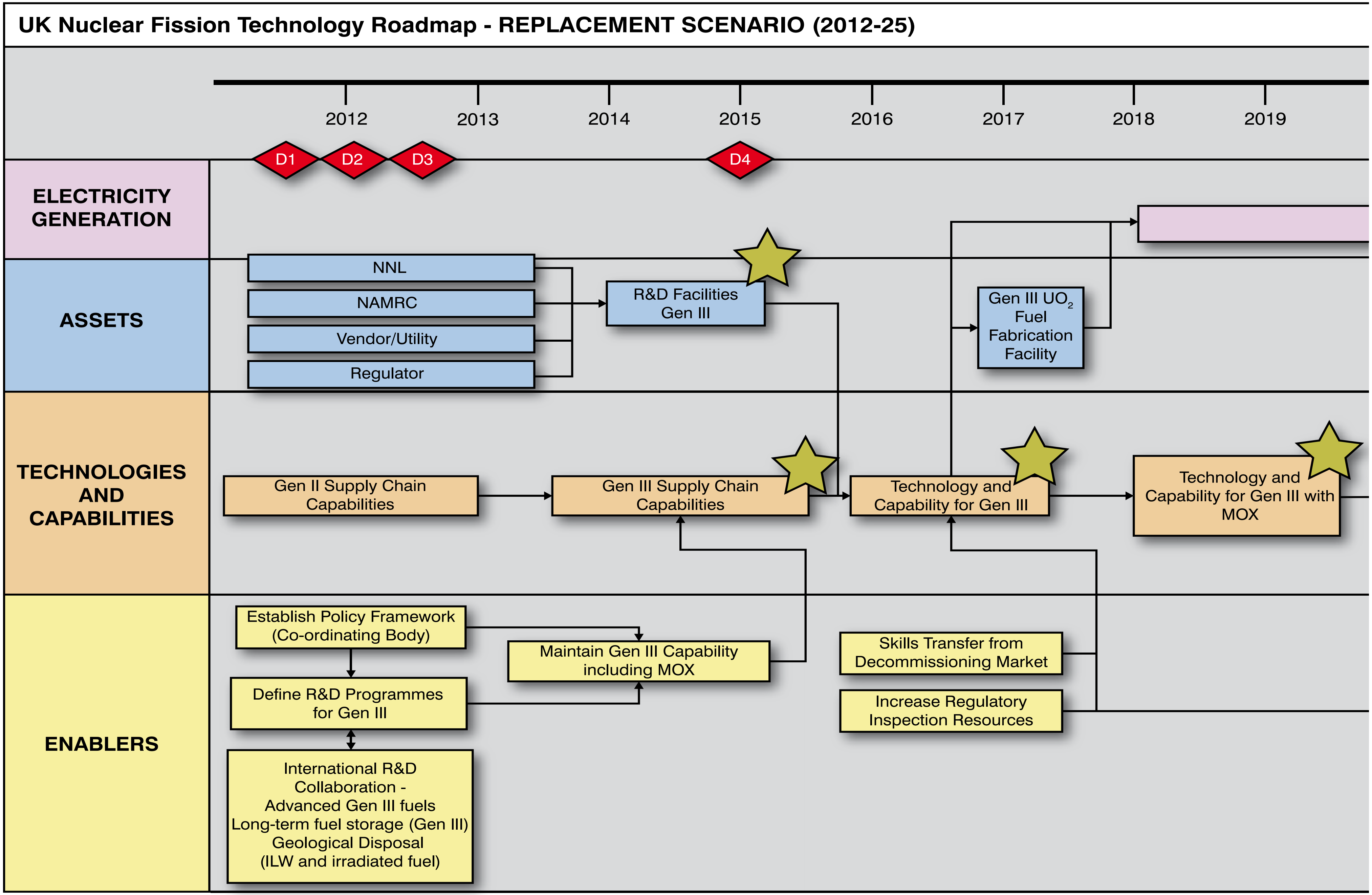
The Roadmap indicates a direction for the UK nuclear industry, which is defined by mapping UK capabilities against the future technology needs of the industry to deliver the scenarios. These needs are shaped by the current trends and drivers. Linking capabilities and future needs indicates opportunity areas where the UK can compete in the global nuclear industry. Realising these opportunities requires enabling actions from a range of stakeholders in the industry. These form a Roadmap which allows the plotting of a course from enabling actions, through the development of capability and technology, to the exploitation of applications in the opportunity areas.

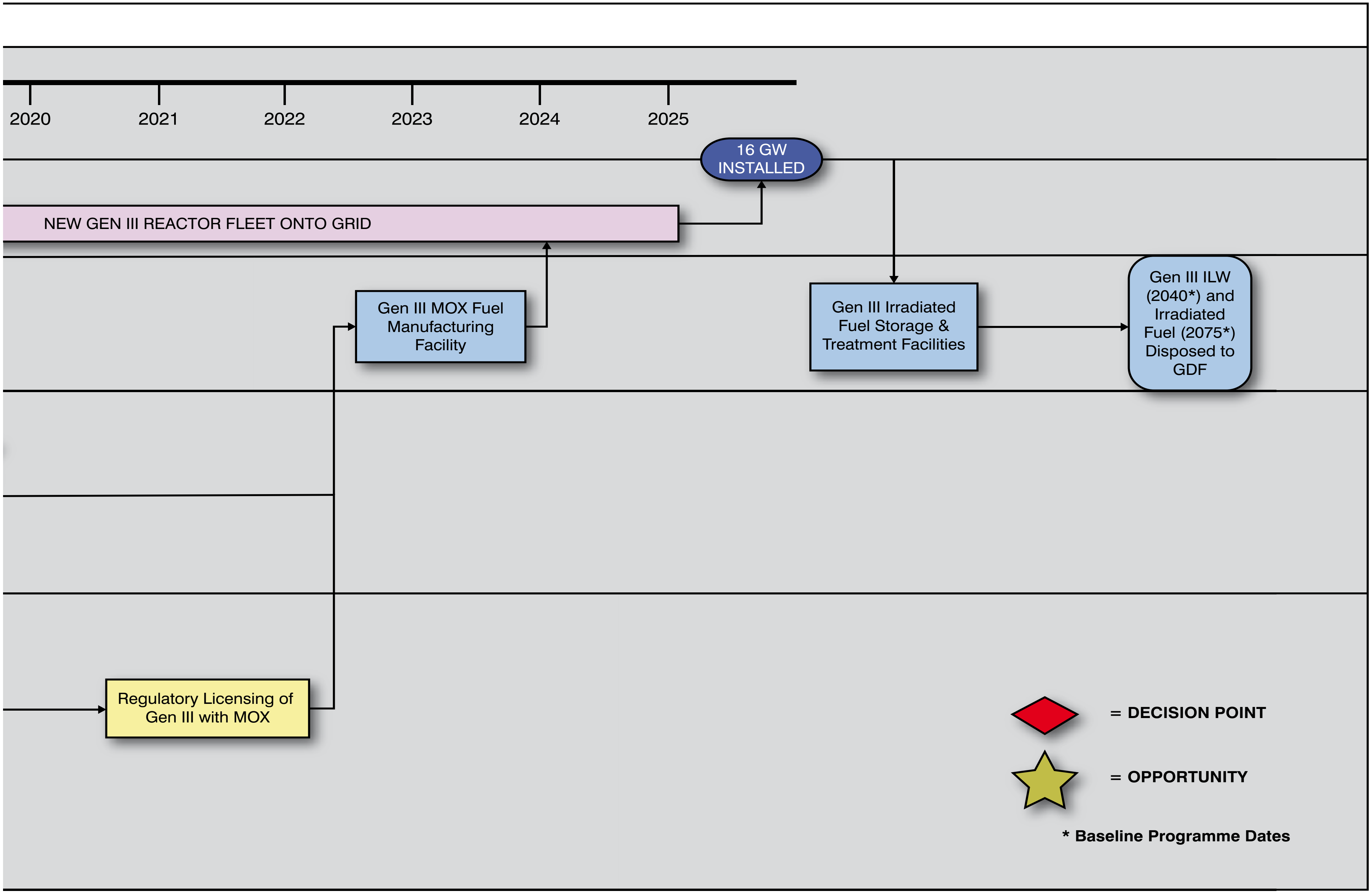
Baseline Programme Dates shown in the Roadmap have been taken from the NDA (2011), 'Geological Disposal - Review of options for accelerating implementation of the Geological Disposal programme. Nuclear Decommissioning Authority' report.

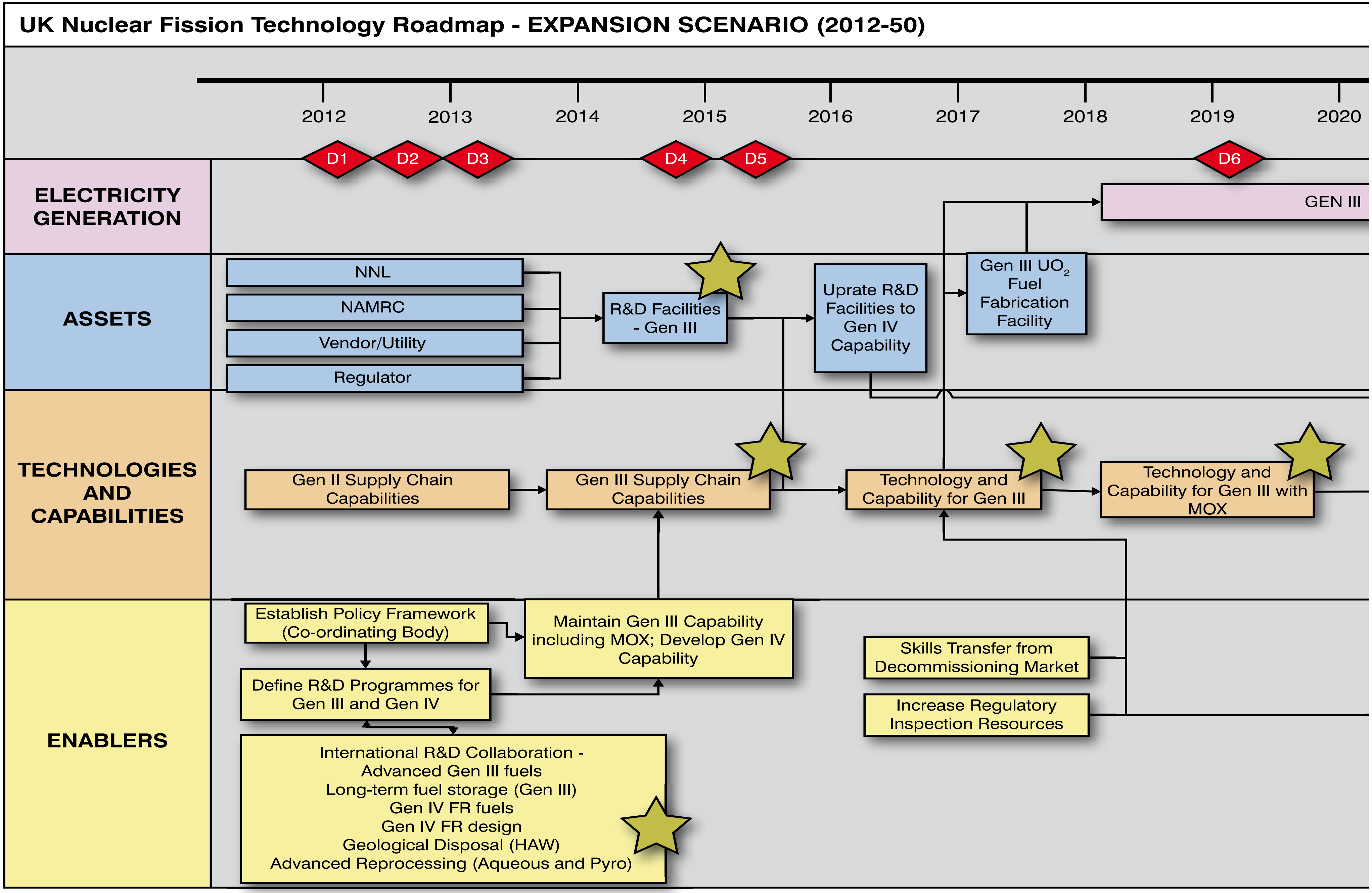
OPPORTUNITY AREAS

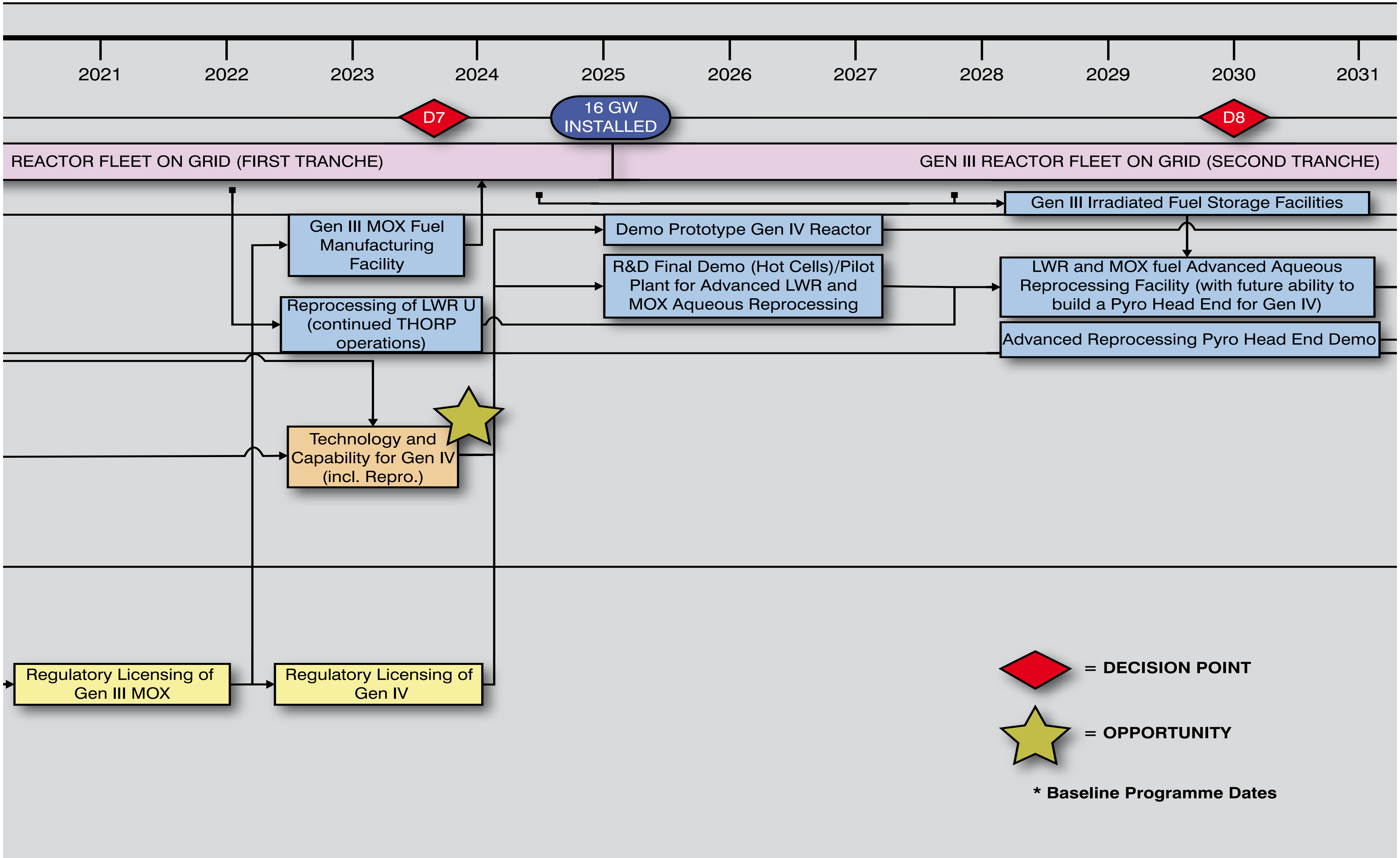
The following opportunity areas were derived during the development of this Roadmap.

- **Supply Chain Opportunities:** ★
  - o Advanced Fuel and Component Manufacturing and Materials
  - o Technical and Engineering Support to New Plants e.g. Condition Monitoring, NDT, NDE
  - o Decommissioning
  - o Waste Disposal Facilities
- **Skills Opportunities:** ★
  - o Fuel Cycle Subject Matter Experts
  - o Safety Management
  - o Radioactive Waste Management
  - o Establishing Regulatory Frameworks
  - o Training
  - o Legal Services
- **Technology Opportunities:** ★
  - o Advanced Modelling and Analysis
  - o Waste Treatment
  - o Decontamination and Decommissioning
  - o Materials Technology
  - o Fuel Design, Manufacture, Enrichment and Recycle
  - o Advanced Instrumentation
  - o Advanced Reactor Designs

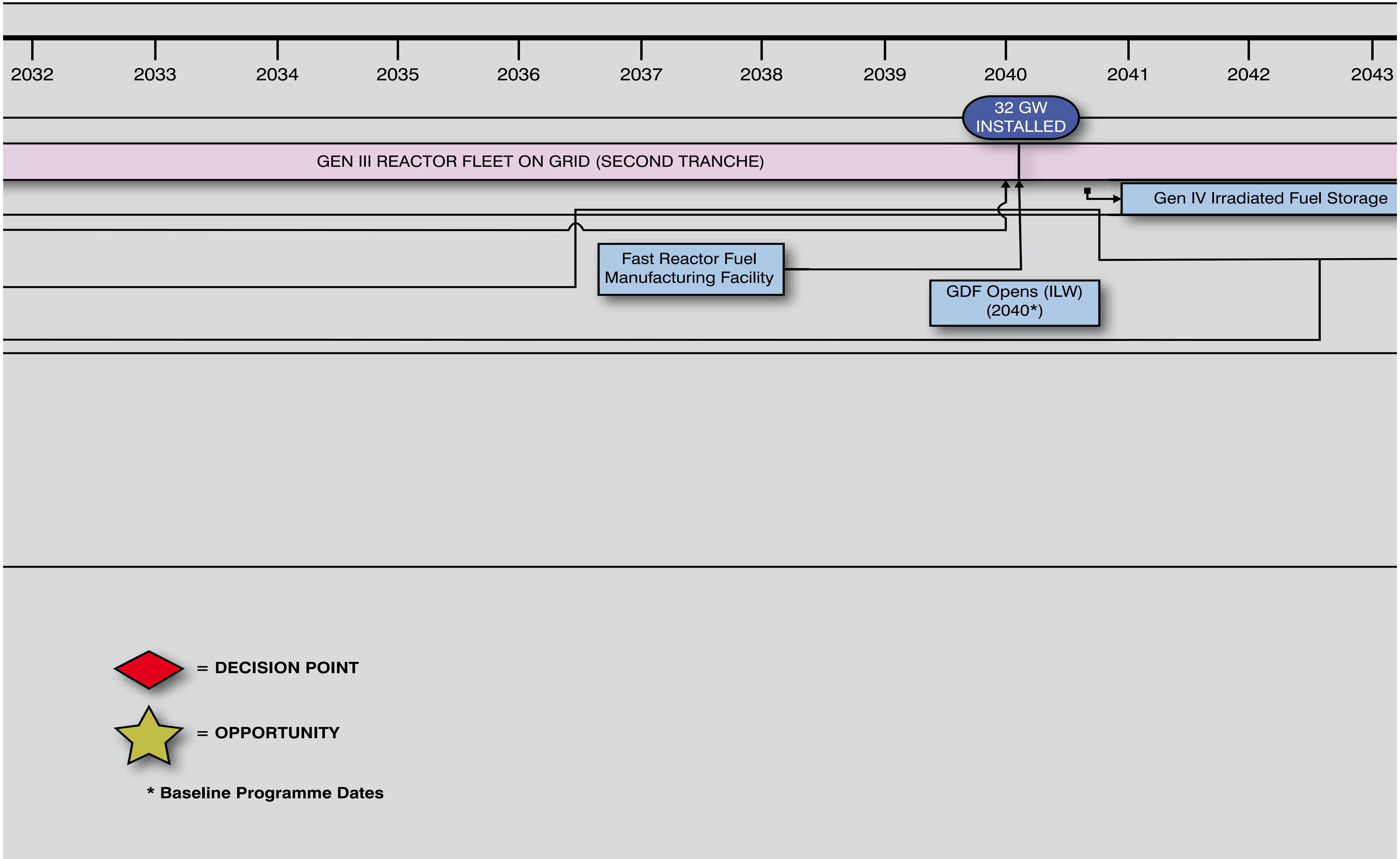

UK Nuclear Fission Technology Roadmap - REPLACEMENT SCENARIO (2012-25)
2012
2013
2014
2015
2016
2017
2018
2019
D1
D2
D3
D4
ELECTRICITY GENERATION
ASSETS
TECHNOLOGIES AND CAPABILITIES
ENABLERS
NNL
NAMRC
Vendor/Utility
Regulator
R&D Facilities Gen III
Gen III UO_2 Fuel Fabrication Facility
Gen II Supply Chain Capabilities
Gen III Supply Chain Capabilities
Technology and Capability for Gen III
Technology and Capability for Gen III with MOX
Establish Policy Framework (Co-ordinating Body)
Maintain Gen III Capability including MOX
Define R&D Programmes for Gen III
International R&D Collaboration - Advanced Gen III fuels Long-term fuel storage (Gen III) Geological Disposal (ILW and irradiated fuel)
Skills Transfer from Decommissioning Market
Increase Regulatory Inspection Resources

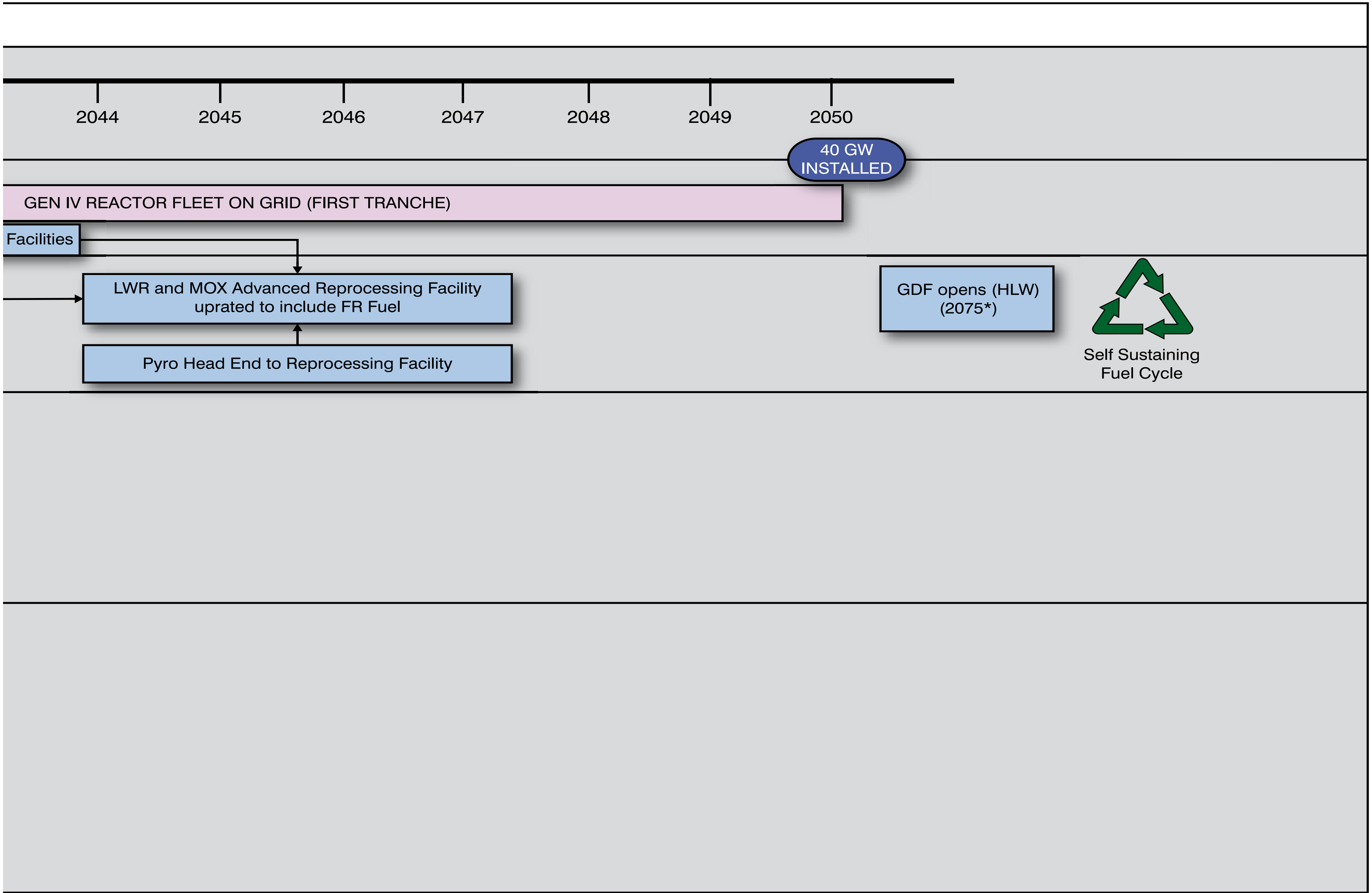

2020
2021
2022
2023
2024
2025
16 GW INSTALLED
NEW GEN III REACTOR FLEET ONTO GRID
Gen III MOX Fuel Manufacturing Facility
Gen III Irradiated Fuel Storage & Treatment Facilities
Gen III ILW (2040*) and Irradiated Fuel (2075*) Disposed to GDF
Regulatory Licensing of Gen III with MOX
= DECISION POINT
= OPPORTUNITY
* Baseline Programme Dates


UK Nuclear Fission Technology Roadmap - EXPANSION SCENARIO (2012-50)
2012
2013
2014
2015
2016
2017
2018
2019
2020
D1
D2
D3
D4
D5
D6
ELECTRICITY GENERATION
GEN III
ASSETS
NNL
NAMRC
Vendor/Utility
Regulator
R&D Facilities - Gen III
Uprate R&D Facilities to Gen IV Capability
Gen III UO_2 Fuel Fabrication Facility
TECHNOLOGIES AND CAPABILITIES
Gen II Supply Chain Capabilities
Gen III Supply Chain Capabilities
Technology and Capability for Gen III
Technology and Capability for Gen III with MOX
ENABLERS
Establish Policy Framework (Co-ordinating Body)
Maintain Gen III Capability including MOX; Develop Gen IV Capability
Define R&D Programmes for Gen III and Gen IV
Skills Transfer from Decommissioning Market
Increase Regulatory Inspection Resources
International R&D Collaboration -
Advanced Gen III fuels
Long-term fuel storage (Gen III)
Gen IV FR fuels
Gen IV FR design
Geological Disposal (HAW)
Advanced Reprocessing (Aqueous and Pyro)



2021
2022
2023
2024
2025
2026
2027
2028
2029
2030
2031
D7
16 GW INSTALLED
D8
REACTOR FLEET ON GRID (FIRST TRANCHE)
GEN III REACTOR FLEET ON GRID (SECOND TRANCHE)
Gen III Irradiated Fuel Storage Facilities
Gen III MOX Fuel Manufacturing Facility
Demo Prototype Gen IV Reactor
R&D Final Demo (Hot Cells)/Pilot Plant for Advanced LWR and MOX Aqueous Reprocessing
LWR and MOX fuel Advanced Aqueous Reprocessing Facility (with future ability to build a Pyro Head End for Gen IV)
Reprocessing of LWR U (continued THORP operations)
Advanced Reprocessing Pyro Head End Demo
Technology and Capability for Gen IV (incl. Repro.)
Regulatory Licensing of Gen III MOX
Regulatory Licensing of Gen IV
= DECISION POINT
= OPPORTUNITY
* Baseline Programme Dates


2032
2033
2034
2035
2036
2037
2038
2039
2040
2041
2042
2043
32 GW INSTALLED
GEN III REACTOR FLEET ON GRID (SECOND TRANCHE)
Gen IV Irradiated Fuel Storage
Fast Reactor Fuel Manufacturing Facility
GDF Opens (ILW) (2040*)
= DECISION POINT
= OPPORTUNITY
* Baseline Programme Dates


2044
2045
2046
2047
2048
2049
2050
40 GW INSTALLED
GEN IV REACTOR FLEET ON GRID (FIRST TRANCHE)
Facilities
LWR and MOX Advanced Reprocessing Facility uprated to include FR Fuel
Pyro Head End to Reprocessing Facility
GDF opens (HLW) (2075*)
Self Sustaining Fuel Cycle

Appendix 1 Roadmap Project Consortium

Energy Research Partnership (ERP)

www.energyresearchpartnership.org.uk

ERP 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. ERP is supported through members' contributions.

National Nuclear Laboratory (NNL)

www.nnl.co.uk

The NNL is a UK Government-owned, commercially operated (by a consortium made up of Serco, Battelle and the University of Manchester) nuclear services technology provider covering the whole of the nuclear fuel cycle. It is fully customer-funded and operates at six locations in the United Kingdom.

Nuclear Decommissioning Authority (NDA)

www.nda.gov.uk

The NDA is a non-departmental public body created through the Energy Act 2004. They are a strategic authority that owns 19 sites and the associated civil nuclear liabilities and assets of the public sector, previously under the control of the UK Atomic Energy Authority (UKAEA) and British Nuclear Fuels Limited plc (BNFL).

Engineering and Physical Sciences Research Council (EPSRC)

www.epsrc.ac.uk

EPSRC is the main UK Government agency for funding research and training in engineering and the physical sciences, investing more than £850 million a year in a broad range of subjects – from mathematics to materials science, and from information technology to structural engineering. EPSRC is a non-departmental public body funded by the UK Government through the Department for Universities, Innovation and Skills.

Energy Technologies Institute (ETI)

www.energytechnologies.co.uk

ETI is a UK based company formed from global industries and the UK Government. ETI bring together projects that create affordable, reliable, clean energy for heat, power and transport. ETI will demonstrate technologies, develop knowledge, skills and supply-chains, inform development of regulation, standards and policy, and so accelerate the deployment of affordable, secure low-carbon energy systems from 2020 to 2050.

Appendix 2 Acknowledgments

The National Nuclear Laboratory (NNL) led the development of the Roadmap and this report on behalf of the project team consortium. The NPL led the design and facilitation of the Expert Group workshops. Thanks are due to the NNL, NIA and NAMRC for hosting the workshops. Input has been provided by the Roadmap Steering and Expert Groups. The views are not the official point of view of any organisation or individual and do not constitute Government policy. The organisations and individuals involved in the development of this report are listed below.

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Appendix 3 Process for Roadmap Development

Roadmapping is a tool used to define future technology and market opportunities and match these with existing capabilities. Roadmapping has been successfully used in other sectors including energy, science, transport and defence.[33] Through wide consultation with industry, academia, Government and research organisations, this preliminary report into a UK Nuclear Fission Technology Roadmap has been created to inform the development of a long term vision of the future of nuclear energy and the associated nuclear industry in the UK, enable strategic direction and ensure actions by key players are aligned in both the public and private sector to enable systems to be commercially deployed to set timeframes.

The Roadmap identifies the UK nuclear fission capabilities and associated expertise required to support the delivery of a 16 GW Replacement Scenario by 2025 and a 40 GW Expansion Scenario by 2050. The analysis does not attempt to look at the more fundamental issue of the arguments for or against nuclear energy and recognises that public acceptability of energy technologies is a key factor in determining their future use.

This report provides an action plan and a framework to identify and address new issues. The Roadmap should be regarded as a living document and form the basis for subsequent work. It is recognised that the recommendations in this report will require public investment in R&D. This preliminary report does not include analysis of this investment; rather it seeks to highlight the issues and the importance of being sufficiently aware of options for detailed review. The process for the development of the Roadmap is shown in Figure 7 and Figure 8.

A Steering Group chaired by Dame Sue Ion OBE FREng was formed in February 2011 to ensure broad stakeholder engagement, opinion, information, expertise and guidance to the development of the Roadmap. The delivery process for the Roadmap was informed by best practice from sources such as the International Energy Agency[34] and the University of Cambridge Institute for Manufacturing[35] and the Roadmap document informed by exemplars such as NEA/IEA Nuclear Energy Technology Roadmap[36], Energy Technologies Institute and UK Energy Research Centre Marine Energy Technology Roadmap[37] and the Automotive Australia 2020 Technology Roadmap[38].

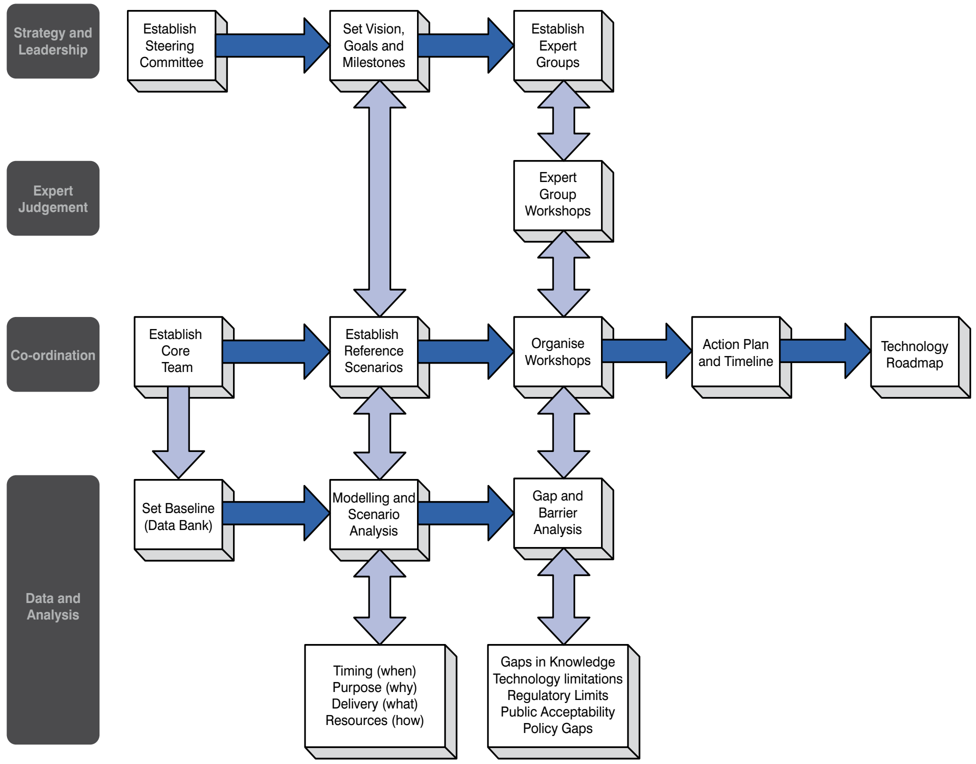


Figure 7: Roadmap development plan

[33] IFM (2011), Institute for Manufacturing, Roadmapping - Resources, Public-Domain Roadmaps. www.ifm.eng.cam.ac.uk/ctm/trm/resources.html

[34] IEA (2010), Energy Technology Roadmaps – a guide to development and implementation.

[35] Phaal R, Farrukh CJP & Probert DR (2001), T-Plan: the fast-start to technology roadmapping: planning your route to success, Institute for Manufacturing, University of Cambridge.

[36] NEA/IEA (2010), Nuclear Energy Technology Roadmap.

[37] ETI (2010), Marine Energy Technology Roadmap. Energy Technologies Institute and UK Energy Research Centre.

[38] AAIIC (2010), Automotive Australia 2020 Technology Roadmap. Australian Automotive Industry Innovation Council, Australian Federal Government, Victorian State Government, AutoCRC, Australian National University, CSIRO and the Institute for Manufacturing (IfM) at the University of Cambridge.

Underpinned by NNL ORION fuel cycle modelling of the two selected scenarios for roadmapping, six Expert Group workshops were held with aims and objectives as per Table 5. NNL led the development of the Roadmap on behalf of the project consortium. NPL led the design and facilitation of the Expert Group workshops.

Analysis for this report involved significant interaction with industry, academia, regulators and other key stakeholders. Substantial underpinning information and detail has been retained but could be made available for further development of this Roadmap.

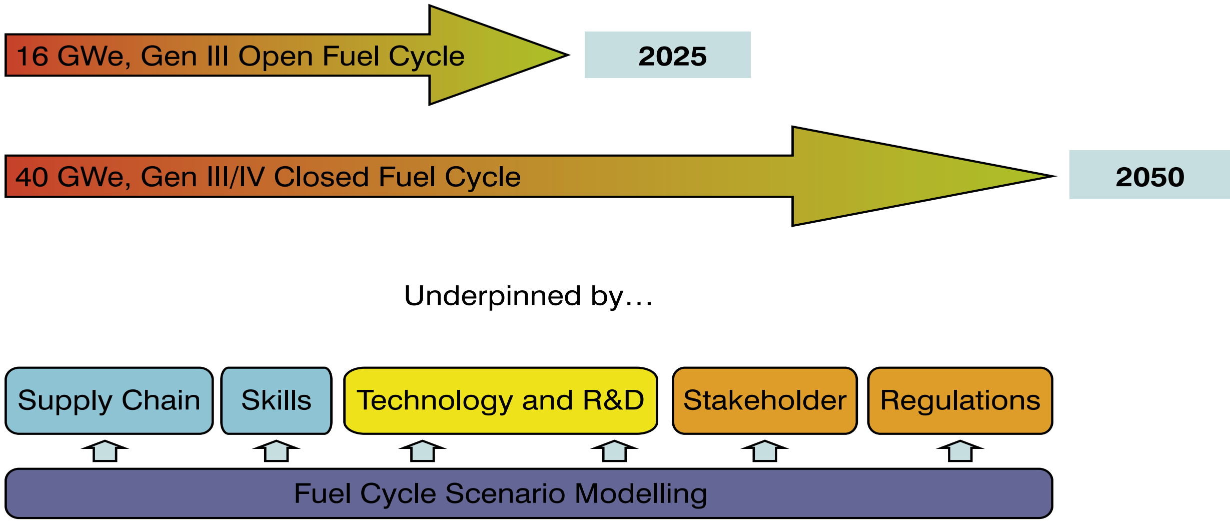


Figure 8: Roadmap process development

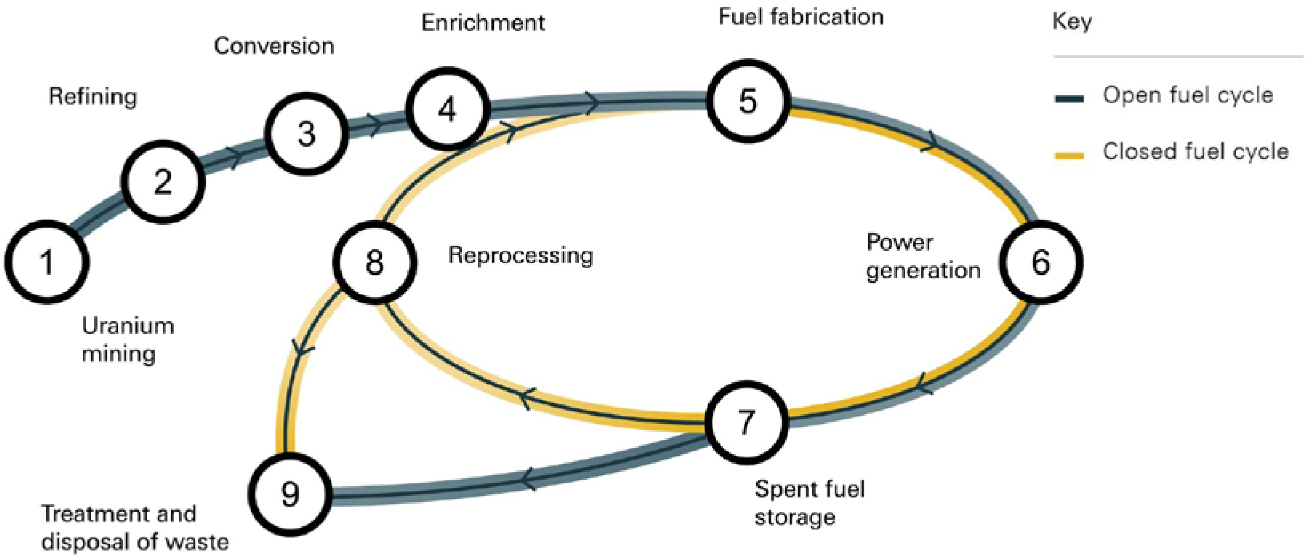
Expert Group	Workshop Aims and Objectives
Technology	Review the 16 GW Replacement and 40 GW Expansion Scenarios and provide validated information for mapping out the underpinning technologies required for delivering these scenarios. Produce a draft Roadmap setting out the targets, delivery milestones and insertion points for underpinning technologies and capabilities.
R&D	Specification of potential R&D programme requirements for providing the technologies required to deliver each of these two nuclear power scenarios. Mapping out the timelines and actions to address the delivery of these R&D requirements.
Regulations	Assess the suitability of the existing regulatory infrastructure in the contexts described by the two scenarios. Outline potential actions required to address any gaps or issues identified as a result of the assessment.
Stakeholder	Provide a view of who should be involved in specific actions that could potentially be required to alleviate stakeholder concerns that might arise from delivering the scenarios under consideration. Focus on stakeholder engagement activities required to maintain public acceptance in enacting the scenarios captured in the Roadmap.
Skills	Confirm the strategy needed to deliver the skills required for the 16 GW Replacement and 40 GW Expansion Scenarios. Outline potential actions required to address any skills gaps or issues identified as a result of the assessment.
Supply Chain	Identify the needs in capability and supply chain shape/content for each stage of the two scenarios, and to identify the gaps and opportunities, consistent with delivering the scenario outputs. Examine how the supply chain could potentially be structured in order to maximise the national benefits from developing an enhanced, but achievable national business, skills and capability opportunity.

Table 5: Aims and objectives of the Expert Group workshops

Appendix 4 The Nuclear Fuel Cycle

Developments in nuclear power include a range of interlinked technologies (see Figure 9). The reactor and the associated electricity and heat generating technologies are at the heart of the fuel cycle, but it is essential that a holistic approach is taken to ensure the overall system is optimised. 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. There are two categories of fuel cycle as described in Table 6.

Figure 9: The nuclear fuel cycle[39]



Open Fuel Cycle	The open fuel cycle is the mode of operation in which the nuclear material passes through the reactor just once. After irradiation, the fuel is kept in at-reactor pools until it is sent to away-from-reactor storage. It is planned that the fuel will be conditioned and put into a final repository in this mode of operation. This fuel cycle strategy is the one currently adopted by many nuclear power countries (e.g. USA).
Closed Fuel Cycle	The closed fuel cycle is the mode of operation in which, after a sufficient cooling period, the spent fuel is reprocessed to extract the remaining uranium and plutonium from the fission products and other actinides. The reprocessed uranium and plutonium is then reused in the reactors. This recycle strategy has been adopted by some countries mainly in light water reactors (LWRs) in the form of mixed oxide (MOX) fuel (e.g. France). Apart from the current LWR recycling experience, another closed fuel cycle practice is the recycle of nuclear materials in fast reactors in which reprocessed uranium and plutonium are used for production of fast reactor fuel. By suitable operation, such a reactor can produce more fissile plutonium than it consumes.

Table 6: Nuclear fuel cycle definitions[40]

[39] Royal Society (2011), Fuel Cycle Stewardship in a Nuclear Renaissance.

[40] IAEA (2009), Nuclear Fuel Cycle Information System, A Directory of Nuclear Fuel Cycle Facilities.

Appendix 5 Nuclear Reactor Systems

Over the next 15 years all but one of the UK's existing nuclear power stations will be closed. Following consultation, 8 sites have been identified (see Figure 10) where new reactors could be built[41]. In response, several consortia have committed to a new build programme, which is expected to see up to 16 GW of new capacity being built on these sites. The investment for building the 16 GW of new nuclear capacity is expected to be between £40 billion and £64 billion[42], 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[43]:

- Électricité de France (EDF) intends to build four new EPRs (amounting to 6.4 GW) at Hinkley Point and Sizewell.
- Horizon Nuclear Power (a joint venture between RWE and E.ON) intends to build at least 6 GW of new nuclear capacity at Wylfa and Oldbury.
- NuGeneration, a consortium of GDF SUEZ SA and Iberdrola SA, has set out plans to build up to 3.6 GW of new nuclear capacity at Sellafield (project name 'Moorside').

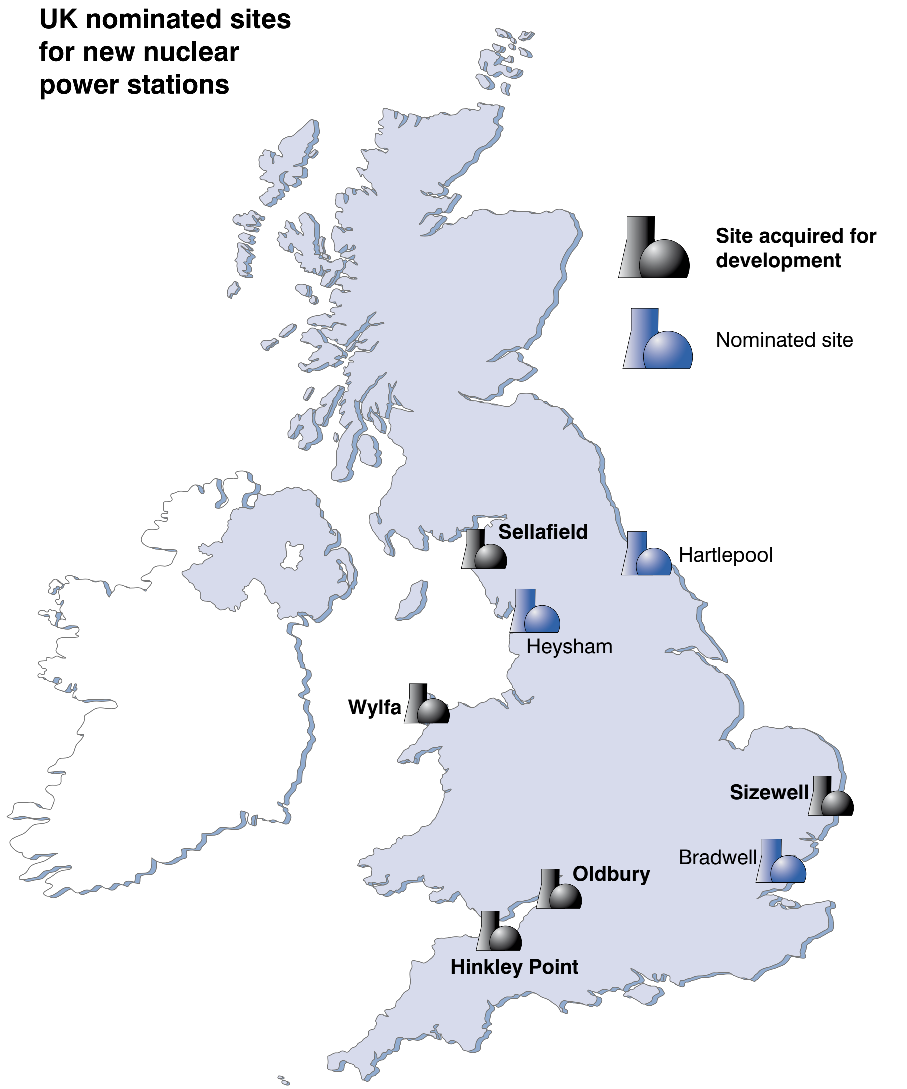


Figure 10: UK nominated sites for new nuclear power stations[44]

[41] DECC (2011), The Government Response to Consultation on the Revised Draft National Policy Statements for Energy Infrastructure.

[42] KPMG (2010), Securing Investment in Nuclear in the Context of Low-Carbon Generation.

[43] DECC (2012), Meeting Energy Demand – Nuclear.

[44] NAMRC (2011), UK New Build Plans.

Nuclear power plant technology has evolved as distinct design generations (as shown in Figure 11):

- Generation I: prototypes, and first realisations (~1950-1970)
- Generation II: current operating plants (~1970-2030)
- Generation III: deployable improvements to current reactors (~2000 and on)
- Generation IV: advanced and new reactor systems (2030 and beyond)

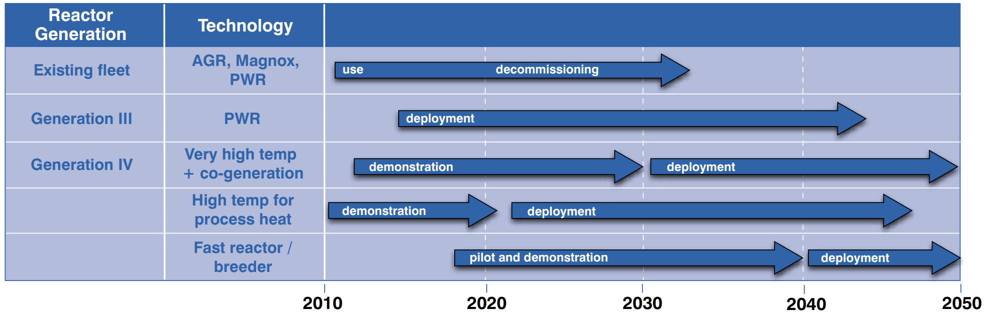


Figure 11: Timeline of nuclear reactor development relevant to the UK[45]

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, generating system and the fuel cycle make them more economic, as well as reducing the amount of waste they produce. Described below (adapted from NEA 2010[46] are the leading designs presently being offered by the major nuclear power plant suppliers worldwide, which are expected to provide the great majority of new nuclear capacity at least until 2020.

The AP-1000 is the flagship design from Westinghouse. The AP-1000 is an advanced pressurised water reactor (PWR) with a capacity of about 1,200 MW. Although majority owned by Toshiba of Japan, Westinghouse is headquartered in the United States.

The EPR is the main offering from AREVA, the main European nuclear industry group which is majority owned by the French state. Also an advanced PWR, it will have an output of 1,600 to 1,700 MW.

The ABWR (Advanced Boiling Water Reactor) units have outputs in the 1,300 MW range, but up to 1,600 MW versions are offered. The basic design was developed jointly by General Electric (GE) of the United States and Toshiba and Hitachi of Japan. GE and Hitachi subsequently merged their nuclear businesses.

The ESBWR (Economic Simplified Boiling Water Reactor), a further development of the ABWR concept, is the latest offering from GE-Hitachi. Its output will be in the region of 1,600 MW.

The APWR (Advanced PWR) has been developed for the Japanese market by Mitsubishi Heavy Industries (MHI). Output will be around 1,500 MW per unit.

The VVER-1200 (also known as AES-2006) is the most advanced version of the VVER series of PWR designs produced by the Russian nuclear industry, now organised under state-owned nuclear holding group Rosatom. The units have a capacity of 1,100 MW.

The ACR (Advanced Canada Deuterium-Uranium (CANDU) Reactor) is the newest design from Atomic Energy of Canada Ltd. (AECL), owned by the Canadian Government. Most CANDUs use heavy water to moderate (or slow) neutrons, making it possible to use natural uranium fuel. However, the 1,200 MW ACR will use enriched fuel, the first CANDU design to do so. AECL also offers the Enhanced CANDU 6, a 700 MW unit using natural uranium.

The APR-1400 is the latest 1,340 MW Korean PWR design. It is based on original technology now owned by Westinghouse. This has been further developed by Korean industry in a series of more advanced designs.

The CPR-1000 is currently the main design being built in China. This 1,000 MW design is an updated version of a 1980s AREVA Generation II design, the technology for which was transferred to China.

India's PHWR (Pressurised Heavy Water Reactor) designs are based on an early CANDU design exported from Canada in the 1960s. The latest units have a capacity of 540 MW, and 700 MW units are planned. Although further developed since the original design, these are less advanced than Generation III designs.

[45] ERP (2010), Nuclear Fission. Energy Research Partnership Technology Report.

[46] NEA/IEA (2010), Nuclear Energy Technology Roadmap.

Generation IV

The Generation IV International Forum (GIF) and the IAEA International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) research collaborations have identified key areas where advanced reactor systems would be expected to demonstrate significantly improved performance compared with current reactors: sustainability; economics; safety and reliability; proliferation resistance and physical protection and waste management.

The Generation IV Technology Roadmap (2002)[47] prepared by GIF member countries, identified six promising reactor system and fuel cycle concepts (see Table 7), along with the research required to study these concepts in view of potential deployment and/or commercialisation.

System	Neutron Spectrum	Coolant	Temperature °C	Fuel Cycle	Size (MW)
VHTR (very-high temperature reactor)	Thermal	Helium	900-1000	Open	250-300
SFR (sodium-cooled fast reactor)	Fast	Sodium	550	Closed	30-150 300-1500 1000-2000
SCWR (supercritical water-cooled reactor)	Fast / Thermal	Water	510-625	Open / Closed	300-700 1000-1500
GFR (gas-cooled fast reactor)	Fast	Helium	850	Closed	1200
LFR (lead-cooled fast reactor)	Fast	Lead	480-800	Closed	20-180 300-1200 600-1000
MSR (molten salt reactor)	Fast / Thermal	Fluoride salts	700-800	Closed	1000

Table 7: Overview of the six Generation IV systems[48]

The six selected systems employ a variety of reactor, energy conversion and fuel cycle technologies. Their designs feature thermal and fast neutron spectra, closed and open fuel cycles and a wide range of reactor sizes. The European roadmap for nuclear technology development is shown in Figure 12.

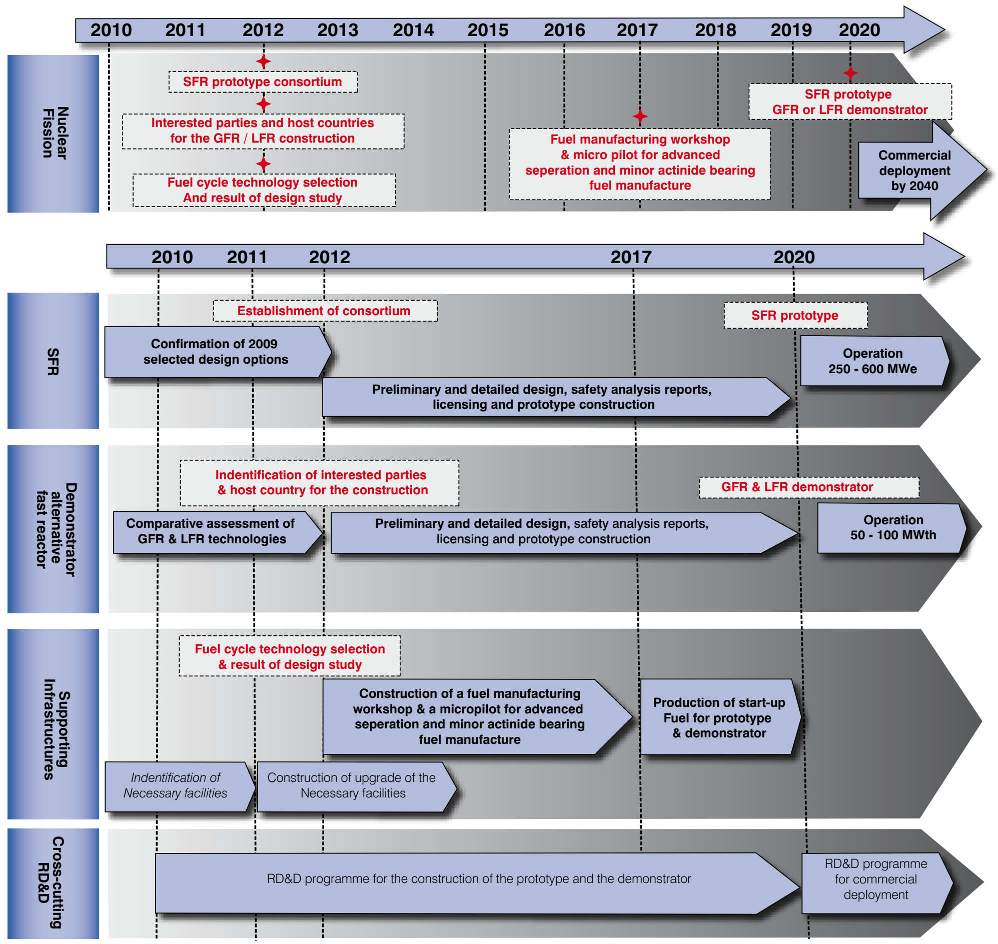


Figure 12: European roadmap for nuclear technology development[49]

[47] GIF (2002), A Technology Roadmap for Generation IV Nuclear Energy Systems. Generation IV International Forum.

[48] Ibid.

[49] EC (2009), Investing in the Development of Low Carbon Technologies (SET-Plan) - A Technology Roadmap. European Commission.

The six types of Generation IV reactor being considered by GIF can be divided into two main types: a) Advanced thermal reactors and b) Fast reactors, with breeding potential. Details of these are listed below (adapted from NEA 2010[50]).

(A) Advanced Thermal Reactors

Advanced thermal reactors are developments of Generation III but operate at very high temperatures. 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.

Very-High Temperature Reactor (VHTR) - A graphite-moderated, helium cooled reactor with a once-through uranium fuel cycle.

The chief attraction of the VHTR concept is its ability to produce the higher temperatures (up to 1,000 ºC) needed for hydrogen production and some process heat applications. However, VHTRs would not permit use of a closed fuel cycle. Reference designs are for around 250 MW of electricity, or 600 MW of heat, with a helium coolant and a graphite-moderated thermal neutron spectrum. Fuel would be in the form of coated particles, formed either into blocks or pebbles according to the core design adopted. VHTR designs are based on prototype high-temperature gas-cooled reactors, including examples built in the United States and Germany, and much R&D has been completed. Remaining challenges include developing improved temperature-resistant materials, and the fuel design and manufacture.

Supercritical Water-Cooled Reactor (SCWR) - A high-temperature, high-pressure water-cooled reactor that operates above the thermodynamic critical point of water.

Of the Generation IV designs, the SCWR is most closely related to existing LWR technology. SCWRs would operate at higher temperatures and pressures, above the thermodynamic critical point of water, allowing design simplification and greatly improved thermal efficiencies. Reference designs provide up to 1,500 MW, use uranium or mixed oxide fuel, and have outlet temperatures up to 625ºC. SCWRs could have either a thermal or a fast neutron spectrum; the latter would use a closed fuel cycle based on centralised fuel facilities. Major R&D challenges involve overcoming safety-related core design issues, as well as developing corrosion-resistant materials.

(B) Fast Reactors

The technology for fast reactors has been around for many years and a number of pilot plants and larger scale plants have been built in France, Russia, China, Japan, India and the UK (demonstration and prototype fast breeder reactors at Dounreay).

Sodium-Cooled Fast Reactor (SFR) - A sodium-cooled reactor with a closed fuel cycle for efficient management of actinides and conversion of fertile uranium.

Several prototype SFRs have already been built and operated in a few countries, making it one of the best established Generation IV technologies. SFRs feature a fast neutron spectrum, liquid sodium coolant, and a closed fuel cycle. Full-sized designs (up to 1,500 MW) use mixed uranium plutonium oxide fuel, with centralised recycling facilities. Small designs in the 100 MW range, using metallic fuel and co-located recycling facilities, are also being considered. SFRs have a relatively low (550ºC) outlet temperature, limiting their use for non-electricity applications. Reducing capital costs and increasing passive safety are important R&D aims, together with the development of advanced fuel reprocessing technologies. Examples of the SFR technologies include:

- ASTRID (Advanced Sodium Technological Reactor for Industrial Demonstration): an SFR led by the French Commissariat a l'Energy Atomique (CEA), involving EdF and Areva.
- PRISM (Power Reactor Innovative Small Module): an SFR designed by GE-Hitachi.

Lead-Cooled Fast Reactor (LFR) - A liquid-metal-cooled reactor using lead/bismuth with a closed fuel cycle for efficient conversion of fertile uranium and management of actinides.

The LFR system would feature a fast-spectrum liquid metal-cooled reactor and a closed fuel cycle. Molten lead is a relatively inert coolant, offering safety advantages as well as being abundant. Designs being investigated to date include both small (20 MW) and mid-sized (600 MW) designs. The former would be a factory-fabricated plant with a very long refuelling interval (15-20 years). Initially, LFRs would be developed for electricity production, but high temperature versions could allow hydrogen production. Major R&D needs are in fuels, materials and corrosion control. An example of this technology is the Myrrha LFR technology pilot proposed by Belgium.

[50] NEA/IEA (2010), Nuclear Energy Technology Roadmap.

Gas-Cooled Fast Reactor (GFR) - A fast-neutron-spectrum, helium-cooled reactor and closed fuel cycle.

The GFR system reference design includes a 1,200 MW helium-cooled reactor with a fast neutron spectrum and a closed fuel cycle with an on-site spent fuel treatment and refabrication plant. It features a high thermal efficiency direct-cycle helium turbine for electricity generation. The high outlet temperature (850^{o}C) could also be suitable for hydrogen production or process heat. Key R&D challenges include the development of new fuels (such as ceramic-clad fuels or fuel particles) and materials, as well as the core design and the helium turbine. An example of this technology is the Allegro GFR supported by Central and Eastern Europe.

Molten Salt Fast Reactor (MSR) - In MSRs, fuel materials are dissolved in a circulating molten fluoride salt coolant.

The liquid fuel avoids the need for fuel fabrication and allows continuous adjustment of the fuel mixture. The current concept is for a 1,000 MW fast neutron reactor with a closed fuel cycle. This could be used for breeding with fertile thorium or for burning plutonium and other actinides. An Advanced HTR with liquid fluoride salt coolant is also being studied. Molten salt chemistry, handling and corrosion resistance, as well as materials and the fuel cycle, are the main R&D challenges.

Small Modular Reactors (SMR)

Designs for SMRs, with generating capacities ranging from tens to a few hundred megawatts, are being developed in several countries, often through cooperation between Government and industry. Countries involved include Argentina, China, Japan, Korea, Russia, South Africa and the United States. SMR designs encompass a range of technologies, some being variants of the six Generation IV systems selected by GIF, while others are based on established LWR technology. Such reactors could be deployed as single or double units in remote areas without strong grid systems, or to provide small capacity increments on multi-unit sites in larger grids.

List of Acronyms

ABWR	Advanced Boiling Water Reactor
ACR	Advanced CANDU Reactor
AECL	Atomic Energy of Canada Ltd
AGR	Advanced Gas-Cooled Reactor
AP1000	Westinghouse PWR
APWR	Advanced PWR
BNFL	British Nuclear Fuels plc
BWR	Boiling Water Reactor
CANDU	Canada Deuterium-Uranium reactor
CCC	Committee on Climate Change
CCS	Carbon Capture Storage
CEA	Commissariat a l'Energy Atomique (France)
DECC	Department of Energy and Climate Change
EA	Environment Agency
EC	European Commission
EDF	Électricité de France
EPR	European Pressurised Reactor
EPSRC	Engineering and Physical Sciences Research Council
ERP	Energy Research Partnership
ESBWR	Economic Simplified Boiling Water Reactor
ETI	Energy Technologies Institute
EURATOM	European Atomic Energy Commission
GDF	Geological Disposal Facility
GDP	Gross Domestic Product
GFR	Gas-Cooled Fast Reactor
GIF	Generation IV International Forum
GW	Gigawatt
HAW	Higher Activity Waste
HLW	High Level Waste
IAEA	International Atomic Energy Agency
IDM	Integrated Decision Management
ILW	Intermediate Level waste
INPRO	Innovative Nuclear Reactors and Fuel Cycles
ITER	International Thermonuclear Experimental Reactor
LFR	Lead-Cooled Fast Reactor
LLW	Low-Level Waste
LWR	Light Water Reactors
MOX	Mixed Oxide fuel
MSR	Molten Salt Fast Reactor
MW	Megawatt
NAMRC	Nuclear Advanced Manufacturing Research Centre
NDA	Nuclear Decommissioning Authority
NDE	Non-Destructive Evaluation
NDT	Non-Destructive Testing
NIA	Nuclear Industry Association
NNL	National Nuclear Laboratory
NPL	National Physical Laboratory
OND	Office for Nuclear Development
ONR	Office for Nuclear Regulation
PHWR	Pressurised Heavy Water Reactor
PRISM	Power Reactor Innovative Small Module
PWR	Pressurised Water Reactor
RAEng	Royal Academy of Engineering
R&D	Research and Development
RCUK	Research Councils UK
SCWR	Supercritical Water Cooled Reactor
Semta	Sector Skills Council for Science, Engineering and Manufacturing Technologies
SFR	Sodium-Cooled Fast Reactor
SMR	Small Modular Reactor
SNETP	Sustainable Nuclear Energy Technology Platform
THORP	Thermal Oxide Reprocessing Plant
UKAEA	UK Atomic Energy Authority
UKERC	UK Energy Research Centre
VHTR	Very-High Temperature Reactor
WNA	World Nuclear Association

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