Towards a low carbon pathway for the UK

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Foreword

With a quarter of the UK's generating capacity coming to the end of its life over the next ten years, as a nation we will need to make strategic investments in our energy infrastructure that will be felt throughout the rest of the century. Furthermore as we progress towards the Government's objective of secure energy, free of carbon, by 2050, our demand for electricity is set to double as we move more transport and heating to a dependence on electricity.


Professor Sir David King, Director, Smith School of Enterprise and the Environment

These scenarios present a number of challenges for the UK. How to ensure that we have a safe, secure and affordable low carbon supply of energy that comes from within the British Isles? How do we keep the lights on while avoiding being beholden to other countries for fossil-based energy supplies? In order to meet the Government objective of becoming virtually carbon free by mid-century, we need to develop the full range of supply options at our disposal: renewables, nuclear, carbon capture and storage and fossil free transportation. This requires a coherent strategy, underpinned by a strong science and engineering base with the requisite skills which would position the UK as a world leader in low carbon energy production and manufacturing.

The UK has reiterated that the decarbonisation agenda and ensuring security of supply of low carbon energy sources will be best served by having nuclear as part of a balanced energy mix. This report *A low carbon future for the UK* explores two important aspects of the UK's nuclear landscape: the future delivery of low carbon energy using new nuclear power generation, and the more immediate imperative of dealing with the UK's legacy nuclear materials.

In my view, more strategic effort and direction is required to make nuclear new build a reality and to address the legacy issues that have been with us for many years. Failure to do so could have a detrimental effect on the UK's decarbonisation agenda. Furthermore, if we are to retain political and public support for nuclear as a key part of our future energy mix, then we have to demonstrate that lessons have been learnt and that a coherent policy framework is in place which will capitalise on the opportunities and benefits on offer.

This study sets out some potential pathways to assist in the development of a long term strategy for UK nuclear energy and its associated fuel cycle. What is clear from our study is that this is desperately needed, particularly for an industry that is essentially making 100 year decisions. I am pleased that Government recently announced its intention to publish a long-term strategy, in the summer of 2012 on the role of nuclear up to and beyond 2050. As lead author, I hope that this report offers some insights into ways that the existing science base and industrial and manufacturing capabilities can be grown to maximise the economic, high value skills and commercial benefits to the nation as a whole.

Contents

Smith School of Enterprise and the Environment

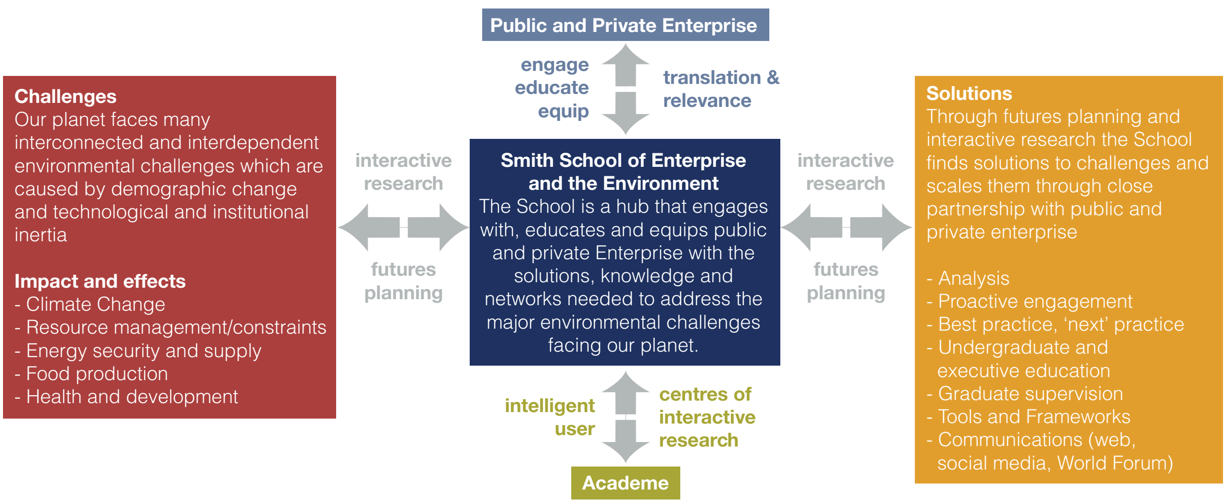
The Smith School is an interactive hub within Oxford University that engages with, educates and equips public and private enterprise with the solutions, knowledge and networks needed to address the major environmental challenges facing our planet.

The School strongly believes that the only way to address the environmental challenges we face is by convening and partnering with both public and private Enterprise

The Smith School helps Public Enterprise with Policies that create opportunities for Private Enterprise to develop Solutions to address the major environmental Challenges facing our planet.

It does this by playing three roles:

- A translator and integrator
- An intelligent user of research
- An inter-disciplinary hub



Executive Summary

Background

To meet the UK Government's decarbonisation targets, the majority of new infrastructure investment needs to be in a diverse range of low carbon generation. Investing in diversity is key to preserving and enhancing the UK's security of supply and maximising the opportunities we can from a low carbon economy. It is also imperative from an economic perspective that we maximise our UK energy production rather than relying on foreign imports.

21st century challenges

There is now a clear decarbonisation agenda in the UK. Meeting our decarbonisation targets calls for intelligent infrastructure investment. The majority of this needs to be in a diverse range of low carbon generation such as renewables, gas and coal Carbon Capture and Storage (CCS), and nuclear power. Investing in diversity is key to preserving and enhancing the UK's security of supply.

Over the coming decade a number of changes will take place in the electricity markets, with the need to replace almost a quarter of our existing power stations by 2020. Furthermore, all but one of our nuclear plants are scheduled to reach the end of their working lives by 2025. The total of new and consented plant is 21.5 GW. Replacement nuclear capacity may also be available by around 2025. Given the significant closures of plant planned – some 19.1 GW could close by 2020, with further closures during the following decade – the new plant must come on stream as scheduled to avoid risks to security of supply.

A key initiative in making new nuclear build a reality was The National Infrastructure Plan, published with the Chancellor's Autumn 2011 Statement. The plan sets out nuclear's role in low carbon economic growth. The Government's Electricity Market Reform White Paper, as well as the introduction of a carbon price floor in the 2011 Finance Act, were also major steps in ensuring that nuclear new build becomes reality.

This report contributes to the discussion of how to transition to a low carbon economy while ensuring a safe and secure energy supply. It emphasises that the UK needs a clear long-term strategy for low carbon growth and a way to engage with the private as well as the public sectors.

Energy demand

To investigate the role nuclear power will play in the UK over the next four decades, the report investigates different scenarios for energy and electricity demand.

- *Business As Usual:* assumes we do not conserve energy but continue the current path over the next four decades.
- *Energy Efficiency:* assumes the economy will be decarbonised and electrified, with energy conservation emphasised in all sectors and electrification of other areas such as heating and transport.

For each of these two demand scenarios, two supply scenarios were modelled leading to a total of four different supply-demand scenarios.

- *Scenario A1:* Business As Usual – Nuclear, Hydroelectricity & CCS
- *Scenario A2:* Business As Usual – Nuclear & CCS
- *Scenario B1:* Energy Efficiency and electrification – Mix
- *Scenario B2:* Energy Efficiency and electrification – Nuclear & CCS

A range of consistent assumptions and parameters were built into these scenarios.

The key findings were that under the Business As Usual scenarios, the emission intensity of electricity production is drastically reduced but the impact on overall emissions is limited. In Scenario A1, emissions are ***only reduced to 73% of 1990 emissions by 2050***. In Scenario A2, emissions are ***reduced to 71% relative to 1990 values.*** In both cases, these results arise because other sectors are not electrified or decarbonised in parallel.

The results for Scenarios B1 + B2 are markedly different because they go beyond mere decarbonisation of the electricity grid. With a higher electricity supply, it is feasible to achieve widespread sectoral electrification that reduces fossil fuel use in other areas, for instance in heating and transport. This shows that in order to decarbonise the economy, other sectors have to be decarbonised or electrified in parallel.

Thus, in Scenario B1, emissions are ***drastically reduced to 16% of 1990 emissions by 2050.*** This shows that large-scale sectoral electrification, energy conversion and grid decarbonisation using nuclear power and, in this case, renewables can meet the Government's emission reduction targets. Moreover, most energy is provided using domestically available sources and the UK's energy security is significantly strengthened.

In Scenario B2, there is a comparable result with emissions drastically reduced to *15% of 1990 emissions by 2050.* This illustrates again that large-scale electrification, energy conversion and grid decarbonisation using nuclear power as baseload and, in this case, abated thermal generation for peak demand can reduce emission significantly below the target set by the Government. Also this scenario, as in Scenario B1, strengthens the energy security of the UK.

The decarbonisation challenge

The report examines approaches to decarbonisation outside the UK to assess whether the role of nuclear envisaged for the UK is applicable to the broader world context.

It notes opposing opinions on nuclear within the EU Energy Roadmap 2050 published in 2011. But it points to unequivocal consensus about the increased role electricity must play in the energy mix if decarbonisation is to be achieved. The most credible scenarios offering adequate decarbonisation of world energy supplies involve major contributions from nuclear.

To assess implications for a world nuclear future, the report examines three cases (each of which is based on a range of modelling assumptions) for how nuclear contributes to world electrical generating capacity.

- *Scenario A:* World nuclear capacity grows at 4% pa until 50% of world capacity is reached, after which it grows at 1.9%, keeping to 50%
- *Scenario B:* World nuclear capacity grows at 5% pa until 60% of world capacity is reached, after which it grows at 1.9%, keeping to 60%
- *Scenario C:* World nuclear capacity grows at 6% pa until 70% of world capacity is reached, after which it grows at 1.9%, keeping to 70%

These nuclear generation figures are then used to calculate uranium demand. The report underlines that forecasting or predicting the amounts of uranium which will be accessible (at given uranium prices) is open to varying modelling techniques and opinions. The levels of variance between the findings of these techniques leave much room for disagreement. We would therefore recommend that further attention is directed to this research in order to achieve consensus on the extent to which nuclear power could contribute to a worldwide decarbonised economy.

The report then examines the merits of Light Water Reactors (LWRs) and Fast Reactors, noting that the "LWR once through" nuclear fuel cycle is relatively profligate in its use of uranium. Other reactor technologies such as Fast Reactors have the potential for comparatively lower and therefore more effective levels of uranium usage, though their deployment to date has been relatively limited.

The report sets out data, once again against a framework of assumptions and parameters, for a scenario in which all the world's electrical generation is delivered by nuclear – either by LWRs or Fast Reactors. Using a uranium reserves figure of 6.3MteU (which the report determines as the amount of "reasonably assured and inferred uranium resources"), it shows that used in LWRs, these uranium reserves would be consumed by the end of 2023. In contrast, if these same reserves were used in Fast Reactors, they would not be fully consumed until 2163.

Thus, a transition from LWR to Fast Reactor could provide a contingency, making nuclear a potential contributor to long-term decarbonisation even in the absence of an expanded uranium supply. However, the economics of fast reactors are not well understood. With this in mind, it is essential that the UK maintains a strategic view of its nuclear aspirations and allows options to be closed off only by positive decision rather than by default.

Developments in the UK nuclear energy landscape

Despite the terrible events at Fukushima, the UK has remained committed to nuclear new build. In the first half of 2012, nuclear new build remains on course but will continue to be a challenge, both in terms of finance and infrastructure planning. Nevertheless, there has never been a better time to ensure we have a coordinated approach to nuclear policy.

Fuel cycle policy and management of UK plutonium stocks is key to the future of nuclear generation. In their report published in March 2011, DECC (Department of Energy and Climate Change) offered qualified support for the re-use of plutonium as MOX fuel in new build reactors. This support was reiterated in a further report published by DECC in December 2011.

The March 2011 Smith School Report reviewed four scenarios for the treatment of the UK plutonium and AGR spent-fuel inventories, considering either re-use or conversion to waste and disposal.

- *Scenario 1:* Initial storage, designation as waste, and disposal of plutonium and spent AGR fuels.
- *Scenario 2:* Conversion of plutonium into MOX fuel for new-build reactors, treating the spent AGR fuel as waste for disposal.
- *Scenario 3:* Conversion of plutonium into MOX, reprocessing of spent AGR fuel in a refurbished THORP, and using separated uranium and plutonium as fuel for new-build reactors.
- *Scenario 4:* As Scenario 3, but with continued reprocessing of UK or overseas fuel in the refurbished THORP and recycling the separated plutonium and uranium as fuel.

Using the UK plutonium inventory to manufacture MOX fuel is now the UK Government's 'minded to' position, and the NDA (Nuclear Decommissioning Authority) position on AGR spent fuel favours long-term wet storage. This means that Scenario 2 stated above represents the de facto UK policy.

Defining a successful UK MOX fuel programme

How should a successful UK MOX programme be defined? What are the obstacles and opportunities which might hinder or promote the successful delivery of the UK's policy position on plutonium management?

The most fundamental aspect of any UK MOX project is that the initiative aims to turn the vast majority of the UK plutonium inventory into MOX, inferring that only a minimum of material becomes waste.

The report proposes the solution of fuel leasing as one that might simplify the MOX utilisation process, leading to greater opportunities to increase value for the UK in the short-term and long-term. In this scenario, the Government would keep title to the MOX fuel and lease it to the utilities to generate power, with the Government taking the fuel back for disposal. The fuel would never leave Government ownership and the utilities are effectively paying for electricity generation.

There are many benefits to fuel leasing. An advantage for the utility is that disposal costs can be subsumed into the lease price, removing a significant risk. In addition, the removal of risks and costs to the utilities should lead to an increase in the price they would be willing to pay for MOX fuel. Furthermore, because the Government has certainty in its ownership of spent fuel and the timing of its availability at reactor sites, it could examine centralisation of storage schemes.

Early announcement of an intention to develop a leasing scheme would provide a positive spur for utilities to commence negotiations before detailed reactor design and procurement is committed, enabling reactor projects to take on board MOX burning at an early stage with minimum additional costs.

To make the MOX fuel use option work, the report envisages arrangements whereby Government, while avoiding the cost of major plutonium waste disposal, contributes to the capital cost of the MOX fuel plant and develops a UK MOX business case. This case would provide suitable returns to attract a private sector 'part-owner/operator', who would be motivated to keep costs down and maximise prices. The report suggests that further study is required into the benefits of establishing valid business structures in this regard.

Consultations

Consultation for this report involved face-to-face meetings and an online written consultation that looked at:

- optimal amount of energy we should aim for in 2050 and 2100;
- impact on the UK's nuclear plans if other countries in the world go down the route of extensive nuclear new build;
- impact this might have on materials and resources available;
- role of a long-term road map for civil nuclear power;
- importance of investing in nuclear R&D to 2050 and beyond;
- UK as a leader in civil nuclear power.

Conclusions

The UK has decided that the decarbonisation agenda and ensuring security of supply of low carbon energy sources will still be best served by having nuclear as part of a balanced energy mix. This study has examined two important parts of the UK's nuclear landscape: the future delivery of low carbon energy, and the more immediate first steps: dealing with the UK's plutonium inventory and the initial moves towards a new build programme, which must both be effective in their own right, and must not preclude reaching the desired future.

- If the UK is going to go down the decarbonisation route there is an enormous challenge in meeting the electricity demand, particularly with its increased use in transport and possibly heating. At present the current proposals for new nuclear reactors will be no more than sufficient in replacing the current fleet.
- If the UK is serious about developing a world leading capability in the UK we need to develop a long term nuclear strategy encompassing both reactors and fuel cycle.
- Use of nuclear power to a degree that cuts global warming will require either much higher uranium reserves than currently identified or a change of fuel cycle to minimise uranium use.

- If the fabrication of MOX fuel is to proceed, it should be as part of an overall strategic plan to maximise the benefit to the UK from the burning of UK plutonium in UK reactors.
- The structure of the UK nuclear industry is aligned more towards the 'no nuclear' stance of 2003 than the 'new build' stance of 2012. There is a clear need for an independent body to advise and drive a long-term nuclear strategy.

21st Century Challenges

The resource challenge

Since the industrial revolution there has been unprecedented growth in the human population. This growth has been developed through the consumption of natural resources, and has helped to create economic prosperity for most of the world during the 20th and 21st centuries. As we are now witnessing, the impact of humanity on the planet is in grave danger of sacrificing the very habitats that provide the air we breathe, the food we eat, the water we drink and the natural resources we use. Failure to address these challenges could result in a planet that can no longer sustain our civilisation.

Over recent years the issue of resource scarcity has risen to the fore as a key challenge facing Governments and business alike. While some progress has been made in raising awareness and mobilising action – including new goals, valuation tools and action strategies on a global scale – we have yet to solve the systemic causes that continue to thwart meaningful and measurable change.

It is clear, as we progress through the 21st century that there are some major challenges ahead for Governments and businesses that require a coordinated approach, even going as far as a long term strategic plan. Even those organisations or countries that don't consider themselves affected by the issue of resource scarcity are likely to be impacted through their supply chains. It is imperative that organisations start looking at how they will manage resource risk to ensure their future sustainability as we move to a low carbon economy.

Decarbonisation agenda

The scientific evidence on climate change, while incomplete, is still compelling enough to have led to successive United Kingdom (UK) Governments to accelerate the transition to a low carbon economy. This drive has been built upon two major pillars; the first to reduce emissions and ensure safe low carbon sources of energy; and the second to ensure we have secure energy supplies from within our own borders.

It does make sense to defossilize our economy. The generation of electricity in particular is a key priority for the UK. Analysis by DECC[1] shows that significant change and investment are needed to meet our 2050 targets, and indicates that the majority of decarbonisation of the power sector will need to be completed by the 2030s. Decarbonising the power sector is essential for facilitating decarbonisation of other sectors in the economy, including transport.

It is crucial for the UK's international competitiveness and economic development that this continues but we do face a number of unprecedented challenges in the coming decades. Furthermore there is also now the real possibility that UK electricity supply will struggle to meet current demand over the next few decades as the ageing nuclear and coal power stations come to the end of their lives.

Intelligent infrastructure investment

To meet the UK Government's decarbonisation targets, the majority of new infrastructure investment needs to be in a diverse range of low carbon generation such as renewables, gas and coal Carbon Capture and Storage (CCS), and nuclear power. Investing in diversity is key to preserving and enhancing the UK's security of supply.

Over £250 billion may need to be spent on energy-related infrastructure in the UK over the next decade[2] and that infrastructure is notoriously long-lived. Unless we are careful with our investments today in developing a balanced portfolio of low carbon energy sources, we could be left with high carbon generating power stations which will not be fit for purpose in the coming decades.

The UK will lose around a quarter (around 20 GW) of its existing generation capacity as old or more polluting plants close. Modelling[3] suggests that de-rated capacity margins could fall below five per cent around the end of this decade, increasing the likelihood of costly blackouts. In addition to this huge reduction in existing capacity, the future electricity system will also contain more intermittent generation (wind) and inflexible generation (nuclear).

This raises additional challenges in terms of meeting demand at all times, while maintaining low costs. This inevitably leads to the need for a secure low carbon form of electricity production as part of the energy mix. Nuclear power is integral to this.

Investments in infrastructure can simultaneously realise the Government's economic goals and help to achieve the very ambitious emissions reduction goals the UK has set. However, without a clear plan and commercially focused models we will continue to have the same recurring issues.

Security of supply

Security of supply has risen up the political ladder in recent years. The National Grid currently projects peak electricity demand to remain relatively stable at around 60 gigawatts (GW) up to around 2025[4], although there are many mitigating factors around this projection. These factors include: fuel prices, energy conservation, population, power generation capacity and output, combined heat and power (CHP) capacity, embedded generation and exports, as well as an assessment of individual market sector growth in electric vehicles and heat pumps.

Generation capacity in the UK currently stands at 90.2 GW. However, as already stated in A Low Carbon Nuclear Future (2011), over the coming decade a number of changes will take place in the electricity markets, with the need to replace almost a quarter of our existing power stations by 2020 as they are ageing and unlikely to meet current, let alone future, environmental regulations. Furthermore all but one of our nuclear power plants are scheduled to come to the end of their working lives by 2025[5].

The Large Combustion Plant Directive[6] will lead to closure of around 12 GW of coal and oil fired generation by the end of 2015 at the latest. The Industrial Emissions Directive[7] could also lead to further closures by 2023. In addition, according to current timetables, up to 7.1 GW of existing nuclear generating capacity is reaching the end of its operational life and will have closed by 2020. Therefore some 19.1 GW could close by 2020, with further closures during the following decade, thus requiring urgent and intense replacement. This raises major issues for the UK as we move forward through the decade.

As of late 2011, around 8.3 GW of new plant to be connected to the National Grid is already under construction. Of this 4.3 GW is gas plant and 3.6 GW is renewable generation. There is planning permission for a further 13.2 GW, of which 8.7 GW is gas-fired generation and 3.7 renewable. The total of new and consented plant is 21.5 GW. Replacement nuclear capacity may also be available by around 2025 following the electricity market reforms. Given the significant closures of plant in the middle of this decade it is important that this new plant comes on as scheduled to avoid risks to security of supply.

Nuclear power and its role in a decarbonised secure economy

Since 2008 nuclear power new build has been back on the UK's agenda. The Coalition Government has stated that the UK's future supply of nuclear energy will be determined by the market. While electricity reform will deliver some incentives in the period up to 2025, a long term strategy is required now to secure energy supplies beyond 2025 which meet the decarbonisation strategy. The Government does see its role in securing private sector investment by developing a long term policy framework.

The Government has confirmed that it does not intend to subsidise nuclear power in the UK, but it does need to encourage industry to build the new power stations we need quickly and economically.

The National Infrastructure Plan published last autumn alongside the Chancellor's Autumn Statement sets out nuclear's role in driving low carbon economic growth[8]. The Government's Electricity Market Reform White Paper alongside the introduction of a carbon price floor in this year's Finance Act[9] were major steps in ensuring that nuclear new build becomes reality.

These steps were vital in delivering new nuclear build in the UK and will help to reduce investor uncertainty, put a fair price on carbon and provide stronger incentives to invest in low carbon generation. The Government's core reform package - a carbon price floor combined with new long term Contracts for Difference will work together to provide stable financial incentives to invest in all forms of low carbon electricity generation, not just nuclear. This will remove exposure to potentially volatile commodity prices for both investors and customers.

These statements are important part of the package of reforms to the planning system, ensuring faster decisions can be made on nationally significant infrastructure projects, whilst still allowing for robust public consultation.

A successful shift to a low carbon economy requires clear direction and early action: investors and consumers require confidence; large building and infrastructure projects require strategic planning; new technology takes time to reach commercial deployment; and behaviour inevitably changes gradually. Furthermore, the decisions that need to be taken will inevitably impact us for the next 100 years.

A low carbon pathway for the UK

It is clear that some major policy decisions and funding decisions need to be made, at a time when finance is in short supply. These critical issues have led us at The Smith School of Enterprise and the Environment at the University of Oxford to explore how the transition can be made to a low carbon economy and have a safe and secure supply of energy. This report, which ensues, is the outcome. It is clear to us that to do this the UK needs a clear long term strategy and a way to engage with the private as well as the public sectors so that the necessary arrangements can be made to and manoeuvre the UK onto a low carbon growth course.

R&D considerations

Any long term strategy for nuclear must include research and development. During the mid-twentieth century the UK was a world leader in nuclear fission R&D. For example, in the 1980s over 8,000 were involved in the UK's nuclear R&D programme[10]. However, with the privatisation of the electricity industry in the 1990's the funding for all areas of research rescinded. Today it is estimated that fewer than 2,000 people work on nuclear R&D in the UK[11].

In November 2011, the House of Lords Select Committee on Science and Technology published a report on Nuclear Research and Development Capabilities[12]. The key recommendations included the development of a long-term strategy for nuclear energy beyond 2025, outlining support for R&D through a Roadmap, and for the commercial exploitation of the UK's current strengths in nuclear research. In order to implement this Roadmap, the Committee recommended the establishment of an independent Nuclear R&D Board, made up of representatives from the Government, industry and academia, chaired by an independent, expert, authoritative Chairman.

In parallel, the Energy Research Partnership commissioned the UK National Nuclear Laboratory (NNL) to undertake a UK Nuclear Fission Technology Roadmap, which was published in February 2012[13]. This preliminary report also recommended that a clearly defined long term nuclear energy and industrial strategy, including a nuclear sector R&D Roadmap was required, and that an R&D co-ordinating body should be constituted to advise Government, in order to realise commercial opportunities and direct and underpinning R&D programme, in part through international collaboration.

Future challenges around nuclear

A Low Carbon Nuclear Future concentrated on four options for the use of current and expected stocks of spent fuel and nuclear materials using existing plants supplemented where required with new plants and operations. The present study goes further – examining a range of UK nuclear profiles and placing them within the world context, which includes the role for nuclear in the decarbonisation of global energy supplies, and the resource requirements that such global programmes will generate. The UK does not exist in a vacuum, and any UK options cannot therefore be realistically studied without asking the simple question *'but what happens if the rest of the world does likewise'*?

The relevance of this question has grown sharply in recent years, as countries as diverse as Vietnam, the United Arab Emirates and Poland have begun making plans for nuclear energy. While most short-term projections remain relatively modest, the range of programmes being studied both in the UK and elsewhere make global considerations an essential element in any strategy. When it is considered that each 1GWe of new LWR capacity commits to using around 11,000 tonnes of uranium in its 60-year life, then a currently assured, reasonably priced uranium supply of around 6 million tonnes will be required to fuel 550GWe of reactors. Current nuclear capacity is around 370GWe, which certainly raises the resources question – and least at the level of *'what if?'*.

Nuclear Facts:

- Nuclear generation currently reduces national carbon emissions by between 7% and 14%
- The estimated investment for planned 16GW new nuclear capacity currently stands at around £50 billion
- The number of people currently employed in the nuclear industry is estimated at 44,000 (24,000 direct; 20,000 contractors) 2011

Source: DECC

[1] Planning our electric future: A white paper for secure, affordable and low carbon electricity (CM8009, July 2011)
[2] Planning our electric future: A white paper for secure, affordable and low carbon electricity (CM8009), July 2011
[3] Statutory Security of Supply Report (HC1604), November 2011
[4] World Nuclear Association http://www.world-nuclear.org/info/inf84.html
[5] Directive 2001/80/EC of the European Parliament and of the Council of 23 October 2001 on the limitation of emissions of certain pollutants into The air from large combustion plants. Directive
[6] 2010/75/EU of the European Parliament and of the Council of 24 November 2010 on industrial emissions (integrated pollution prevention and control) (Recast)
[7] National Infrastructure Plan, November 2011
[8] Finance Act 2011
[9] UKAEA
[10] Sellafield Ltd
[11] House of Lords Select Committee on Science and Technology, Third Report, Session 2010-12, November 2011
[12] Energy Research Partnership: http://www.energyresearchpartnership.org.uk

Energy Demand

The scenarios

In our study of the role nuclear power will play in the United Kingdom over the next four decades, we investigated different scenarios for energy and electricity demand. The scenarios have been developed using the DECC 2050 scenario calculator[1], but are distinct from the scenarios published by DECC[2].

Herein, we use two extreme demand scenarios in order to illustrate the very different paths the UK might take: one that assumes that we do not conserve energy and continue on the current path, and one that assumes that the economy will be decarbonised and electrified and energy conversation will be emphasised in all sectors. We will refer to these demand scenarios as ***Business-As-Usual*** and ***Energy Efficiency,*** respectively.

For each of the two demand scenarios, two supply scenarios were modelled which meet each of the respective demand scenarios using different, feasible electricity mixes powering the grid, giving a total of four scenarios.

Assumptions for the demand scenarios:

In order to forecast electricity and energy demand using a scenario approach, a certain set of distinct, consistent assumptions is required. We outline the assumptions for the two demand scenarios in the following sections. Tables with a comprehensive list of assumptions are given in appendix 1.

Demand scenario A - business-as-usual

In the business-as-usual scenario, we assume that society continues on the current energy trajectory, i.e. the demand for energy increases while it is used marginally more efficiently. In the case of transport, it is assumed that in 2050 individuals travel 9% further than today without a noticeable modal shift to public transportation. The vehicle fleet will grow and 20% of these vehicles will be plug-in hybrid electric while 2.5% will be electric 'zero emission' vehicles hence the increase in demand for electricity. For the built environment, it is assumed that the average room temperature is increased to 20°C (a 2.5°C increase compared to 2007) while the average thermal leakiness falls by 25%. Electricity demand for domestic lights and appliances increases by 20% (relative to 2007) while the energy efficiency of appliances is assumed to increase steadily. In the case of industrial energy demand, it is assumed that energy intensity improves marginally. In the commercial sector demand for lights & appliances increases by 33%, heating demand increases by 50% and cooling demand increases by 250%. Hence, the economy will remain dependent on fossil fuels, especially oil, as no major electrification will take place and demand will steadily grow. In this scenario the energy demand in 2050 will be 33% higher than in 2007 (Figure 1) and the demand for electricity will have risen by more than 50%.

Demand scenario B - energy efficiency & electrification

In the energy efficiency scenario, we assume that society will adapt serious behavioural changes, that energy will be conserved through large scale energy efficiency endeavors and additionally major parts of the British economy will be electrified. In the case of transport, it is assumed that individuals travel the same distance as today, but a major shift to public transport occurs. By 2050 the road vehicle fleet is made up exclusively from zero-emission vehicles, and all passenger trains are electrified. In the case of the built environment, it is assumed that the average room temperature is decreased to 16°C and that the average thermal leakiness of buildings is decreased by 50%. In the case of domestic lighting, the electricity demand is reduced by 60% due to the maturing of novel technologies such as LED lighting and lighting management (e.g. motion sensors). Space heating is assumed to be electrified, drastically reducing the need for fossil fuels in the built environment. In the case of the industrial sector, a high rate of electrification is assumed and CCS is applied in areas where electrification is not possible. The commercial sector shifts towards electricity as a fuel for heating and cooking. Overall, the energy demand in this scenario is 38% lower (Figure 1), however, the demand for electricity is 44% higher owing to the sectoral electrification measures.

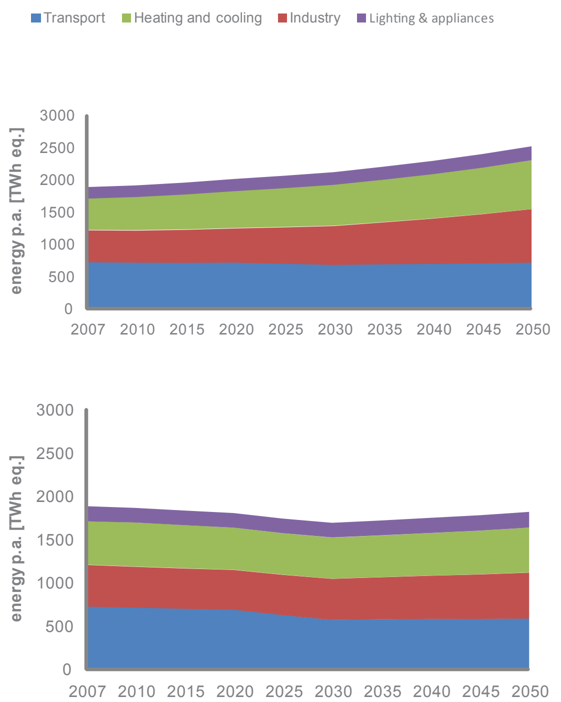


Figure 1: Energy Demand Scenarios for the United Kingdom up to the year 2050: Business-As-Usual (top) and Energy Efficiency (bottom); all energy units are converted to TWh [TWh eq.]

Both scenarios are possible outcomes and their environmental impact as well as their energy security implications greatly depend on the electricity grid that is backing them. For each of the two demand scenarios, two electricity supply scenarios were developed which meet the electricity demanded in each case.

Supply-demand scenarios

For each of the two demand scenarios described above, two distinct supply scenarios were modelled leading to a total of four different supply-demand scenarios. Scenarios A1 and A2 consider business-as-usual demand over the next four decades, while scenarios B1 and B2 consider energy efficiency measures and electrification of other sectors. The latter two scenarios consequently provide significantly more electricity in order to meet the additional demand from the sectoral electrification measures.

Each of the four scenarios achieves a significant decarbonisation of the grid electricity and meets the projected electricity demand. However, the implication of those four scenarios on energy security as well as overall emissions vary greatly. The evolution of the electricity mix and the installed capacity over the next four decades are depicted in Figure 2 and Figure 3, respectively.

Scenario A1: bau – nuclear, hydroelectricity & ccs

In Scenario A1, civil nuclear capacity is expanded, thus reducing the share of thermal (coal, oil, gas) electricity generation for the UK. Baseload electricity is mainly provided by nuclear power while thermal generation covers some of the baseload capacity and will be online on-demand during hours of peak demand[3].

Thermal generation plants are gradually replaced, and coal is substituted by gas and biomass. In addition, new-built thermal generation plants are fitted with state-of-the-art CCS technology in order to further reduce emissions. Simultaneously hydropower is expanded in order to be able to store overproduced electricity during low-demand and reutilise it during peak demand[3].

All capacities used for each power source are within the limits modelled by the 2050 pathways. The Government's National Renewable Energy Action Plan, which was submitted to the EU in July 2010, contains a central scenario for hydro that envisages between 40 MW and 50 MW a year being installed annually up to 2020.

Civil nuclear capacity is expanded to 40 GW in 2050, producing approximately 280 TWh of electricity or 47% of overall electricity demand. Consequently, most of the baseload electricity provided will be generated by nuclear power plants. Electricity generated by fossil fuels will mainly be responsible for supply during peak demand; the installed capacity of 40 GW will produce 269 TWh[4] according to our simulation. Emissions from scenarios, thermal electricity generation will further be reduced by substituting coal with gas and biomass as well as using CCS technology. Unabated thermal electricity generation is phased out and non-existent by 2050 in this scenario. In the case of renewables, wind will be phased out in this scenario while hydropower will be expanded to 2.1 GW capacity by 2050 producing 7 TWh annually. In this scenario, the British grid has a capacity of 87 GW producing 586 TWh per annum[5].

Even though the emission intensity of electricity production is drastically reduced in this scenario, the impact on overall emissions is limited. According to our calculations, emissions are only reduced to 73% of 1990 emissions by 2050, because other sectors are not electrified or decarbonised in parallel. This scenario consequently illustrates that a mere decarbonisation of the electricity grid is not sufficient to decarbonise the economy. Other sectors have to be decarbonised or electrified in parallel in order to make an impact on overall emissions.

Scenario A2: nuclear & ccs

In Scenario A2, the baseload is provided by nuclear power and onshore wind. Thermal generation and hydropower will ease out fluctuations in windpower and cater for peak demand.

As in scenario A1, nuclear capacity is expanded to 40 GW in 2050 producing ~280 TWh[6] of electricity. However, in this scenario we assume that part of the primary electricity generation is provided by 20 GW of onshore wind capacity producing 53 TWh[7] annually. Thermal generation will ease out fluctuations in electricity produced by windfarms and additionally will provide electricity during peak demand. As in the previous scenario, thermal electricity production, i.e. by fossil fuel combustion, is combined with CCS technology; coal is substituted by biomass, waste, biogas and natural gas. CCS plants have a capacity of 40 GW and produce ~270 TWh[8] in 2050. Unabated thermal generation is phased out and essentially non-existent in 2050. Hydropower capacity is expanded to 4 GW in 2050 producing 13 TWh per annum, hydropower will also be used to store and reutilise potential electricity overproduction during times of low-demand or high production from windpower. Overalll installed capacity in this scenario is 106 GW producing 609 TWh[9] of electricity annually.

Even though the emission intensity of electricity production is - similar to scenario A1 - drastically reduced, the impact on overall emissions in the UK is limited. According to the simulations carried out for this scenario, emissions are reduced to 71% relative to 1990 values. This is again due to the lack of decarbonisation in other sectors, as well as insufficient electrification. Consequently, the second scenario for business-as-usual demand also achieves significant decarbonisation of the grid, but fails to decarbonise the economy. Other sectors have to be decarbonised or electrified in parallel in order to make an impact on overall emissions and achieve the government's target.

Scenario B1: energy efficiency – mix

In Scenario B1, civil nuclear capacity is expanded, reducing the share of thermal electricity generation on the British electricity grid analogue to scenarios A and B. Baseload electricity is provided by nuclear power as well as off and onshore windpower. Fluctuations in electricity supplied from windpower will be backed up with abated thermal generation.

Nuclear capacity is expanded to 40 GW in 2050, producing 275 TWh of electricity and wind capacity is expanded to 80 GW (20 GW onshore & 60 GW offshore) producing ~290 TWh of electricity[10]. For peak demand and to compensate for fluctuations in wind, 40 GW of abated thermal generation are installed producing roughly 270 TWh[11] of electricity annually. In this scenario, hydroelectricity is expanded to 4 GW in order to store excess electricity generated by the nuclear-wind baseload. Overall capacity installed is 163 GW producing 846 TWh[12] of electricity annually: this scenario provides substantially more electricity than scenarios A1 and A2 in order to support the sectoral electrification assumed in the Energy Efficiency demand scenario.

In this scenario, the net demand for electricity increases by 121% over four decades due to widespread sectoral electrification and economic growth overwhelming the decrease due to energy efficiency measures. The electrification of other sectors reduces fossil fuel use in other areas, for instance in heating and transport. Consequently, the ***primary energy demand decreases by 2.5%*** between 2010 and 2050 in this scenario. Not only does this reduce emissions drastically, but also mitigates fossil fuel dependence and hence increases energy security of the United Kingdom. The decreased fossil fuel dependence moreover reduces the economic risk supply shortages pose to the British economy as electricity produced from domestically available wind and fissible material is the main fuel in this scenario.

According to our calculations, emissions are drastically ***reduced to 16% of 1990 emissions*** by 2050. This scenario consequently illustrates that large-scale sectoral electrification, energy conversion and grid decarbonisation using nuclear power and renewables present a means to meet the emission reduction targets set out by the Government. Moreover, most energy is provided using domestically available sources[4]. The energy security of the United Kingdom would be significantly strengthened.

Scenario B2: energy efficiency – nuclear & ccs

Scenario B2 is a high nuclear scenario in which nuclear power provides all of the baseload capacity while electricity for peak demand is produced using abated thermal generation mainly from natural and bio gas combustion.

Nuclear capacity is expanded to 90 GW in 2050 producing ~640 TWh of electricity, which is more than the baseload for the UK grid. Four GW of hydroelectricity are installed in order to store overproduction of nuclear electricity and to be reutilised during peak demand. Abated gas-fired power plants are used to cater for peak demand; in this scenario they have a capacity of 40 GW and produce ~270 TWh per annum with gas CCS as back up. The capacity of the UK grid is extended to 134 GW in this scenario, producing 907 TWh[19] annually. The capacity deployed is significantly lower than in scenario C as this scenario delivers a secure supply and is not subject to fluctuations in wind, for instance.

In this scenario, the demand for electricity increases by 121% over four decades due to widespread electrification and economic growth while primary energy demand is reduced by 2.5% as in scenario B1. Not only does this reduce emissions drastically but also mitigates fossil fuel dependence and hence increases the energy security of the United Kingdom. The decreased fossil fuel dependence moreover reduces the economic risk supply shortages could pose to the British economy as electricity is the main fuel in this scenario and is produced from domestically available fissible material. Also, this scenario neglects windpower; this has the advantage that supply fluctuations do not have to be compensated by gas-fired power stations. This further reduces emissions.

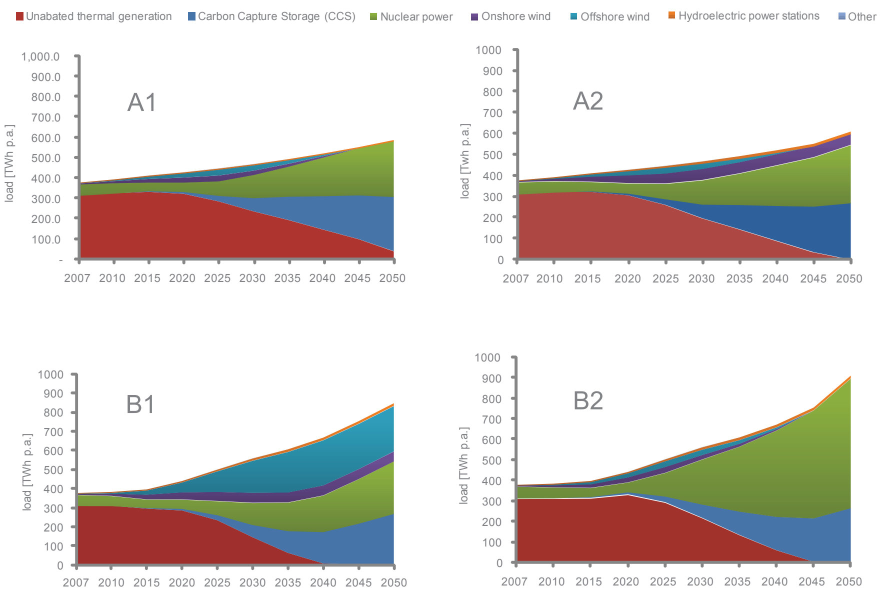


Figure 2: Evolution of the capacity installed up to 2050

According to our calculations, emissions are drastically ***reduced to 15% of 1990 emissions by 2050.*** This scenario consequently illustrates that large-scale electrification, energy conversion and grid decarbonisation using nuclear power as baseload and abated thermal generation for peak demand can reduce emission significantly below the target set by the Government. Also this scenario, as in scenario B1, would strengthen the energy security of the United Kingdom.

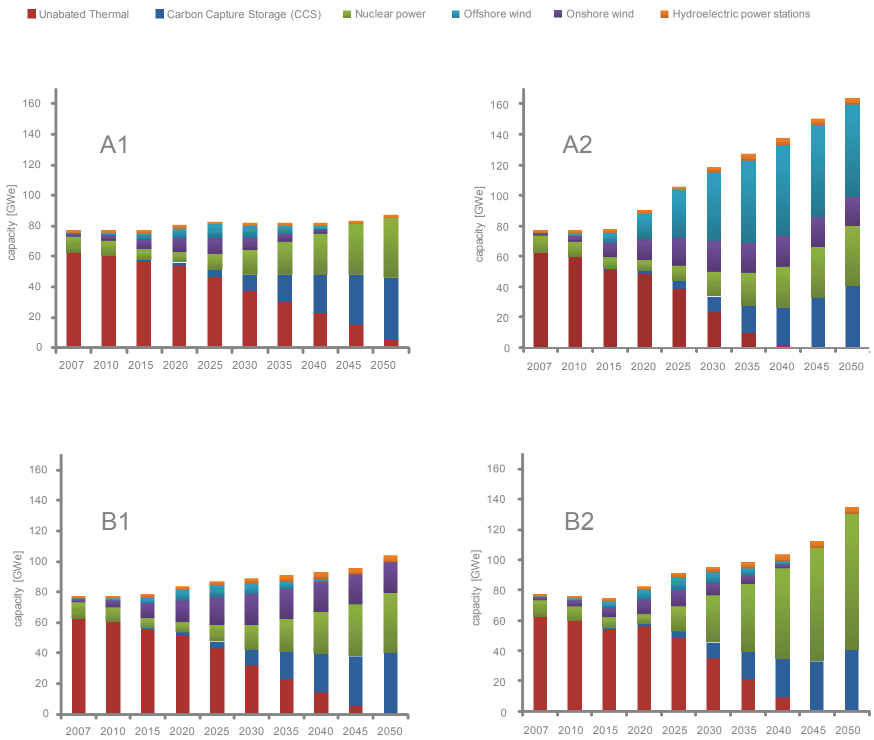


Figure 3: Evolution of the capacity installed up to 2050

The scenarios set out in this chapter clearly illustrate that a pure decarbonisation of electricity generation is not sufficient to meet the government's target of 80% emission reduction by 2050. Energy has to be conserved in order to make an impact and high-carbon sectors such as transport have to be electrified in parallel. If combined with the decarbonisation of grid electricity, further emission reductions could be achieved

There are several ways to decarbonise electricity, all of which have pros and cons. CCS can help decarbonisation, however, on a large scale it can exacerbate the amount of resource imports and therefore potentially weaken energy security. Moreover, the amount of gas stored subsurface would be enormous. Renewables are difficult to scale up and are subject to uncontrollable factors (wind patterns, water availability etc). Nuclear power on the other hand can provide safe, low carbon electricity for base supply. The following chapters will illustrate the potential of nuclear power in the UK and will set out a possible pathway for nuclear power in a low carbon economy.

[1]http://www.decc.gov.uk/en/content/cms/tackling/2050/calculator_exc/calculator_exc.aspx
[2]http://www.decc.gov.uk/en/content/cms/news/pn10_85/pn10_85.aspx
[3]The 2050 pathways gives four levels of hydro GWe/TWh/(load Factor) of 1.6/5.5/39%, 2.1/7.0/38%, 2.5/8.3/38%, 4.0/13.3/38%. 2050 pathways assumes 35-40% across the year for all levels – which makes it seem as if it's assuming hydro without increasing pumped storage
[4]The model is based on DECC assumptions; the load factor is assumed to be 35% to 2035 and 45% thereafter for offshore wind http://www.decc.gov.uk/assets/decc/Consultations/2050/1344-2050-pathways-analysis-response-pt2.pdf

The Decarbonisation Challenge

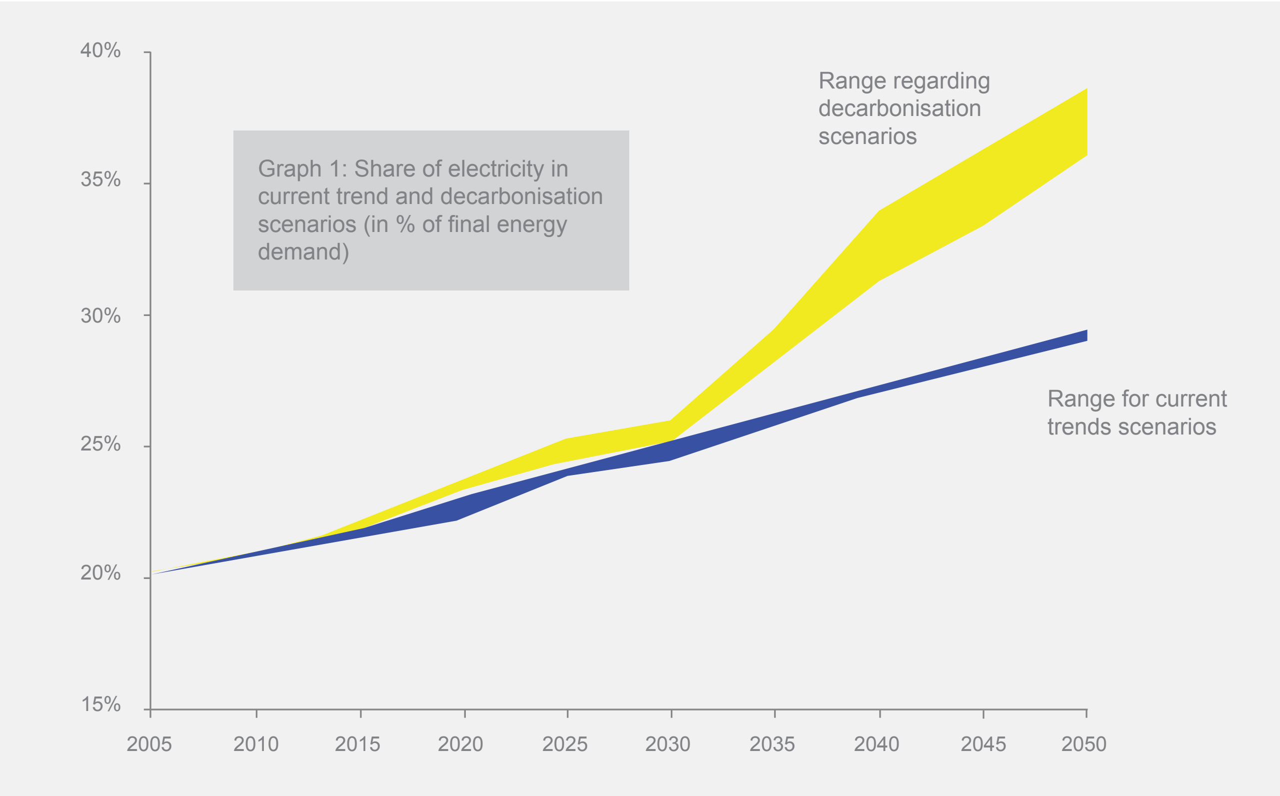
Decarbonisation

This section will examine approaches to decarbonisation outside the UK to assess whether the role of nuclear energy envisaged for the UK is applicable to the broader world context.

The dichotomy of opinions on nuclear within the EU is neatly summed up in the Energy Roadmap 2050 of 2011, it states:

"Nuclear energy is a decarbonisation option providing today most of the low-carbon electricity consumed in the EU. Some Member States consider the risks related to nuclear energy as unacceptable. Since the accident in Fukushima, public policy on nuclear energy has changed in some Member States while others continue to see nuclear energy as a secure, reliable and affordable source of low-carbon electricity generation".

However, it is unequivocal about the increased role that low carbon electricity must play in the total energy mix if decarbonisation is to be achieved. This is well illustrated by Graph 1.



This emphasises that all EC decarbonisation scenarios rely on a shift from fossil fuel consumption to low carbon electricity.

The world is now on track for a comprehensive global treaty on climate change to be implemented agreement reached at the COP meeting in Durban, South Africa in December 2011. For the first time all countries agreed that climate policies were currently inadequate. The Durban agreement explicitly refers to the "emissions gap" – the difference between the aggregate impact of commitments that countries have made, and the upper limit of emissions required to have a chance of meeting the globally agreed goal of no more than two degrees of global warming.

The Durban agreement also saw the extension of the Kyoto Protocol, the legally binding treaty signed in 1997. Although only the EU and a few other countries are likely to maintain their commitment to it, it is, in the short term vital to preserve its legal rules and mechanisms, which have underpinned much to enable climate policy in the last decade.

The roadmap towards a new treaty to succeed Kyoto in 2020 requires all countries, including the large emerging economies such as China, India and Brazil, to make legally binding commitments. This is a vital recognition of the key role these countries now play, and will need to play, in tackling climate change, given the rate at which their economies and emissions are growing and the emissions they produce.

However, the counterbalance to this is that demand for energy is likely to grow by a third between now and 2035. This additional energy will have to be provided by low or zero carbon energy sources. Events in Fukushima raised questions about the role of nuclear power but it has not changed policy in countries such as China, India, Russia and Korea, which are now the major countries driving growth globally.

The 2009 IEA World Energy Outlook gives nuclear a 6.75% share of primary energy in 2007. In comparison, Updated Energy and Carbon Emissions Projections, The Energy White Paper, BERR, Feb 2008, gives nuclear a 7.45% share of UK's primary energy in 2005, falling to 6.97% in 2010. Therefore, the UK makes a fairly convincing template for the world, and also fortuitously consumes almost exactly 2% of the world's primary energy.

In the following sections, therefore, "World Nuclear Decarbonisation Scenarios" are postulated and examined for their sustainability on a world scale. These Scenarios may then be compared to the UK nuclear programmes under examination here.

The most credible scenarios that offer adequate decarbonisation of world energy supplies involve significant contributions from nuclear power. Without nuclear energy and with continuing and increasing energy demand, we would actually increase our consumption of fossil fuels globally.

A clear pathway is needed to bridge the energy gap, ensuring we have the ability to meet these challenges, from a safety, economic, environment and resource efficiency position.

Implications for a world nuclear future

World electricity generating statistics are generally quoted in terawatt-hours (TWh), but these include generation from many sources that are used only intermittently, for example during periods of high demand or when other sources are not available. For this study we have defined a 'standard 1GWe generating station working at 90% load Factor' (see appendix 2), and base all the generating cases on multiples of these stations. The three cases examined are based on a 2011 world electrical generation equivalent to 2,400GWe of generation capacity operating at 90% Load Factor[1].

Scenario A: World nuclear capacity grows at 4% pa until 50% of world capacity is reached, after which it grows at 1.9%, keeping to 50%

Scenario B: World nuclear capacity grows at 5% pa until 60% of world capacity is reached, after which it grows at 1.9%, keeping to 60%

Scenario C: World nuclear capacity grows at 6% pa until 70% of world capacity is reached, after which it grows at 1.9%, keeping to 70%

This gives the capacity build-up with time seen in Figure 2 below.

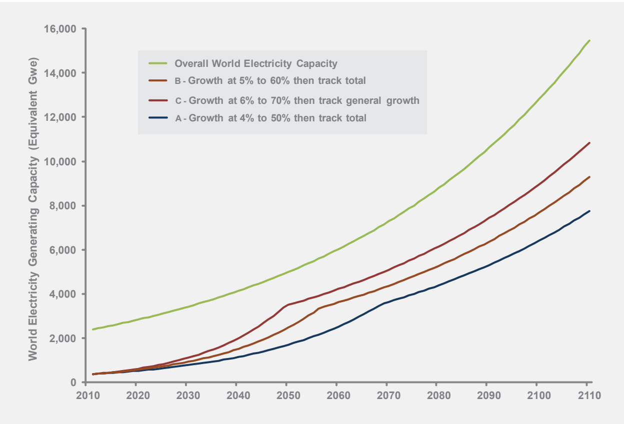


Figure 2. World Electrical Generating Capacity and Nuclear Scenarios

These nuclear generation figures may be compared, at least up to 2050, with scenarios being examined in the UK and elsewhere. Examples are shown in Figure 3 and include:

- US Energy Information Administration (EIA) International Energy Outlook, September 2011 (noting that this extends only to 2035)
- The MIT 2.5% Nuclear growth case[2] (noting that this case is identical to the EIA case up to 2035)
- The MIT 4.0% Nuclear growth case[3] (noting that this case is identical to Scenario A of the present study)
- Nuclear Power Levels 2, 3 and 4 from 2050 Pathways Analysis, HMG, July 2010
- The High case from "Energy Electricity and Nuclear Power Estimates to 2050" IAEA, 2010, gives a programme very close to Scenario A
- The World Nuclear Association Nuclear Century (High) programme (January 2012)

In addition, the ERP-commissioned a UK Nuclear Fission Technology Roadmap which examines an, 'Expansion Scenario' of 16GWe of PWRs to 2025, with expansion to 40GWe by 2050 including a tranche of fast reactors. The results demonstrate the lower uranium requirements of scenarios which include fast reactors.

This shows that the US 2.5% growth cases are the lowest of those examined, the MIT 4.0% case is identical to Scenario A. Scenario B is close to 2050 Pathways Level 2, with Scenario C lying between 2050 Pathways Levels 2 and 3.

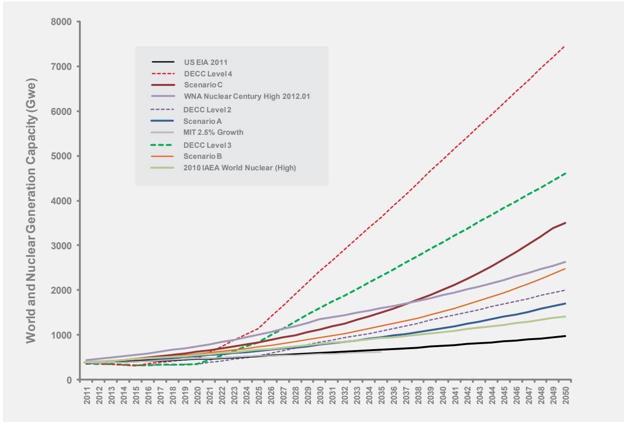


Figure 3. A Selection of Nuclear Programmes to 2050

In figure 4 the three Scenarios from the present study are compared with the MIT 4% Growth, the IAEA High Nuclear Power Estimate and the WNA Nuclear Century High programmes, up to the year 2100, extrapolated where necessary.

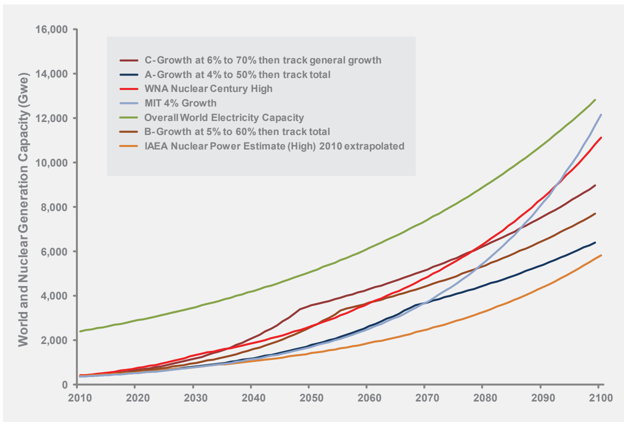


Figure 4. A Selection of Nuclear Programmes to 2100

This shows that Scenarios A and B are generally between the MIT and WNA estimates in the period up to 2070.

These nuclear generation figures can then be used to calculate uranium usage, for the three Study Scenarios, based on the 180teU/a for the 1GWe reactors as defined in appendix 2.

For a reactor with an expected 60-year life, the expectation for the reactor utility is that 60 years of uranium supply will be available. Hence each GWe of LWR started up effectively commits to around 10,800teU of uranium production. When these figures are combined with the nuclear generation in each Scenario, the resulting cummulative uranium demand is shown in the summary Tables 1, 2 below.

Table 1. Modelled scenario uranium use

	Scenario A	Scenario B	Scenario C
2011	0.066	0.066	0.066
2020	0.800	0.838	0.878
2030	1.983	2.202	2.450
2050	6.329	8.045	10.291
2070	15.828	21.010	25.736
2090	31.903	40.300	48.241
2110	55.325	68.407	81.032

Use to end of year, million teU

Table 2. Modelled scenario uranium commitment

	Scenario A	Scenario B	Scenario C
2011	1.998	1.998	1.998
2020	3.690	4.201	4.753
2030	6.421	8.100	10.092
2050	16.449	24.794	35.805
2070	37.346	45.215	53.084
2090	55.330	66.795	78.261
2110	81.533	98.240	114.946

Commitment to end of year, million teU

The uranium usage and commitment figures are shown in Figure 5 below.

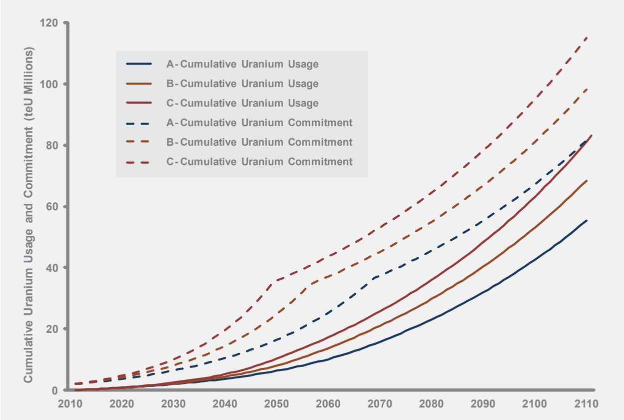


Figure 5. World Uranium Consumption and Commitment

The uranium requirements of the Scenarios can be summed up in the need for tens of millions of tonnes of uranium before the middle of the century.

Uranium resources

Global uranium reserves far exceed any of the quantities derived above, with around 80x1012 teU estimated in the crust of the earth to a depth of 25km[4]. The question, however, is how much of this uranium can actually be made available at a reasonable cost in financial and environmental resources?

OECD, NEA & IAEA publish estimates of uranium resources for known and inferred reserves which can be accessed at given costs. A recent publication[5] gives Reasonably Assured and Inferred resources as in Table 3.

The data indicates that the 2050 usage (and commitment) of uranium inferred by the three Scenarios is greater than currently reasonably assured and inferred uranium resources by factors of:

Scenario A	1.003	(2.608)
Scenario B	1.276	(3.932)
Scenario C	1.632	(5.678)

Extraction Cost		Reasonably Assured (kteU)	Inferred (kteU)	Total (kteU)
$/kgU	lb U3O8			
<40	<15.4	569.9	226.6	796.5
<80	<30.8	2,516.1	1,225.8	3,742.4
<130	<50	3,524.9	1,879.1	5,404.0
<260	<100	4,004.5	2,301.8	6,306.3

Table 3. Reasonably Assured and Inferred Uranium Resources

Thus for any of the three Scenarios to be viable even in the medium term, either considerably more economically retrievable uranium must be found, or more uranium-efficient technologies are required.

Extending uranium resources

As indicated above, the reserves of uranium is not a problem, but extracting it at a reasonable cost and with acceptable environmental impacts would be a challenge. In particular, the use of poorer grade ores using energy provided by fossil fuels would increase the emission of carbon dioxide and decrease the effectiveness of nuclear as a low carbon technology.

Forecasting or predicting the amounts of uranium that will be accessible at any given price is open to varying modelling techniques and opinions. The range of opinions has been summarised in a 2008 study by Schneider and Sailor[6], who reviewed the various methods used in the literature and produced the composite figure seen below.

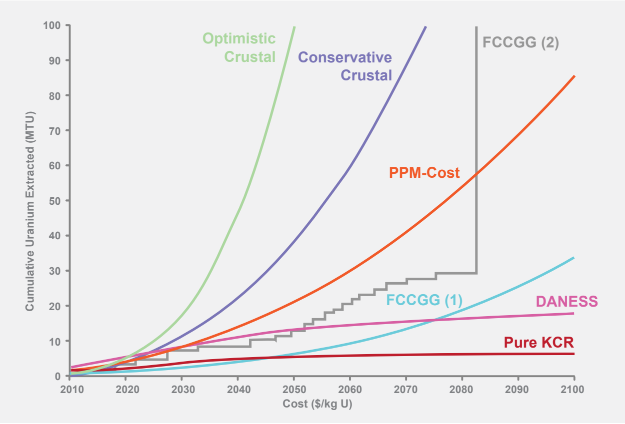


Figure 6. Uranium supply curves from the literature (Schneider and Sailor, Figure 3)

Such variance leaves a great deal of room for disagreement between academic groups. For example, a 2011 MIT Fuel Cycle Study[7] concluded that

"Our analysis of uranium mining costs versus cumulative production in a world with ten times as many LWRs and each LWR operating for 100 years indicates a probable 50% increase in uranium costs. Such a modest increase in uranium costs would not significantly impact nuclear power economics."

This implies the building of 3,050GWe of LWRs and their operation for 100 years, giving a cumulative uranium usage of around 61 million teU, or 10 times currently estimated reserves from Table 3.

On the other hand, several of the more pessimistic studies quoted by Schneider and Sailor give a much greater increase in unit uranium costs with the exploitation of increasing reserves, and recent studies at the University of Manchester[8,9] have tended to support a more conservative estimate. Certainly, this is a field which justifies more attention, and the emergence of a consensus would be a great aid to understanding the extent of the role that nuclear power generation could make in a worldwide decarbonised economy. Until this is achieved, however, it must be advisable to keep nuclear fuel cycle options open as far as is practicable.

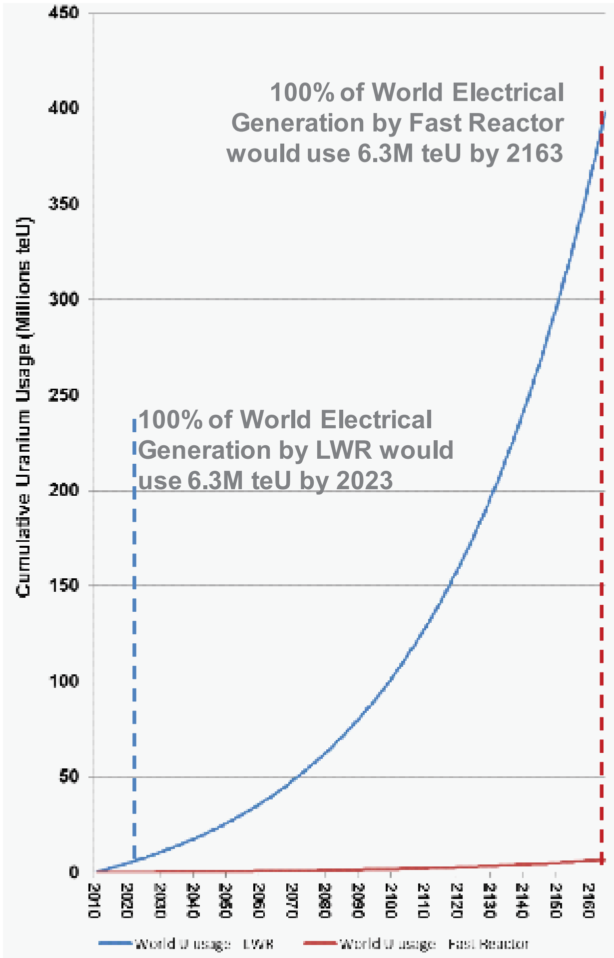
Increasing uranium efficiency

As has been explored, the "LWR once through" nuclear fuel cycle is relatively profligate in its use of uranium, leading to a figure of 180teU/a being adopted in this study for a 1GWe PWR operating at 90% load factor. Other reactor technologies and fuel cycles have the potential to decrease uranium usage from 180teu/a to 3-4teU/a, and these possibilities are outlined in (see appendix 2).

The effect of a reduction in uranium usage to 3teU/GWe/a is illustrated by the figure below.

- This figure takes the extreme case where all the world's electrical generation assumed for the three Scenarios A, B, C is generated by nuclear – either by LWRs at 180teU/GWe/a or by Fast Reactors at 3teU/GWe/a
- Such 'whole world' generation is considered to start at the end of 2010
- As an illustration, the world's uranium resources from Table N are considered as the available reserves
- If used in LWRs, 6.3MteU reserves are consumed by the end of 2023
- If used in Fast Reactors the 6.3MteU reserves are consumed by the end of 2163
- A transition from LWR to Fast Reactor could provide a contingency, making nuclear energy a potential contributor to major long-term decarbonisation even in the absence of a major expansion of uranium supply

While Fast Reactors hold out the promise of a considerably more effective use of uranium, their actual deployment to date has been relatively limited, with prototype reactors being built in the US, France, UK, Russia, Japan, Germany, India, Kazakhstan and China. However, although some 20 reactors have been operated, the technology, with its fuel cycle, has not progressed past the prototype stage, and has not benefitted from the 50 years of learning curves and economies of scale that LWRs have experienced while becoming the dominant world technology.



The economics of fast reactors are therefore not well understood, but are generally held to be inferior to 'once-through LWR' as long as there are reasonably assured uranium supplies at credible prices. Since the proportion of the cost of LWR power which derives from uranium is small (3% is commonly quoted), rising uranium prices are only a weak incentive to change technology. Reduced security of uranium supply is a more credible trigger for change, particularly for a country such as the UK with no indigenous uranium resources, and no strategic involvement in ensuring the security of uranium supply[10].

While uranium resources are uncertain and world nuclear programmes in doubt, it is essential that the UK maintains a strategic view of its nuclear aspirations and allows options to be closed off by positive decision rather than by default.

[1]For example, US Energy Information Administration (EIA) International Energy Outlook, September 2011, gives world total generating capacity in 2008 as 19.100TWh, which converts to the output of 2,421 1GWe generators at 90% load factor.
[2] From The Future of the Nuclear Fuel Cycle, MIT, April 2011
[3] From The Future of the Nuclear Fuel Cycle, MIT, April 2011
[4]K S Deffeyes and I D MacGregor, 'World Uranium Resources', Sci. Am., Vol 242, I, 66 (1980), reported in 'Long-Term Uranium Supply Estmates, E A Schneider and W C Sailor, Nuclear Technology, Vol 162, June 2008
[5]OECD NEA & IAEA, Uranium 2009: Resources, Production and Demand ("Red Book")
[6]Long-Term Uranium Supply Estimates Schneider Sailor Nuclear Technology V162_n3_pp379-387
[7]The Future of the Nuclear Fuel Cycle, MIT, April 2011, Page 4
[8]Joint economic and physical constraints on nuclear power: How much uranium would be needed to decarbonise? David Liu, Gregg Butler, Stuart Hall, Paul Johnson, Peter Duck, Geoff Evatt, Sydney Howell, November 2011, to be published
[9]Challenges for worldwide nuclear programmes: some major technical and economic constraints on responses by various fuel cycles, G. G. Butler, S. D. Howell, P. V. Johnson, S. J. Hall, D.W. Liu, P.W. Duck, to be published
[10]For example, 'China begins trial p[roduction at its first overseas uranium mine in Niger', March 2011, http://www.chinadaily.com.cn/business/2011-03/24/content_12220006.htm

Current Nuclear Energy Landscape

Developments in the UK nuclear energy landscape

2011 was always going to be a very important year for nuclear new build in the UK, even without the terrible events at Fukushima. The UK has remained committed to nuclear new build, whilst also ensuring that the industry revisits the way it provides assurance in terms of safety standards and the need to demonstrate transparency in how they operate.

The Weightman Review[1] concluded that there was no reason to curtail the operation of UK sites, although operators should continue to follow the founding principle of continuous improvement. It went on to conclude that there were no fundamental weaknesses in the UK nuclear licensing regime or the safety assessment principles that underpin it, and to support the intention to create the Office for Nuclear Regulation (ONR) in statute which will further enhance confidence in the UK's regulatory regime.

For nuclear new build, the publication of the Electricity Market Reform White Paper, published in July 2011, alongside the introduction of a carbon price floor in the Budget, were vital for the on-going nuclear new build. This core piece of legislation, combined with long term contracts will hopefully provide stable financial incentives for all forms of low carbon electricity generation.

In July 2011, the House of Commons debated and approved the six National Policy Statements (NPS) for Energy. The energy NPSs set out national policy against which proposals for major energy projects will be assessed and decided on by the Infrastructure Planning Commission. The Statements are a vital part of the reforms package to the planning system, which should mean that faster decisions can be made on nationally significant infrastructure projects.

As we stand here in the first half of 2012, nuclear new build remains on course but will continue to be a challenge, both in terms of finance and infrastructure planning. There has never been a better time to ensure we have a coordinated approach to nuclear policy, from nuclear new build to managing our existing assets.

Developments in UK fuel cycle policy landscape

At the time of publication of ***"A low carbon nuclear future: Economic assessment of nuclear materials and spent nuclear fuel in the UK"*** (March 2011), DECC had recently published its "Management of The UK's Plutonium Stocks: A consultation on the long-term management of UK owned separated civil plutonium", and NDA had issued a "Plutonium Strategy Current Position Paper".

The DECC publication concluded that:

"The UK Government's preliminary policy view is that proceeding on the basis that reusing plutonium either in the UK or overseas in the form of MOX fuel offers the best prospect to deliver a solution for long-term plutonium management.

This preliminary view will be conditional in that it will have to be tested to show that it is affordable, deliverable and offers value for money, taking into account safety and security requirements, before the UK Government will be in any position to take a final view".

This offered qualified support to Scenarios considering re-use of plutonium as MOX fuel in new build reactors.

In April 2011, the NDA issued its latest "Strategy Effective from April 2011". For plutonium, the strategy supported the options discussed by DECC until such time as Government policy was determined. For spent AGR fuel, the emphasis was on "enabling a transition away from reprocessing to wet storage", with the amount of AGR fuel reprocessed to be defined by studies to determine the most cost-effective lifecycle management option.

In June 2011, the DECC ***"National Policy Statement for Nuclear Power Generation (EN-6)"*** affirmed 8 sites[2] as potentially suitable for the deployment of new nuclear power stations in England and Wales before the end of 2025, thus providing reactor capacity for using MOX fuel from UK plutonium.

On 1st December 2011, DECC issued ***"Management of the UK's Plutonium Stocks A consultation response on the long-term management of UK-owned separated civil plutonium"***. The principal conclusion was that:

"the right preliminary view was selected in the consultation paper and that to manage the vast majority of our separated plutonium in the long-term, the best prospect of success lies with the "reuse as MOX" option. This option should therefore be taken forward as the principal policy for long-term plutonium management".

This offered further support to Scenarios considering reuse of plutonium as MOX fuel in new build reactors.

The nuclear non-proliferation regime and the Nuclear Non-Proliferation Treaty (NPT) is not covered explicitly in this report but will be covered in a future report.

NDA produced an *"Oxide Fuels Credible Options"* assessment in November 2011 which made the following points:

- In the foreseeable future there was no perceived demand for THORP's reprocessing services beyond the current contracts.
- The recycling of spent fuel in the UK in thermal reactors was unlikely to be commercially attractive, at least for the foreseeable future.
- The delivery of the current strategy, to complete the reprocessing contracts, remained the most viable and cost-effective option, and envisaged the closure of THORP around 2018.
- On a like-for-like basis storage followed by disposal of spent fuel was currently more cost-effective than reprocessing, and the option envisaged the long term interim storage of unreprocessed AGR spent fuel in the THORP Receipt and Storage pond, dosed with a corrosion inhibitor to make it caustic.

Review of nuclear materials and spent fuel management scenarios

The March 2011 Study reviewed four Scenarios for the treatment of the UK plutonium and AGR spent fuel inventories, considering either re-use or conversion to waste and disposal. Re-use options using reprocessing also studied the possibility of additional overseas reprocessing business. The range of materials, products and plants which made up the Scenarios is illustrated in Figure 1 below.

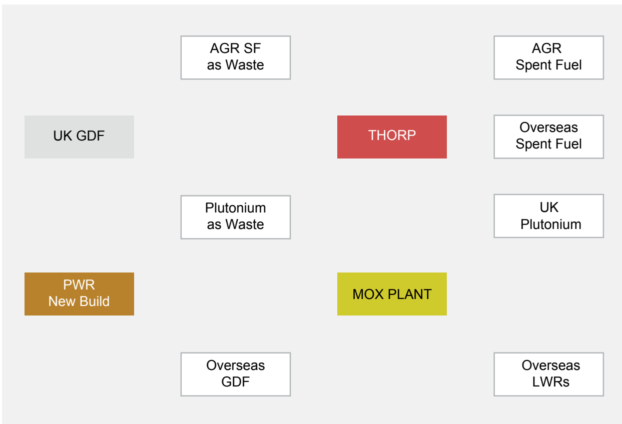
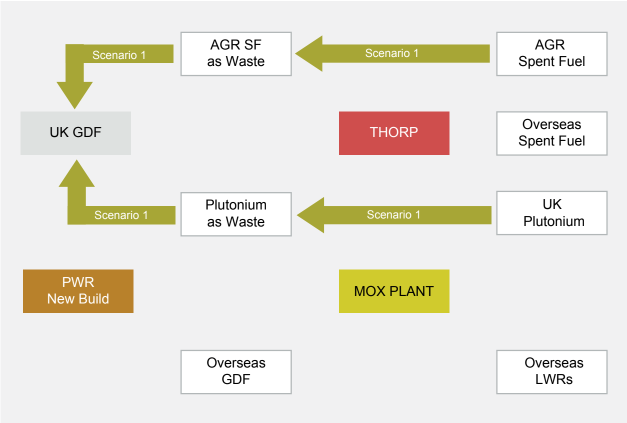


Figure 1. Materials, Products and Plants

The following sections summarise the Scenarios considered and their current status given the developments in policy and economics which have occurred since March 2011.

Scenario 1. Initial storage, designation as waste, and disposal of plutonium and spent agr fuels.



The Scenario converted the UK plutonium inventory to waste, using a modified and simplified Sellafield MOX plant to generate the low-specification MOX waste-form. This probably represented a minimum cost option.

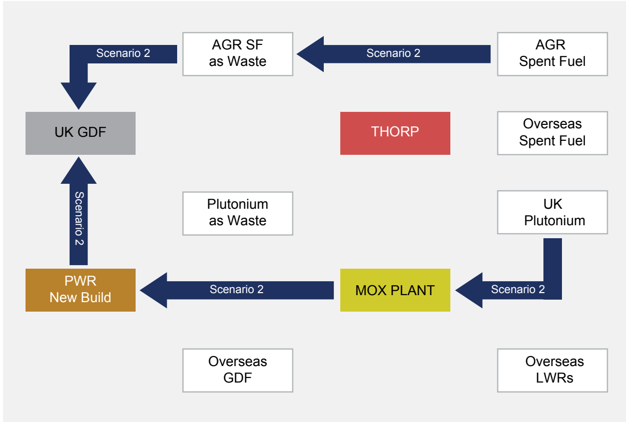
Spent AGR fuel was retrieved from the storage ponds where it is currently held, dried, and dry-stored prior to conditioning for eventual disposal in the planned Geological Disposal Facility (GDF) after 2075.

While minimising commercial risk, Scenario 1 gave the certainty of the UK Government paying for the discharge of a liability. This Scenario probably gives the greatest risk of escalating costs due to technical uncertainty, and is the only option that does not generate any sales income, merely representing a method for discharging a UK liability.

March 2011 Main Conclusion: Only favoured if waste costs (particularly for plutonium disposition) are very low.

Current Position: There has been little development in Pu waste costs, while discounted spend on an AGR Spent Fuel disposal route may have been minimised by NDA proposals for extending interim wet storage in the THORP Receipt and Storage pond. The Government 'minded to use MOX in new build reactors' position, if realised, would significantly reduce the proportion of the UK plutonium inventory to be processed as waste.

Scenario 2. Conversion of plutonium into MOX fuel for new-build reactors, treating the spent AGR fuel as waste for disposal

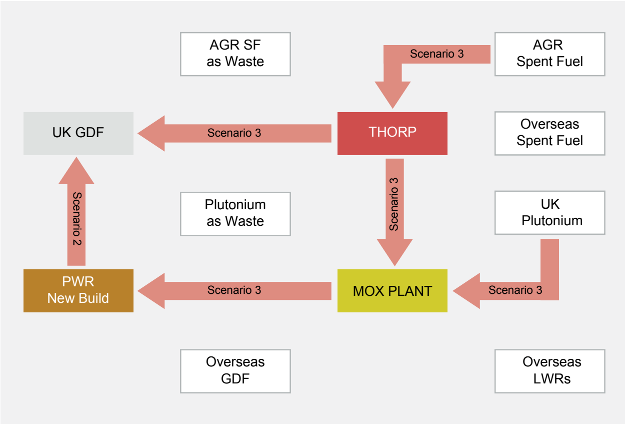


The Scenario assumed the building of a new MOX plant in or near Sellafield, which would fabricate MOX fuel for loading the fuel into new-build reactors. It was assumed that the NDA would derive an income from the sale of the fuel based upon the price of the natural uranium fuel displaced. AGR fuel stocks were assumed to be dismantled, and the fuel pins dried and stored prior to conditioning and disposal in the GDF (as for Scenario 1). Although Scenario 2 introduced an initial plant cost, it turned the UK plutonium liability into an energy asset, and offered the prospect of generally being significantly less costly than Scenario 1.

March 2011 Main Conclusion: Favoured if 'AGR to waste' costs and 'Pu to MOX' costs are low, and reprocessing is expensive.

Current Position: 'AGR to waste' costs have been contained by the plan to move AGR spent fuel storage to the THORP Receipt and Storage pond with caustic dosing. This will at least delay any major removal/drying/conditioning spend, and discounting at 3.5% halves costs every 20 years. Taken together with the Government 'minded to use MOX in new build reactors' position, Scenario 2 appears to reflect the *de facto* UK policy on the management of plutonium and AGR spent fuel.

Scenario 3. Conversion of plutonium into MOX, reprocessing of spent AGR fuel in a refurbished THORP, and using separated uranium and plutonium as fuel for new-build reactors.

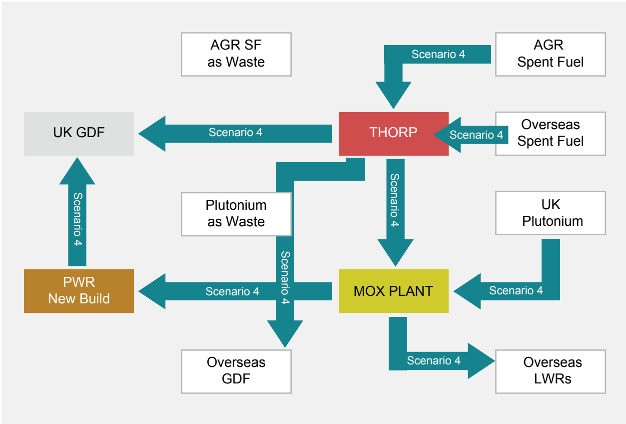


The Scenario reprocessed all AGR spent fuel through a refurbished THORP plant, thus avoiding the need to provide long-term storage of spent AGR fuel and the associated development and operation of a suitable conditioning and disposal route. It also assumed that the additional plutonium would be processed into MOX fuel from which NDA would derive an income.

March 2011 Main Conclusion: Favoured if 'AGR to Waste' costs are high, reprocessing costs are at the bottom of the assumed range, and MOX prices are high.

Current Position: 'AGR to waste' costs have been contained by the plan to move AGR spent fuel storage to the THORP Receipt and Storage pond with caustic dosing (see Scenario 2), and reprocessing costs (particularly capital) appear to be at least at the maximum of the range assumed. Note that the current NDA preferred reprocessing case requires long term storage and ultimate disposal of substantial quantities of AGR spent fuel.

Scenario 4. As Scenario 3 above, but with continued reprocessing of UK or overseas fuel in the refurbished THORP and recycling the separated plutonium and uranium as fuel.



This Scenario proposed that excess capacity in the refurbished THORP was used to reprocess overseas spent fuel until 2040, and the expense of treating spent AGR fuel as a waste was avoided. This used the assumed income from overseas spent fuel reprocessing to offset the costs of THORP and associated plant refurbishment, with the separated plutonium refabricated into MOX.

March 2011 Main Conclusion: Favoured if 'AGR to Waste' costs are high, reprocessing costs are at the bottom of the assumed range, and sufficient overseas reprocessing business is available at adequate prices to partially offset THORP costs. Also favoured by high MOX prices.

Current Position: The NDA has concluded that, in the foreseeable future, there is no perceived demand for THORP's reprocessing services beyond the current contracts. Reprocessing costs (particularly capital) appear to be at least at the maximum of the range assumed[3]. Scenario 4 does not currently appear to be viable.

March 2011 scenarios - current position

The current view of continued reprocessing in THORP is that high volume overseas business is unlikely and costs are high, effectively downgrading Scenarios 3 and 4, both of which depend on minimising THORP and associated plant costs and, in the case of Scenario 4, attracting significant overseas reprocessing business. Using the UK plutonium inventory to manufacture MOX fuel is now the Government 'minded to' position, and the NDA position on AGR spent fuel favours long term wet storage. This means that Scenario 2 represents the de facto UK policy. When Magnox reprocessing ceases, the UK will have adopted a 'once-through' fuel cycle with spent fuel disposal, which has implications for the supply and consumption of uranium for new nuclear reactors, as discussed elsewhere in this report.

Reprocessing

Reprocessing - background

As has been illustrated in Chapters 2 and 3, the decarbonisation of world energy supplies needed to limit climate change is much more unlikely to be achieved without a significant contribution from nuclear power. However, nuclear programmes which would achieve such a contribution, well exemplified by the LWR nuclear new build programmes being examined in the UK would, if applied worldwide, require either a much increased uranium resource or migration from LWR to a more uranium-efficient reactor type and fuel cycle.

If total UK reliance on overseas uranium supply developments is to be avoided, then it becomes important to have a strategy which keeps open the possibility of a future change in the reactor and fuel cycle choice, should uranium supplies become limited, expensive, or insecure.

As illustrated in appendix 2 one way of increasing the effectiveness of uranium usage in LWRs is to reprocess the fuel in plants such as THORP, and to re-use the separated uranium and plutonium as REPU and MOX fuel. However, this will only reduce LWR uranium usage by around 20%, which is small in terms of the overall uranium supply increases discussed in Chapter 2. However, as was envisaged by over three decades of UK policy, reprocessing of thermal reactor fuel can provide the plutonium necessary to start up fast reactors, which could increase the effectiveness of uranium usage by a factor of 50-60[4].

Some studies, notably by MIT[5], have shown that, for best uranium economy, early adoption of fast reactors is favoured even if they are initially charged with enriched uranium rather than plutonium. However, this fails to address the most likely situation, which is that migration to fast reactors is likely to be triggered only after uranium supplies have become limited and/or expensive, thus making the *'enriched uranium fast reactor start-up'* route problematic.

If 'plutonium start-up' remains the most likely migration route to fast reactors, then keeping open the option of reprocessing existing spent fuel to separate out the necessary plutonium would appear to be key to keeping open the fast reactor option itself.

Existing UK reprocessing plants

There are currently two suites of reprocessing plants operating in the UK, both at the Sellafield site. The Magnox plants are scheduled to close once the reprocessing of the inventory of Magnox fuel has been completed. In programmes issued in 2000-2006 this was scheduled to be around 2012, but the 2007 programme extended this to 'around January 2016', and the closedown of the Wylfa station has since been delayed, making a further reprocessing extension likely. As the Magnox reprocessing plants cannot reprocess oxide fuels, they have little bearing on ongoing reprocessing strategy for the UK.

For Oxide fuel reprocessing, the current NDA position[6] is that the cost of keeping THORP in operation beyond 2018 is very high, and that the overseas reprocessing business which might make ongoing operation feasible is not available. While not disagreeing with the NDA conclusions based on the current evidence available to them, the comments below might be worth consideration:

- Part of the rationale for the timing of THORP closure hinges on the costs of ancillary plants (waste storage tanks etc) which would be required if THORP continued in operation. A potential risk is that these 'extra' costs are derived from an over-optimistic baseline, and that the 'avoided plants' would be required in any case as part of the ongoing decommissioning mission of the Sellafield site.

- Another possible development is that, post-Fukushima, there is world attention on the potential vulnerability of long term wet spent fuel storage, particularly in ponds adjacent to reactors. This might trigger a number of developments, two of which have interest for reprocessing and THORP:
  a. Possible pressure on utilities, for example in Japan, to reduce the amount of spent fuel stored at reactors. Shipment of fuel for reprocessing would provide an alternative spent fuel management option, especially as an alternative to reactors being taken off-line (or not allowed to restart). The need to move spent fuel out of congested reactor ponds was a prime motivator for the original THORP overseas customers.
  b. In the UK, regulatory pressure on wet spent fuel storage might make virtually indefinite wet storage of AGR spent fuel less acceptable. Though the March 2011 Report examined dry storage, the only currently available AGR spent fuel management alternative is reprocessing.
- NDA's objectives as laid out in the Energy Act 2004 are on nuclear clean-up and decommissioning whilst meeting the commitments of existing commercial activities and contracts. This is a different emphasis from commercial reprocessing organisations, which, if faced with the current analysis on the ongoing use of THORP, would seek to review whether there were any innovative, and therefore cost-effective, ways of keeping the reprocessing option open, even if only as a contingency for long term UK and overseas spent fuel management.
- Convening a review using a team of talented scientists and engineers who were encouraged to 'think out of the box' would at worst provide reassurance to the NDA and Government that options were not being foreclosed and potential opportunities missed. Even if the chances of success were thought to be low, the cost/potential reward balance might be assessed as worthwhile.
- Other possibilities may be presented by options for the treatment of 'exotic' or 'orphaned' materials or fuels. NDA's recent consultations on Dounreay Fast Reactor (DFR) fuel[7],[8] and Harwell exotic fuels, nuclear materials and wastes[9],[10] have raised the prospect of using existing plants to process different materials (e.g. DFR fuel in Magnox reprocessing, Dragon fuel through Magnox Encapsulation Plant), and it is quite possible that other varied materials from different sites could be combined as the feed to a common process plant.

Keeping UK reprocessing options open

The NDA Oxide Fuel Credible Options Paper[11] notes the Government has requested *"that NDA . . use our work as the basis for providing advice to them about the wider, long-term potential for reprocessing in the UK"*[12]. NDA concludes that, in the absence of a UK policy leading to the deployment of fast reactors, and as *"we could not foresee fast reactors becoming commercially available in the UK before about 2060"*, there is little credibility in seeking to extend the life of THORP to contribute to such a programme, particularly as *"it is questionable whether a THORP-type process would be used to reprocess spent fuels from fast reactors"*.

However, NDA also states:

"if there was a national strategic requirement to retain a reprocessing "skills" capability we would question whether this would be best maintained by operation of a production plant. Rather, the technical capability to do so might be best maintained by a research and development programme into advanced separations technologies".

The 'next steps' which might be examined above would appear to be:

- Is there sufficient interest to commission, incentivise and finance a short-term 'thinking outside the box' review of THORP life extension – especially as THORP is in any case envisaged to operate for another 6 years?
- Are the world developments post-Fukushima sufficiently well understood that the prospects for overseas reprocessing can be discounted – particularly given THORP operations to 2018?
- The developing strategy for 'exotic' and 'orphaned'

materials might well bring up the possibility of 'jobbing shop' level operations, where a small but versatile plant could provide cost-effective treatment options for a collection of fuels and/or materials.

- If there is indeed enough UK strategic interest in future fuel cycle developments for options to be maintained, what is the best means of maintaining the necessary technical, operational and regulatory capacity to nucleate a major programme if this were required in the future? Certainly a "research and development programme into advanced separations technologies" is one option, but there is a whole spectrum of national and international options which could be considered which might provide various capacity options across the policy, skills, science, engineering, and regulatory spectrum.

These initiatives would need to be targeted and structured to be cost-effective, but could answer many of the points made by the House of Lords report on nuclear R&D[13]. It would, however, be important that any actions were set up to encourage 'blue sky thinking' even though the resulting proposals should be subjected to the searching examination required by the UK's currently straitened economic position.

[1] Japanese earthquake and tsunami: Implications for the UK nuclear industry - Final report, October 2011. HM Chief Inspector of Nuclear Installations
[2] Bradwell, Hartlepool, Heysham, Hinkley Point, Oldbury, Sizewell, Sellafield, Wylfa
[3]ibid
[4]See 'BOX – Nuclear Fuel Cycles'
[5]The Nuclear Fuel Cycle, Massachusetts Institute of Technology, 2011
[6]Oxide Fuels - Credible Options, NDA, November 2011
[7]Credible and Preferred Options for Exotic Fuel DFR, NDA, July 2011
[8]Exotic Fuels – Dounreay Fast Reactor (DFR) Breeder NDA Response to Stakeholder Comments on Credible & Preferred Options, November 2011
[9]Credible and Preferred Options for management of Harwell exotic fuels, nuclear materials and wastes, NDA, August 2011
[10]Exotic Fuels Nuclear Materials and Waste Management - RSRL Harwell - NDA Response to Stakeholder Comments on Credible and Preferred Options, NDA, November 2011
[11]Oxide Fuels - Credible Options, NDA, November 2011
[12]ibid Section 8, page 30 et seq
[13]Nuclear Research and Development Capabilities, House of Lords, Select Committee on Science and Technology, November 2011

UK MOX Fuel: Buying in a Sellers' Market, Selling in a Buyers' Market?

Emerging government policy

The Government has concluded[1] that

". . . . . . for nuclear security reasons the preferred policy for managing the vast majority of UK civil separated plutonium is reuse and it therefore should be converted to MOX fuel for use in civil nuclear reactors. Any remaining plutonium whose condition is such that it cannot be converted into MOX will be immobilised and treated as waste for disposal".

"While the UK Government believes it has sufficient information to set out a direction, it is not yet sufficient to make a specific decision to proceed with procuring a new MOX plant. The Government is now commencing the next phase of work, which will provide the information required to make such a decision".

The remainder of this Chapter examines a range of issues associated with the definition of a successful MOX programme, and the obstacles and opportunities which might hinder or promote the successful delivery of the UK's policy position on plutonium management.

Buying in a sellers' market?

The above statement underlines perhaps the most fundamental aspect of any UK MOX project: that the initiative aims to turn the vast majority of the UK plutonium inventory into MOX, which would infer that only a minimum of material becomes waste. This is crucial, because :

- Any plutonium not converted to MOX will reduce the income from MOX sales
- Minor amounts of plutonium could be expected to be satisfactorily disposed of using basic, economic and mature technologies such as cementation. However, larger quantities would face greater disposal challenges, and could lead to a requirement for the development of less mature and more challenging technologies, such as Hot Isostatic Pressing, with increased R&D, development, risk and expense.

Any MOX project should therefore 'start from the inventory' and ensure that an holistic development programme is put in place to cover an 'optimisation envelope' which includes all stored plutonium and must take into account the residues produced during various process stages (in the context of overall Sellafield and NDA plutonium residues) and the 'fitness for purpose' of the MOX fuel product. This is illustrated in Figure 1 below.

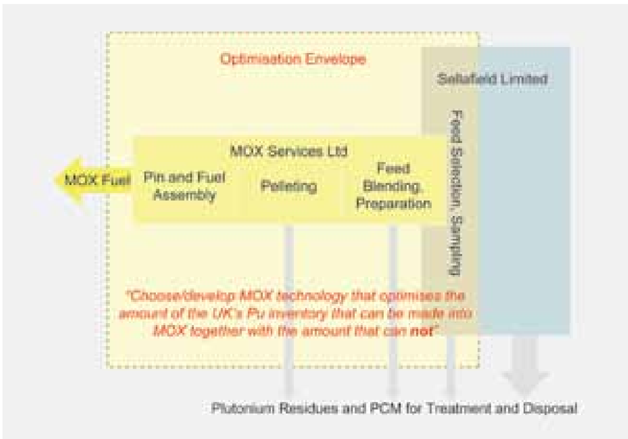


Figure 1. Optimisation and a MOX plant

In comparison, one very simple way of sub-optimising the MOX route would be to *'use the best material first'* – as this could lead to material either chemically contaminated or high in americium becoming subject either to expensive pre-treatment, or to increasing the amount of material to be treated as waste. Alternatively, as identified in the NDA analysis, many of the plutonium quality options may be ameliorated or removed by a blending regime across the entire inventory. It is therefore essential to ensure that optimal blending schemes are both identified and operable.

More fundamentally, an uncritical 'buy the necessary modules from the shop window' approach would place all power in the hands of the technology vendors, especially as the market is not well developed and choices are very limited. This is what appears to be envisaged by the current strategy:

" . . . . . other discussions will focus on detailing the costs and timescales for procuring services or facilities, including a suitable MOX plant, which can be delivered at minimum risk to UK Government".

On the other hand, "buyer power" could be increased by setting up a concentrated technology study, drawing upon a wide range of expertise – scientists, technologists, engineers and regulators - set up and suitably motivated to identify the optimum technology for the UK. A key question is then how (or whether) this can be achieved within the current institutional set-up. This might point to the technology study being paralleled by a review of the existing organisational responsibilities and structures to give Government a high level of confidence that a successful MOX project can be carried out. Such an examination could lead to changes to responsibilities and may point to a purpose-designed organisational structure.

Selling in a buyers' market?

The fundamental worth of MOX fuel is related to the cost of the uranium fuel it displaces in any given reactor. This was outlined in appendix 2 of the March 2011 Report:

"Both the new build PWR reactor designs are stated to be capable of working with 100% MOX cores, or to be able to work with a proportion (typically 30%) of MOX fuel as achieved in most currently MOX-burning PWRs".
"Any differences between the performance of MOX and uranium fuel are likely to be relatively small . . . . . Provided, therefore, that MOX-burning is decided upon early in the reactor project, there seems no compelling reason why the price achieved for MOX fuel should be significantly different from that of the corresponding uranium-based fuel . . . . . this parity of value is unlikely to persist where MOX burning is introduced as a modified scheme into an existing reactor, where the relative bargaining positions of the reactor owner and fuel vendor may be very different".

The two fundamental 'market' points leading from these observations are:

- The price achieved for MOX fuel should be measured against its 'worth' – the replacement uranium fuel value – and shortfalls against this 'worth' should be regarded as shortfalls in the value for money achieved for the UK.
- The likelihood of achieving an acceptable price will be maximised by
    - Engaging utilities at an early stage in their reactor build projects – ideally even before a technology choice has been made. This would minimise any extra costs required to make the reactors and their fuel routes suitable for MOX burning after the reactors have been commissioned.
    - Examine MOX fuel supply from the utility's viewpoint. If MOX introduces extra costs and risks, are there ways of structuring the MOX supply which will minimise these, or even turn the use of MOX fuel into an advantage?

Considering that both new build PWR designs are already asserted to be capable of burning MOX, the potential market envelope for MOX burning would seem to be set by the new build utilities' plans. In the light of this, the 'next steps' envisaged by the Government strategy:

"will see further information being gathered by the UK Government and NDA through detailed commercial discussions on the market for MOX fuel and the availability of reactors in which it can be burned".

This would appear to be information gathering about 'whether utilities want to burn MOX' rather than 'whether utilities can burn MOX' which, following suitable regulatory justification and licensing approvals, should be taken as a given. With normal commercial considerations, this *must* prompt every utility to respond *'provided that I get a significant discount compared to uranium fuel costs".*

The very basic considerations in this section and section 5.2 strongly point to the danger that the next phase of Government/NDA activity will reduce, rather than increase, the market position of the UK in pursuing a MOX project – minimising the power both of 'UK as a plant procurer' and 'UK as a MOX vendor'. The next sections will address ways in which these problems could be addressed, to the overall benefit of the 'UK MOX Project'.

MOX as a business?

The March 2011 report results for Scenario 2 (UK plutonium to MOX, AGR fuel to waste) envisage, for median assumptions, an overall discounted cost of Scenario 2 of around £1.5B i.e. the scenario costs the UK around £1.5B after netting off the income from MOX sales. Re-examination of the scenario shows that the cost assumed for AGR drying, storage and disposal is around £2.5B undiscounted, £414M discounted (Treasury discount rate), with the large difference being due to the bulk of the costs attributed to long-delayed AGR spent fuel disposal. This might imply a discounted 'loss' of slightly over £1B on the 'UK MOX' business.

However, the overall loss can vary very markedly with the capital and operational costs assumed for MOX fabrication, and with the price assumed for MOX sales. The DECC view on costs[2] is:

"3.12. While there is uncertainty over the cost of a reuse option, it does employ proven technology and a successful plant is already operating. The lifetime undiscounted cost of building and operating ,over roughly 30 years, a plant in the UK can only be described in approximate figures, but nonetheless, from NDA data could be expected to be around £5 - £6bn. In discounted cost terms an estimate could be around £3bn. However, because the resulting MOX fuel will have a value that could be in excess of £2bn on an undiscounted basis (circa £1bn discounted), although these figures cannot be predicted with accuracy at this time, it could to some extent, offset the cost of its manufacture. That said it is unlikely that the value of the fuel will reach a point where it covers the full cost of its manufacture. It is not possible to more accurately predict what the value of the MOX fuel would be as prices would ultimately have to be negotiated with the reactor operators, and this in turn will be influenced by the price of natural and enriched uranium through market supply and demand".

These figures predict a 'loss' on the MOX 'business' of around £2B. It is, however, clear that a business *'buying cheap and selling dear'* that loses £2B is a lot better than one that *'buys dear and sells cheap'* and loses £4B. This study therefore considers the UK MOX project as a business, and will refer to the activities and specifications that ensure the loss is smaller rather than larger as *'Generating a Business Case'.*

Generating a business case

This activity is covered in the DECC Response[3].

"Developing the requirements for implementation of reuse including consideration of procuring services or facilities, including a suitable MOX plant for reuse of plutonium, which can be delivered with minimum risk to UK Government"

For this analysis, the assumption is made that *'minimum risk'* does have a sub-text of *'seeking a minimum loss on the business'* – for it is quite possible to imagine a business model which increased the probability of, say, the loss being almost exactly £5B, while removing all possibility of it being £1B. The fundamentals of a process which will deliver 'minimum risk' under this definition should include:

a. Maximising incentives to keep costs down and prices up.

b. Becoming an intelligent purchaser and an intelligent vendor.

c. Intelligent enterprise design to maximise the chances of delivering (a) and (b.

The overall aim would be to increase the understanding and the power of the position of the enterprise – to maximise the chances of *setting* the market rather than being *led* by it – in order to establish that *'the option is affordable and represents value for money'*[4].

As has been commented on Sections 5.2 and 5.3, the supplier and customer activities as expressed appear to be an information gathering exercise, rather than being based on a set of commercial objectives. If this is so, there is nothing to begin to motivate either supplier or customer to leave their comfort zone – the suppliers will give information on what they want to sell and the price they want, and the customers will seek to maximise the perceived disadvantages of the MOX product to justify lower prices.

An alternative approach might start with "before finding out what *they* want – let's find out what *we* want", and might include studies such as:

1. What do we need before talking to utilities?

a. Clarify our best thoughts on their cost developments – what are the costs of MOX-burning - when-how they can save money (and at what phase of the reactor project) — what would it be worth to them if they did not have to store spent MOX fuel and/or did not have the spent MOX fuel disposal liability?

b. What burn programme is best for the UK from the range of possibilities which can be studied? Which is the best for a variety of plant costs/fuel prices/MOX plant throughputs, and what does that say about preferred numbers of reactors and percentage of MOX fuel in reactor cores?

c. This programme optimisation should be co-ordinated with the work on plutonium inventory blending – for example, some MOX fabrication/ burning programmes may allow the elimination of purification or treatment stages (e.g. americium removal).

d. What is the Government view about the number of reactor sites to be used for MOX burning as a larger number of sites would increase the amount of transport movements and the number of stakeholders impacted?

2. What do we need before talking to technology vendors?

a. Clarify views on likely cost of plant versus throughput[5], and compare with (1b).

b. A wide range of plutonium blending schemes are currently being examined by NDA, which should allow the attributes of the best schemes and their contingencies to be identified. By comparing these with the results of the studies defined in 1b, 1c, and 2a, a clearer view could be obtained as to an optimum UK MOX project.

c. Business structures – seek ways of increasing commitment to reduce risk, as this is likely to be more effective that trying to transfer risk using normal contractual arrangements. The potential role of private equity involvement should be considered.

The most important and fundamental shift in emphasis would be to acknowledge that UK MOX burning should be treated like a business, and approach the MOX project accordingly. The next sections of this report will outline some of the concepts which the Smith School has studied as exemplars of the analyses that could and should proceed. It must be borne in mind however, that all this work uses costs based on public domain information and 'nuclear project judgement' – it can point out possible areas of interest, but cannot and does not say 'this is the answer'.

Fuel leasing

One of the main disincentives for utilities to burn MOX is the increased cost and uncertainly of spent MOX storage and disposal. Current UK new build policy is based on spent fuel being treated as a waste, and stored on the reactor site until it is capable of being disposed in the planned national Geological Disposal Facility. For this disposal service, the utility must accrue, in a segregated fund, sufficient finance to transfer the spent fuel to Government ownership by the payment of a Spent Fuel Transfer Price. The Spent Fuel Transfer Price is based on the assessed disposal cost to the Government, and includes risk factors to ensure that the Government is not subsidising the spent fuel disposal.

This means that, for a conventional MOX fuel sale, the state-owned MOX fuel transfers into private ownership, only to revert to state ownership for disposal.

In many cases, the technical limits on the geological disposability of spent fuel are driven by the heat being emitted by the fuel elements. Spent MOX fuel emits more heat for longer than uranium fuel, and for this reason the examples of the Spent Fuel Transfer Price which have been published by DECC and NDA have assumed that the loading of the disposal canisters for MOX fuel is restricted to one element in a 4-element canister. This multiplies the disposal cost and liability by four, and gives a disincentive for a utility to burn MOX, or an incentive to assume a fuel price reduction.

An alternative scenario takes the view that the MOX fuel's excursion into private ownership merely adds risk and complication, and that applying fuel leasing might simplify the MOX utilisation process, leading to greater opportunities to increase value for the UK in the short and long term. In this scenario, the Government would keep title to the MOX fuel and lease it to the utilities to generate power, with the Government taking the fuel back for disposal. The fuel would never leave Government ownership and the utilities are effectively paying for electricity generation.

An advantage for the utility is that disposal costs can be subsumed into the lease price, removing a significant risk as high MOX disposal costs will be perceived to be totally out of utility control. In fact the Government can ensure that the disposal of the UK's waste and spent fuel inventory is optimised, both in its timing and in the mix of fuel types disposed to remove any requirement for 'single element MOX disposal'. Thus the Government's view of the disposal cost to be subsumed in the lease fee is likely to be considerably less than the published estimates. One reason for signalling 'MOX alone' disposal prices may be a desire to avoid allegations of subsidy which could lead to Government and NDA being wary of optimising across the totality of legacy and new build. Leasing would immediately remove this barrier, as spent MOX fuel would always remain Government-owned.

The removal of risks and costs to the utilities should lead to a marked increase in the price which they would be willing to pay for MOX fuel, and should, if more than one utility does develop new build reactors, create a more competitive market for the fuel, perhaps supporting a higher price. Fuel leasing could also offer the utilities a Government-backed security of supply, with the potential for pre-production and stocking of MOX fuel.

Additionally, because the Government has certainty in its ownership of spent fuel and the timing of its availability at reactor sites, it could examine optimisation (e.g. centralisation) of storage schemes – on the basis that it is difficult to imagine a less economic solution than decades of storage on multiple isolated sites. Some sort of centralised fuel storage with earlier removal of spent MOX fuel from sites should offer significant savings on the current new build reactor programme, which would feed into reduced costs for the utilities, and thence into increased MOX value. The prospect of earlier spent fuel removal from sites would also remove a major source of stakeholder negativity towards new build spent fuel storage in general and MOX storage in particular.

Simple economic modelling has been carried out using the costs and prices derived for the March 2011 report, and taking disposal costs and provisioning methodologies from published reports[6]. These calculations show that the removal of the perceived risk from escalating disposal costs, together with the potential for reductions in the capital and operating costs of reactor site spent fuel storage, should allow for significantly increased prices for leasing, as opposed to selling, MOX fuel, with the potential for significantly reduced overall cost to the taxpayer.

The early announcement of developing a leasing scheme would provide a positive spur for utilities to commence negotiations before detailed reactor design and procurement is committed, enabling reactor projects to take on board MOX burning at an early stage with minimum additional costs. The time window available is quite narrow, but with two of the three consortia yet to make their technology choice, a prime opportunity exists.

During the preparation of the March 2011 report, both reactor vendors confirmed that their designs were capable of operating with 100% MOX cores[7], so one technology would not be favoured over the other. However, it is probable that the most advanced projects, principally Hinkley Point C, might find it more difficult to respond positively to a leasing proposal.

A MOX joint venture – incentivising value for money?

As discussed above, it is unlikely that a MOX business wholly based on UK plutonium could support the full capital and running cost of a MOX plant by the income from MOX fuel sales (or indeed leasing) at currently credible prices. As previously noted, this has led DECC to an expectation of a 'loss' of around £2B.

The important consideration to be borne in mind, is that the Government's alternative to a MOX fuel use option is one where the UK's plutonium inventory is declared a waste and disposed of. The likely costs of such a route were set out in the Government's consultation on plutonium options[8] as £5 - £7B undiscounted, £2 - £3B discounted – and this remains the fallback position in the event of the MOX project not going ahead. Such a route would have no balancing income, no scope for innovative commercial arrangements, and would rely solely on contractual provisions to incentivise value for money.

Against this background, there could be arrangements whereby the Government, while avoiding the cost of a major plutonium waste disposition route, contributes to the capital cost of the MOX fuel plant and develops a UK MOX business case which would make suitable returns to attract a private sector 'part-owner/operator', who was in turn suitably motivated to keep costs down and to maximise prices. Such a private sector entity would license, operate and effectively part-own the UK MOX plant, and would sell (or gain the bulk of the proceeds from leasing) the resulting MOX fuel.

The modelling used for the March 2011 Report has been developed to examine a stand-alone MOX business. The fundamental features of the model, and the business, can be summed up as:

1. The delay between the capital spend on the MOX plant and the income from MOX fuel (with MOX campaigns between 15 and 50 years having been examined) gives capital a major role in overall business return.
2. Plausible operating costs and MOX prices should give a good business return during the operational phase of the project, even including decommissioning.
3. The viability of the 'UK MOX as a business' thus depends very strongly on the amount of capital the private sector entity must contribute.
4. If a method could be found for Government (directly or indirectly) to contribute to the capital cost of the plant, a business model would be set up which:
    a. Considered a Government funding level below the 'loss' to be expected on a state owned/run MOX project – and very substantially below any expected fallback position.
    b. Left private industry committing considerably to the capital cost of the project, thus ensuring their overall business commitment.
    c. Gave a reasonable assurance that a well-run MOX project would provide sufficient return to justify the initial private sector involvement.

Of course, the success of the model depends on the MOX price achieved, and this would be very doubtful in the market situation currently envisaged. However, with the addition of fuel leasing as a concept, the prospects become very much more realistic, as the enthusiastic participation of new build utilities becomes more likely.

The difficulty of establishing valid business structures and avoiding charges of state aid cannot be underestimated. These are not an area of expertise of the Report authors, and would require further study. However, whatever structure for the MOX enterprise is ultimately implemented, it is surely essential that there is clarity on the financial outcome of the MOX project, rather than it being an internal NDA transaction which could prevent the ultimate performance of the project being visible, and remove accountability. In short – it is essential that MOX is treated as a business.

MOX fuel technology

Any arrangements for the burning of MOX fuel in UK new build reactors will, of course, rely on the construction and operation of a MOX fuel plant which can operate reliably at near to its nameplate output. The economics of the operation will also depend on the plant being able to deal with the large majority of the UK plutonium inventory, with the minimum amount of plutonium being declared as waste. Arguably, the worst of all possible outcomes would be to install a MOX plant capable of using most of the plutonium, whilst leaving enough as waste to require a high-technology (and therefore expensive) waste management route.

The Sellafield MOX plant, with its Short Binderless Route (SBR), had a very poor production record from the time of its commissioning in 2002 to its abandonment in 2011. By contrast, the French MELOX plant, employing the MIMAS route, has had a generally impressive record, having produced over 1,700teHM of MOX fuel to the end of 2010, and having been permitted to progressively expand its capacity to 195teHM per annum. However, it is felt to be too simplistic to adopt an *'SBR bad – MIMAS good'* position without a further study into the optimisation of the UK requirement to produce good quality MOX fuel from a fixed, but imperfectly characterised, plutonium inventory.

The NDA has announced more work to characterise the plutonium inventory, and also raised the possibility of various pre-treatment options, some of which could alternatively be carried out as the initial stages of a MOX fuel fabrication process. A holistic approach to this work is recommended – aimed at optimising the economics of *'UK Pu to MOX'* while producing a high performance MOX fuel product. A project conforming to the overall thrust of the previous section – *'treat MOX as a business'* – would maximise the chances of aligning a proper programme of technology optimisation with a detailed materials' flowsheet, which could then be combined with a project and commercial structure that optimises costs and maximises the chances of success.

Alternative disposition options

In response to the UK Government consultation on the long term management of UK-owned plutonium, GE-Hitachi proposed the use of its PRISM fast reactor concept, which had been developed during the US Advanced Liquid Metal Reactor Program. Presentations have subsequently been given to a wide range of stakeholders. This section summarises the prism concept, and makes some comparisons with the existing Government preferred plutonium management option of re-use as MOX fuel in new build reactors.

PRISM

PRISM is a metal fuelled, sodium-cooled fast reactor developed by GE-Hitachi, based on the concept generated by the Fast Flux Test Facility (USDOE Hanford, operated April 1982 to April 1992) and the EBR-II reactor which provided heat and power to the DoE Idaho facility from 1963-1994. EBR-II was 62.5 MW thermal, and it typically operated at 19 MWe.

Today's PRISM is a GE-Hitachi design for compact modular pool-type reactors with passive cooling for decay heat removal. It was developed as part of the US Advanced Liquid Metal Reactor Program, and represents GEH's Generation IV solution to closing the fuel cycle in the USA.

The conceptual design has been reviewed by the US Nuclear Regulatory Commission, which issued the public document "Preapplication Safety Evaluation Report for the Power Reactor Innovative Small Module (PRISM) Liquid-Metal Reactor - Final Report" (NUREG 1368) in February 1994.

Perhaps the clearest statement of the status at that time is given in page iii of the abstract.

"The PSER is the NRC staff's preliminary evaluation of the safety features in the PRISM design, including the projected research and development programs required to support the design and the proposed testing needs. Because the NRC staff review was based on a conceptual design, the PSER did not result in an approval of the design. Instead it identified certain key safety issues, provided some guidance on applicable licensing criteria, assessed the adequacy of the preapplicant's research and development programs, and concluded that no obvious impediments to licensing the PRISM design had been identified".

NUREG-1368 considered a core designed for 471 MWt (155 MWe) power output per reactor module, around half the output of the current proposal (see Table 1 below).

Table 1. PRISM Basic Parameters

Type	Sodium cooled, metal fuelled fast reactor
Fuel	Metal fuel - 20% Plutonium with uranium and zirconium
Clad/element	Ferritic steel alloy HT9 clad, sodium in can for heat transfer
Reactor output (thermal)	840MWth
Reactor output (electrical)	322MWe
Power Block	2 reactors totalling 622MWe, 1 turbine generator

Though the original PRISM concept was for a fast breeder reactor with fuel reprocessing, in the UK it is offered as a disposition option for the UK plutonium inventory of around 100tePu, with a breeding ratio of 0.8 (i.e. it is an actinide burner). The objective of the scheme is to process the UK plutonium inventory into spent fuel which would then be directly disposed, presumably in the UK Geological Disposal Facility (GDF). The scheme offered envisages the following stages and timescales.

Figures printed in *blue* have been calculated by this study from data in GE-Hitachi documentation.

As seen in Table 2, the scheme involves the irradiation of all the fuel manufactured from the UK Pu inventory to a relatively low burnup (5 atomic %) over 5 years. This will mean that the plutonium is contained in spent fuel which has a radiation barrier[10] giving increased resistance to theft or diversion. The low burnup spent fuel is then re-irradiated to 20 atomic % burnup over the next 55 years, generating more power, before being stored as spent fuel and ultimately disposed in the GDF.

On the assumption that the fuel is of the same composition as that examined by USNRC in 1994[11], 100te of plutonium would produce around 346teHM of fuel.

Projected power output

The PRISM power generation figure of 282TWh calculated above may be compared with a similar calculation of the power generation to be expected[12] from the 1500teMOX fuel assumed to be fabricated from the UK plutonium inventory under Scenario 2. This is 630TWh, or around 2.2 times that calculated for the PRISM option.

Stage	Process	Timescale
Reactor Licensing		5 years
Reactor construction		5 years
Pu metal production	Electrolytic reduction of plutonium oxide to Pu metal in molten salt	
Fuel production	Injection casting of Pu/U/Zr metal fuel, and installation in stainless steel can with sodium for heat transfer	
Initial fuel irradiation	10tePu/a into each reactor	5 years
	40 cores, 45 days irradiation	
	45% Load Factor	
Power generation during initial 5 year irradiation (TWh)	*12*	
Power generation during remaining 55 years (TWh)	*270*	55 years
Total power generation over 60 year reactor life	*282*	
Spent fuel for disposal	~346teHM*	
Pu in spent fuel for disposal	Data not available but >80teHM	

*Calculations for US NRC documentation

Table 2. UK PRISM – Stages, Processes, Timescales

Challenges

The principal challenges to the scheme will be the licensing, procuring and building of the fuel plants, the reactor, the fuel handling and storage systems, and ultimate licensing of the fuel type as suitable for geological disposal as part of the UK spent fuel and fuel inventory already destined for disposal.

While the cost, procurement and build programme must be a matter of commercial policy for GE-Hitachi, the licensing activities in the UK will follow UK procedures. The regulators will need to satisfy themselves that these processes and plants, which would be new to the UK, and proposed on a scale larger than previously carried out anywhere, can be licensed.

Some guidance on likely timescales might be made by analogy with the Generic Design Assessment process, which is being used by the UK regulators to license new build PWRs, taking into account that the regulators were able to build on the experience of licensing the generically similar PWR, Sizewell B.

The licensing of Sizewell B was preceded by a 3 year programme examining the generic licenses of PWRs, using, as a surrogate for PWRs in general, the Trojan reactor, a 1095 MWe PWR in the USA which stared operation in 1975. This generic review lasted from 1975 to 1977. The specific licensing campaign for Sizewell B (1188 MWe) started around 1978, and the regulator would have been ready to give its consent to commence construction around the end 1981/early 1982, but for a public inquiry, which lasted from 1982 to 1985.

Thus UK regulators took some 6 years to approach specific licensing of a long-established commercial reactor system which had many generically similar stations operating around the world, and several individual reactors which were very similar to the Sizewell B base design. For UK new PWR reactors, the Generic Design Assessment (GDA) started with the publication of Guidance by in EA and HSE in January 2007, and led to the granting of interim design acceptance on 14 December 2011 – a period of almost 5 years.

Against this experience it is likely that the licensing timescale for the re-emergent PRISM technology would be extremely challenging given the novel design, the fact that the UK regulator has never licensed a fast reactor and the ONR inspectors have little experience of fast reactor technology. In addition any assessment process would have to take into account, and resolve, points such as:

- The UK fast reactor programme moved away from metal fuel to uranium oxide and MOX ceramic fuels. Similarly the civil thermal reactor programme moved away from metal fuel in the Magnox programme to oxide fuels in both the AGR and PWR programmes. The use of metal fuel would have significant implications with respect to the substantiation of the plant safety case and for security and safeguards considerations.
- The Office for Nuclear Regulation would need to find (or generate) the appropriate level of in-house capability: once the Dounreay Prototype Fast Reactor (PFR) shut down in 1994, the level of knowledge and experience of fast reactor systems and fuel cycle performance started to erode across the nuclear sector. ONR would need to train inspectors to understand FR technology, the fuel type and its behaviour. Although ONR has taken advantage of overseas regulatory experience as part of the GDA review of PWR designs, access to direct experience on fast reactor systems, especially with the novel fuel that is proposed, could be problematic.
- There are limited international opportunities to examine the technical challenges of such a novel system, where work on such subjects as fuel manufacture and operability, effect of reactor transients and fuel/coolant interactions would typically involve access to research data and experimental testing facilities.
- The proposed location of the PRISM fast reactor on, or close to, the existing Sellafield site would be preferred to avoid transporting quantities of plutonium around the UK. However, the UK's fast reactor was located on a very remote site, and the siting of a fast reactor near such a sensitive site as Sellafield has significant implications, and the potential impacts of co-location deserves scrutiny.

As the reactor design and fuel cycle are both new to the UK, an early activity would be to decide on the class or type of practice (or classes or types of practices) that would require regulatory justification under the current regulations. For new build reactors in the UK, the need for Justification was set out in the Energy Review of July 2006[13]. The process was initiated in May 2007 by a Government consultation on the potential process for Justification[14] which led to a Decision Document in November 2011. Bearing in mind that the new build fuel cycle introduced no new practices, and that the reactors were of a type which could call on over 50 years of experience, the procedural challenge represented by the regulatory justification of a novel fuel route, reactor, and spent fuel disposal concept should not be underestimated.

None of this is to say that these challenges are insurmountable, but that the resources, time and cost of addressing them would need to be included in any project plan, together with clarifying the division and extent of costs and risks between Government and commercial suppliers and operators.

[1] Consultation response on the management of UK's plutonium, DECC, December 2011
[2] Management of the UK's Plutonium Stocks, DECC, February 2011, p18
[3] Consultation response on the management of UK's plutonium, DECC, December 2011
[4] Consultation response on the management of UK's plutonium, DECC, December 2011
[5] For example, a 100teHM/a plant is likely to cost far less than twice the cost of a 50teHM/a plant
[6] For example, "Consultation on an updated Waste Transfer Pricing Methodology for the disposal of higher activity waste from new nuclear power stations", DECC, December 2010
[7] To be exact, both reactors would continue to use some uranium-based fuel as carriers for gadolinium burnable poison loadings, but the amounts would not be significant at the broad planning level
[8] Management of the UK's Plutonium Stocks, A consultation on the long-term management of UK owned separated civil plutonium, DECC, February 2011
[9] On the basis that even if all the 20% burnup was fissile Pu and there was no breeding, there would be 80tePu left
[10] Quoted as 100REM/h (1SV/h) at 1 metre
[11] 26%Pu, 10% Zr, 64% U – from NUREG-1368, Pre-application Safety Evaluation Report for the Power Reactor Innovative Small Module PRISM Liquid-Metal Reactor, USNRC, 1994
[12] MOX burnup of 50,000MWd/teHM assumed for UK new build PWRs
[13] The Energy Challenge: Energy Review – A Report, Cm 6887, DTI, July 2006
[14] The Role of Nuclear Power in a Low Carbon UK Economy: Consultations on the proposed processes for Justification and Strategic Siting Assessment, DTI, May 2007

Consultation Findings

Who did we consult with?

At the core of our Low Carbon Nuclear Pathway Study we have sought to assess and understand the views of a host of stakeholders: government, MPs, local authorities, quasi government organisations, learned societies, research bodies, research councils, universities, industry, trade bodies, unions, and NGO's. The report was predominantly focused on the UK, however where possible, we canvassed the opinion of international stakeholders.

Why undertake a consultation process?

At the Smith School we consider stakeholder consultation a very important strand of our work when developing important future facing reports of this kind. Our consultation has enabled us to:

- Build on the established body of knowledge and expert opinion already in existence ensuring that our work is high quality and up to date.
- Seek opinions across the spectrum, from those who are positive about a nuclear future as well as those who are more negative. Understanding a wide range of perspectives helps to challenge and ultimately strengthen our thinking.
- Get a sense of where the consensus may lie, enabling us to make appropriate recommendations
- Keep open to others points of views and not be driven alone by our own natural biases.

Ultimately we believe that consulting with others ensures a better report at the end of the project and perhaps most importantly the best set of recommendations achievable.

When did we consult with them?

Our consultation was on-going throughout the project from October 2011 to February 2012, involving face-to-face meetings, with a formal online written consultation running from 7th November 2011 to the 12th January 2012 on the Smith School website[1]. We are very appreciative of all those who took the time to see us during the consultation period and to all those who submitted a written response.

Themes

We consulted on five key issues as below, but invited wider comment on any other issues stakeholders considered pertinent.

The key areas of the consultation:

- the optimal amount of energy we should be aiming for in 2050 and 2100.
- the impact on the UK's nuclear plans if other countries in the world go down the route of extensive nuclear new build.
- the impact that this might have on materials and resources available.
- the role of a long term road map for civil nuclear power.
- the importance of investing in nuclear R&D forward to 2050 and beyond.
- the UK as a leader in civil nuclear power.

Stakeholder views

In the following sections we provide an overview of the range of views and opinions garnered through the online consultation. We would stress that the following section seeks to reflect only those written responses rather than the wide ranging and detailed discussions that we had with many other stakeholders.

In total we received 16 written responses as well as meeting with over 40 other stakeholders during the period.

What do you think is the optimal amount of nuclear power generation we should be aiming for by 2050 and 2100?

(Example given: Italy currently at 0%, UK at about 15%, France at about 80%)

Just over half of those consulted considered the optimal amount of nuclear energy that should be aimed for in 2050 and 2100, to be at least 40%. And just over half of them, were keen to see nuclear energy at 60% or 80% in 2100. The range of reasons given for this included:

- The key assumptions behind these responses included: that new technology does not arise e.g. allowing exploitation of nuclear fusion, the arrival of other new technologies, that there is not a major improvement in energy efficiency, that renewable sources are not suddenly more easily exploited and that there is not suddenly a large societal change in our energy consumption.
- Nuclear energy provides a *"stable baseline of energy generation with a lower carbon footprint than the alternatives".*
- It is of fundamental importance if we are to *"stand any chance"* of meeting the government's carbon reduction targets, and combat the associated challenges of climate change.
- Carbon capture and storage is as yet unproven: *"it is likely to be very expensive and unsuitable for large scale industrial application".* Even if affordable a minority consider that CCS will only delay the problem. Underground storage of CO2 could leave future generations with the possibility of a catastrophic uncontrolled release of CO2 if the storage system were to fail.
- Greater use of electricity for heating and transport or moving to a *"hydrogen economy"* will drive the need for more energy.
- Renewable technologies, whilst considered to have a role to play, are considered too intermittent and by a few stakeholders considered inefficient for the amount of CO2 they offset versus the CO2 they require to be manufactured and maintained. It was also considered that there may be issues with security of supply in relation to renewables and that some of the materials underpinning these technologies are relatively scarce e.g. lanthanides for magnets in wind turbines.
- To ensure security and diversity of supply.

A minority of respondents did comment that nuclear power is most economic at base load, running all year round, therefore the capacity of nuclear should never exceed the summer evening minimum demand level, so never go beyond 40%.

Alongside this positive rationale a minority also commented at this point on the important responsibilities that come with the use of nuclear power:

"Responsibilities to ensure that nuclear facilities are safe … , nuclear material are secure to prevent their use by people with malicious intent, nuclear materials used in or generated by the civil nuclear programme are not diverted for use in illicit nuclear weapons programmes and radioactive waste that is generated is managed safely and will not become a burden on future generations."

Other respondents considered it inappropriate and difficult to commit to a level of nuclear power at this stage:

"We cannot know what is optimal this far ahead in light of fundamental uncertainties about: the feasibility of CCS: renewables costs: ability to build nuclear to time and cost. The path ahead for the next 10 years or so is clear – work on all options and try to resolve uncertainties."

"We do not consider it necessarily helpful to set a cap or target on the level of nuclear generation needed as scenarios will obviously be affected by a variety of market and political drivers."

"The UK's energy mix should be determined by the lowest cost solution for meeting our multiple objectives of security of supply and low carbon generation."

A very small minority of detractors commented that there should be 0% nuclear power.

What impact, if any, would there be on the UK's nuclear plans if other countries go down a route of extensive nuclear new build?

It was generally considered by those we consulted that if other countries go down a route of extensive nuclear new build, that there could be both positive and negative ramifications for the UK. At the very least it was mentioned that it would clearly raise the strategic question, *"of whether or not the UK wants to be a supplier of nuclear energy technology or merely an intelligent customer for it."*

It was commented that depending on the scale of other countries' activities, this could delay the current UK nuclear development programme, due to pressure on the supply chain, raw materials, project management etc. In the extreme, this could mean that the plans to replace existing capacity would not be so easily possible, forcing the UK to compete on the open market for fossil fuels resulting in the cost of electricity increasing. Security of supply would decrease with increasing dependence on imported oil and gas. All of this could have a considerable impact on the UK economy.

"Potentially investors who are currently committed to new build in the UK may be lured to other countries where seeking permission and approval is less rigorous and less expensive."

On the positive side of things:

Opportunities for the UK nuclear industry

- It was generally considered that if the UK can establish its nuclear programme ahead of others, there could be a great number of opportunities for the UK, not least helping new nuclear countries to develop their infrastructure to meet international standards.

"The UK has a worldwide reputation for nuclear governance including its nuclear safety regulatory regime. The UK is currently one of only a handful of countries with the full range of nuclear fuel cycle technology capability. The UK could therefore become a major supplier of: nuclear fuel enrichment; nuclear fuel manufacture for both enriched uranium and mixed oxide fuels; spent fuel recycling; and radioactive waste management services including safe and secure marine transport".

"An expansion of foreign civil nuclear programmes could increase the demand for MOX and uranium based fuel, creating more favourable market conditions."

"[Increased demand] will stimulate increased global capacity and so provide greater competition which would be good for the UK."

"Extensive international new build could help address the UK skills gap in the nuclear area (at the higher levels at least), assuming that these areas are accompanied by adequate international investment in training and mobility of engineers from international projects to the UK to support new build in the UK."

Wider industry development enabling greater technological progress

- It was recognised that in the longer term increased demand could create a more mature industry with a wider and stronger supply chain in the round which could deliver benefits in many areas.

"Greater operational experience and a wider safety network could see increased opportunity for sharing lessons learned, and more signatories contributing towards R&D projects can accelerate technological progress."

Increased public approval for nuclear

- It was also considered by a minority that enhanced public approval of nuclear activities might result if many countries moved in the direction of nuclear energy. However, others commented that concerns over nuclear proliferation are also likely if there is extensive nuclear new build in countries which are seen to be less politically stable.

"It is also important that there is broad public support for nuclear power, which can only be achieved if the industry is seen to be safe and successful, providing benefits to society and electricity consumers."

In your view could this have an impact on materials and resources available?

All respondents agreed that greater international take up of nuclear power could have a significant impact on the available materials and resources, however opinion varied on how extensive this impact might be. The impacts discussed included:

1. Competition for skills:

"There is already a shortage of experienced and qualified engineers for nuclear power plant design, construction and operation. This could be exacerbated by extensive development in other countries."

"The build programmes will become a magnet to skilled nuclear workforces and may cause a drain of experience that has a negative impact on the UK's ability to expand its own nuclear fleet."

"Currently the UK only has a limited capability of growing its human resources to meet the demand of a new programme… The UK needs a co-ordinated approach to undergraduate and postgraduate provision for nuclear education so that there will be sufficient people with the right skills available at the right time to deliver the programme … the longer the delay in the new build programme … the more difficult it will become not only to persuade students to take up nuclear related courses but also have sufficient universities and colleges with the capabilities to teach the required courses."

"Although a major expansion of worldwide nuclear new build could create shortages especially in terms of availability of experienced engineering skills, these are likely to be pinch point rather than fundamental barriers to successful developments being carried out in the UK."

2. Higher priced fuel:

"At some point the rate of uranium usage will drive the fuel price up as well as increase concerns regarding waste streams. This will increase pressure on recycling facilities and also the need for fast reactor technology."

"At current rates of consumption, the NEA has estimated the planet's economically accessible uranium resources will last for over 200 years, and so we are unlikely to encounter serious fuel problems for stations built in the near term …. Uranium price changes are unlikely to significantly impact the operation of existing nuclear power stations … however … [They] will certainly impact the economics of future projects."

3. Shortages in manufacturing capacity:

"In the medium term we could see supply chain congestion restricting the availability of key components (reactor vessels) and pushing up prices (as happened recently with offshore wind turbines)."

4. Shortages in other resources:

"There would be serious implications for raw materials including … high quality steel supplies."

How important is a long term road map for civil nuclear power in the UK?

Almost all respondents considered it at least important, more often vital for the UK to have a long term approach to civil nuclear power.

"It is vital. We already face several grand challenges on a 50-100 year timescale, including plutonium management, new build nuclear generation, spent fuel management, decommissioning and clean up, and geological disposal. Future innovations in nuclear fission, for example fast

reactors, modular reactors or thorium fuelled systems will present challenges over comparable timescales. So we already have long term challenges, and there are more looming... we cannot afford to take a piecemeal approach to meeting them."

There was widespread agreement that some sort of long term roadmap or framework would hugely help the industry to develop and forge ahead. The rationale for such a roadmap or framework covered the following themes:

1. To encourage industry investment

"Nuclear power is a long term business, requiring large scale capital investment in facilities designed to operate for 60 years or more. In the absence of an overall strategic plan for energy policy and particularly electricity policy, then it is unlikely that commitments to invest will be made."

"Due to a lack of investment in the industry the UK has slipped as a market leader and needs to invest heavily in modernisation and education."

2. To encourage investment in industry skills and know-how

"These skills have been diminishing over recent decades. If not maintained in support of a roadmap, the UK could be in a position of starting again from scratch when the time comes for significant nuclear build in the UK."

3. To build capability to export

"[We continue] to be disappointed that it focuses on the short to medium term and ignores the potential export market. To compete in the global market will be challenging and the more holistic the offering arising in the UK (bundling), the more likely we will be successful."

4. To ensure a more integrated approach and industry collaboration

"A long term commitment to a significant nuclear power programme will encourage the development of a more integrated approach with the inclusion of reprocessing, and the use of fast reactors to burn Plutonium and other conventional reactor by-products."

"We believe that it would be in the UK's long term interest to establish an effective framework to enable industry collaboration and support investor confidence."

5. To enable the alignment of research

"In nuclear power where fundamental science/ engineering research and training should support a national need, it would be extremely helpful to be able to align activities against a government backed road map. A roadmap would also provide a focal point for further co-ordination of the UK research base and would facilitate the building of international collaborations by endowing the research base with an enhanced identity and making it clear that the UK is a serious partner."

6. To understand where else nuclear might have a role to play

"It is also possible that nuclear power will have a role to play in other industrial activities such as the provision of high temperature heat for some process industries and for the propulsion systems for commercial shipping."

Some specific comments were made by a minority on the more specific content of such a roadmap:

- Any roadmap needs to be co-ordinated with NDA activity.
- There are limited areas where fission and fusion programmes overlap and this should be considered.
- It is not necessary to set detailed targets rather broad objectives and identify the policy instruments that will facilitate the delivery of these objectives.
- It's important to have a flexible roadmap that can be adjusted in the light of uncertainties, new knowledge arising or issues being resolved.
- The emphasis for a road map should be on 'decommissioning, waste disposal and storage."

It was very clear from nearly all responses that any road map needs to be holistic in its approach and built on a long term nuclear strategy:

"A road map for civil nuclear power would only be of use if it was built on a long term nuclear strategy that covered

… [for example] the role of Government in the delivery of the identified actions; the educational and training programmes that will be necessary to produce the whole range of people that will be needed; and the nuclear regulatory requirements."

How important will it be for the UK to invest in nuclear R&D going forward to 2050 and beyond?

The majority of respondents considered it vital that the UK invest in nuclear R&D. Again a range of reasons were given to justify this point of view:

1. To meet current plans and ensure the UK is an intelligent buyer

"If we do not invest urgently there is a real risk that we will not be able to meet our current national needs in nuclear energy, let alone exploit future opportunities. At a bare minimum we have to ensure that we can be an intelligent customer for the nuclear technologies we presently have, or are committed to having. Currently this is in severe doubt."

"If the UK wishes to generate significant amounts of nuclear electricity (in contrast to importing it), it must have a credible scientific and engineering research base to support the design, regulation and operation of a nuclear plant."

2. To encourage investment in new technologies for the future

"The UK has lost its position as one of the leading countries in terms of research into new technologies and has withdrawn from providing financial contributions to the International Generation IV studies. It is important that a research base is maintained to provide a stimulus for innovation to attract high quality academic staff to teaching institutions and to maintain a competitive edge for the UK in a world market. Research needs to be relevant to future needs and linked to developing new technologies which then have a prospect of being taken forward into commercial development."

3. To support the exploitation of the export market

"The higher value, higher margin opportunities require businesses to be able to trade higher up the food chain. This will require investment in IPR and broader capabilities."

"[This is] very important if the UK is to maintain its leading position in nuclear safety as a thorough understanding of all the issues is essential. As nuclear power continues to expand around the world, the UK needs to take advantage of this potentially significant market."

"An investment in a well-planned and coordinated R&D programme to underpin the needs of a UK civil nuclear 'road map' will not only be necessary but it could also bring considerable benefits for the long term development of the UK economy."

On the points raised previously, a small number of detailed comments were provided in relation to what the R&D programme should cover. Areas of focus were most frequently suggested to include fast reactor technology, and nuclear fusion. Other areas of focus suggested included:

"We believe that the primary focus [of R&D] must focus on key projects such as the Geological Disposal Facility (GDF). We cannot afford to wait for new technology to become commercially viable before tackling the challenges the industry currently faces."

"It is vitally important to look at what the UK needs, how these needs can be met over the next 50 to 100 years and what research and development is needed to develop: the future nuclear reactors with better and more efficient uranium utilisation; better use of plutonium; advanced spent fuel recycling technologies and transmutation technologies to eliminate long term radioactive waste issues."

"We will need to develop: fast breeder reactors to provide better utilisation of uranium; fast reactors for actinide transmutation to reduce or eliminate long term radioactive waste issues; we will need to develop small, safe and secure nuclear reactors for marine propulsion for both freight and leisure purposes; transmutation technology; advanced nuclear fuel manufacture; advanced recycling

technologies to enable the reuse of unused uranium and plutonium; the treatment of radioactive waste; and thorium based technologies. All of these activities will require advances in: materials technologies; heat transfer and thermal hydraulics, understanding of corrosion properties of materials such as molten lead; nuclear chemistry; control and instrumentation, protection systems, non-proliferation technologies etc.

Only two respondents were much more ambivalent on the role of R&D:

"This is optional. It is not absolutely necessary to develop technology or manufacturing in order to own and operate plant from elsewhere."

"Not very [important] apart from in waste disposal, treatment and storage. Better to invest in renewables / energy efficiency."

The recent House of Lords Report was quoted by a minority stating that the strengths of the UK nuclear industry are built on past investments that will soon be depleted, reinforcing the need for a long term strategy for nuclear, a nuclear R&D roadmap and an independent nuclear R&D board.

Should the UK look to be a leader in civil nuclear power in the coming decades?

Views in response to this question were mixed with half of those consulted commenting that the UK should and could seek to be a leader in nuclear power.

"The UK is in a unique position to demonstrate leadership in civil nuclear power, which it can establish over the next 10 -20 years."

"It is very likely that there will be a substantial resurgence in nuclear energy worldwide, and that is an opportunity the UK certainly could exploit. The UK currently has some very effective, if rather niche, players who are likely to compete effectively, and there are other areas which the UK can potentially exploit (for example high level skills development), provided the potential suppliers have confidence that they can do so effectively. Key elements in giving them that confidence are a stable policy environment over the long term so they can plan ahead and the creation of a thriving nuclear energy sector 'at home' to give them credibility overseas."

"In addition to global governance it is essential for the UK to play a leading role because of the economic benefits that would flow from being a leading provider of nuclear technology and services. I believe the UK currently has the core capabilities, including nuclear reactor design, to be a major world player. We remain, in spite of the demise of BNFL, one of the world's leading nuclear fuel cycle service providers. However, this capability will not remain for much longer unless there is a clear commitment by the UK Government to the long term future for nuclear power as a major contributor to electricity generation."

"Yes. Nuclear is, and will continue to play, an important part of the mix in helping countries such as the UK reduce their carbon emissions and reaching their targets. Investment in R&D is essential to establish the UK as a leading expert in the field."

The majority of others were clear that the UK has fallen behind other countries on nuclear R&D; however, some suggested that going forward there may be areas the UK could lead on:

"I doubt it. The UK has wandered down two technological blind alleys with regard to nuclear since the 1950's/60's and catch up with global leaders would require an enormous and expensive effort. Note that Abu Dhabi awarded its recent nuclear contract to a Korean consortium rather than Areva or Westinghouse. The UK is just not in the game. In its report on low-carbon innovation, the Committee on Climate Change placed nuclear in the category 'focus on deployment' rather than 'research and develop' or 'develop and deploy'."

"The UK is no longer a leader in civil nuclear power, and will not be without very significant investment over a long period of time. The design of next-generation civil nuclear power generation is technologically complex and demanding and its development would be best achieved through international collaboration. Within this the UK could aim to be leading in some areas."

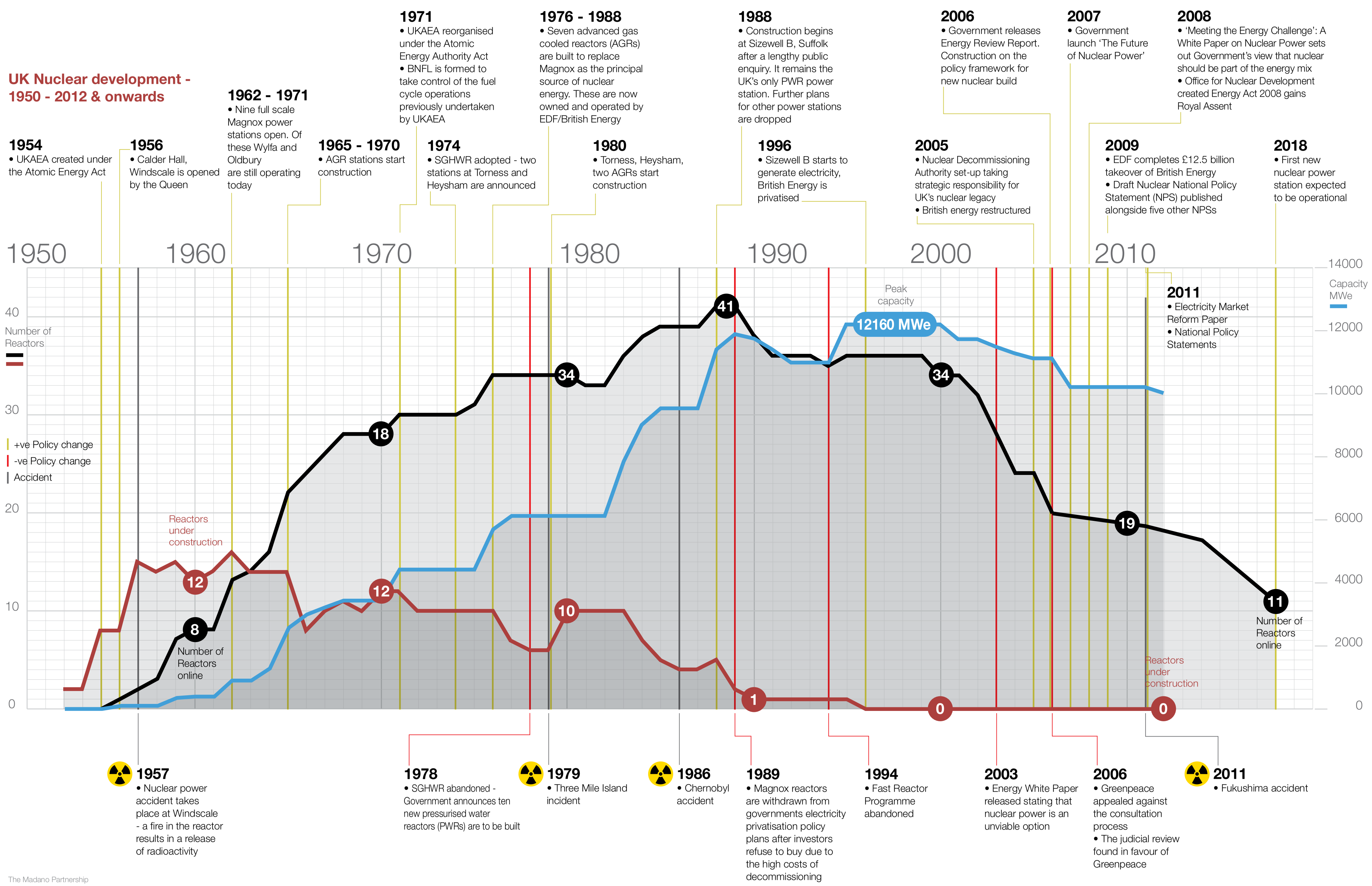
"The UK should certainly maintain its position in nuclear

safety and continue to set high standards."

"The UK (and the USA and Germany) have lost their leadership over the past decades. The knowledge base in the UK, if continually expanded to back a growing national nuclear programme could put the UK back into position as one of the scientific / technical leaders .. but for current generation plants it can at most be a supplier of components. With advanced SNRs and later FRs there could be chances."

One of the respondents, who was naturally more negative, argued that to be able to state that the UK should be a leader needed more analysis, whilst another emphasised that aspirations in this territory need to be balanced against the prospects of alternative low carbon generation, with the key being to ensure security of supply and to reduce carbon emissions at the lowest overall cost to society and to consumers. Only one respondent clearly stated that the UK should not seek to become a leader in civil nuclear power. Whilst another considered that it may be an option but that it was difficult to see how it might happen given that *"much of the worldwide expertise is now outside the UK and [that the] manufacturing base is still in decline."*

[1] [http://www.smithschool.ox.ac.uk/research-centres/reports/a-low-carbon-nuclear-pathway-for-2050-and-beyond/]


UK Nuclear development -
1950 - 2012 & onwards
1954
• UKAEA created under the Atomic Energy Act
1956
• Calder Hall, Windscale is opened by the Queen
1962 - 1971
• Nine full scale Magnox power stations open. Of these Wylfa and Oldbury are still operating today
1965 - 1970
• AGR stations start construction
1971
• UKAEA reorganised under the Atomic Energy Authority Act
• BNFL is formed to take control of the fuel cycle operations previously undertaken by UKAEA
1974
• SGHWR adopted - two stations at Torness and Heysham are announced
1976 - 1988
• Seven advanced gas cooled reactors (AGRs) are built to replace Magnox as the principal source of nuclear energy. These are now owned and operated by EDF/British Energy
1980
• Torness, Heysham, two AGRs start construction
1988
• Construction begins at Sizewell B, Suffolk after a lengthy public enquiry. It remains the UK's only PWR power station. Further plans for other power stations are dropped
1996
• Sizewell B starts to generate electricity, British Energy is privatised
2005
• Nuclear Decommissioning Authority set-up taking strategic responsibility for UK's nuclear legacy
• British energy restructured
2006
• Government releases Energy Review Report. Construction on the policy framework for new nuclear build
2007
• Government launch 'The Future of Nuclear Power'
2008
• 'Meeting the Energy Challenge': A White Paper on Nuclear Power sets out Government's view that nuclear should be part of the energy mix
• Office for Nuclear Development created Energy Act 2008 gains Royal Assent
2009
• EDF completes £12.5 billion takeover of British Energy
• Draft Nuclear National Policy Statement (NPS) published alongside five other NPSs
2018
• First new nuclear power station expected to be operational
2011
• Electricity Market Reform Paper
• National Policy Statements
1950
1960
1970
1980
1990
2000
2010
40
30
20
10
0
Number of Reactors
+ve Policy change
-ve Policy change
Accident
14000
12000
10000
8000
6000
4000
2000
0
Capacity MWe
Peak capacity
12160 MWe
Reactors under construction
Number of Reactors online
12
8
18
12
34
10
41
1
34
0
19
0
11
1957
• Nuclear power accident takes place at Windscale - a fire in the reactor results in a release of radioactivity
1978
• SGHWR abandoned - Government announces ten new pressurised water reactors (PWRs) are to be built
1979
• Three Mile Island incident
1986
• Chernobyl accident
1989
• Magnox reactors are withdrawn from governments electricity privatisation policy plans after investors refuse to buy due to the high costs of decommissioning
1994
• Fast Reactor Programme abandoned
2003
• Energy White Paper released stating that nuclear power is an unviable option
2006
• Greenpeace appealed against the consultation process
• The judicial review found in favour of Greenpeace
2011
• Fukushima accident
The Madano Partnership

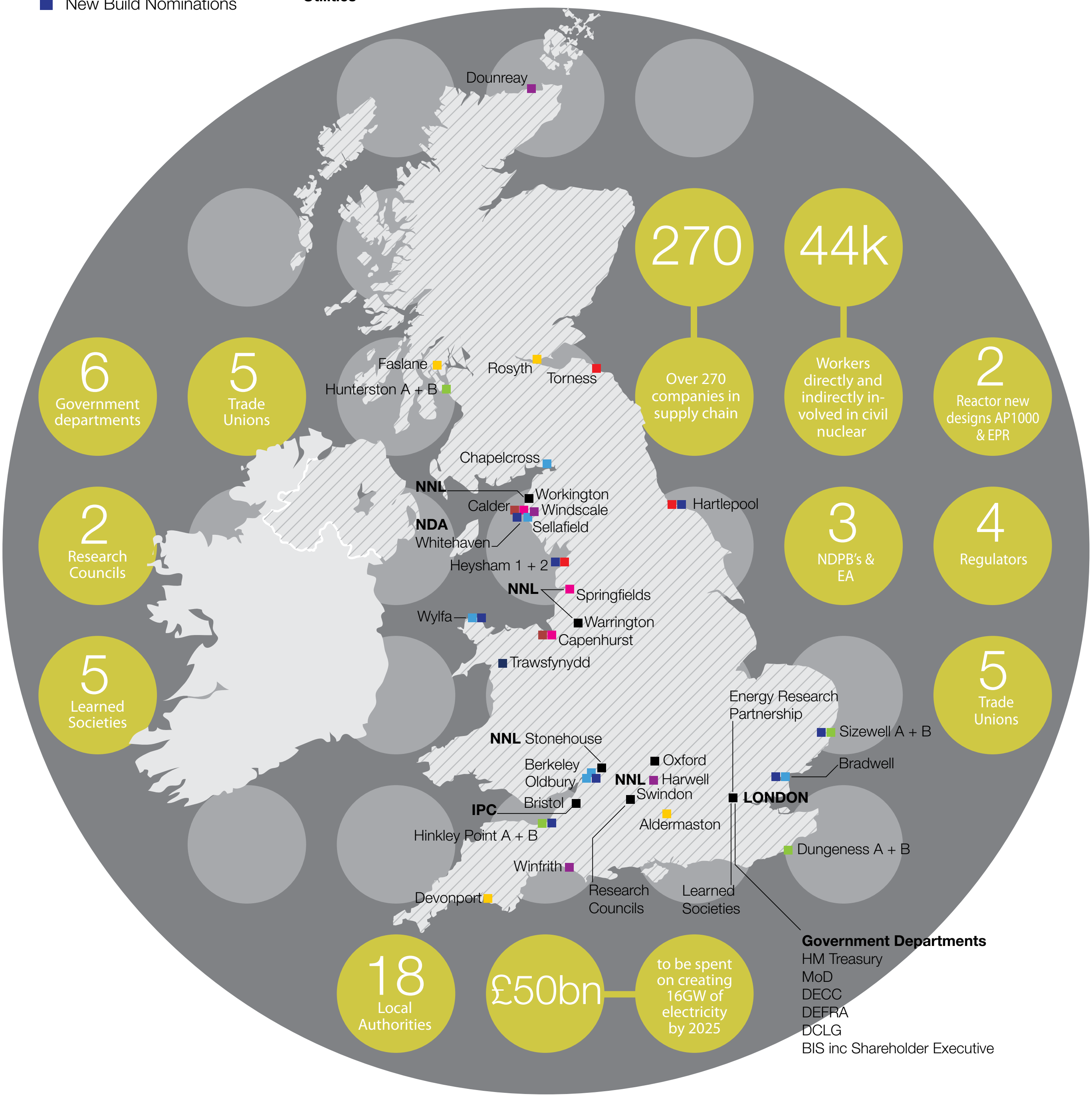
The UK's nuclear industry

LEGEND

- MoD Site
- UKAEA Site
- EDF
- Magnox + EDF
- Magnox Site
- NDA
- Fuel Cycle Site
- New Build Nominations

UK wide bodies & organisations

Academic Institutions
Trade Unions
Health & Safety Exec
Local Authorities
NDPBs
Regulators
Utilities



UK Nuclear Energy Strategy

Coordination

Observations made in earlier chapters have emphasised the need for the UK to develop a co-ordinated, long term strategy for nuclear power and the nuclear fuel cycle. This strategic necessity is highlighted by a consideration of the timescales involved in nuclear reactor and fuel cycle development compared to the frequent changes, pauses and reversals of policy which have been such a dominant feature of the last five decades.

Chapter 2 has emphasised that nuclear power must have a significant role to play in any future decarbonised UK energy system. Chapter 3, in examining the UK nuclear programme in a world context, has pointed to a potential uranium resource constraint should other countries adopt the nuclear energy future that would make world decarbonisation feasible. The UK, therefore needs to monitor world resources and maintain the option of moving to less uranium-intensive fuel cycles. Keeping these options open requires that the UK does not lose the knowledge and skills of recycling nuclear fuel. Chapter 4 has reviewed the Scenarios examined in the March 2011 Report in the context of developments in the UK nuclear energy and fuel cycle policy landscapes, and presents some options for maintaining the UK's fuel recycling knowledge and expertise, given the NDA decision to end THORP reprocessing around 2018.

The consideration of the Government's preferred plutonium management strategy (re-use as MOX fuel in new build reactors) in Chapter 5, has led to the view that unless there is a strategic integration of technology, fuel manufacture, fuel sales and business structures, there will be significant obstacles to achieving an outcome for the UK offering best value for money.

Taken as a whole, these findings reinforce the conclusion reached in the March 2011 Report: that the current structure of the UK Nuclear Industry is still aligned towards the 'no nuclear' stance of 2003 rather than the 'new build' stance of today.

As an example of how long term strategic direction could be provided, a House of Lords Science and Technology Select Committee Report[1] recommended a body (which was suggested to be called the Nuclear R&D Board: "the Board") with both advisory and executive functions to advise on UK Nuclear R+D. The Government's response[2] proposed that an Advisory Board be established under the auspices of the the Government Chief Scientific Adviser. Such an Advisory Board is to be welcomed, but would seem to be aimed at a much more limited remit than the need for an overall strategic direction which has been identified in this study. Improved UK nuclear R&D capability alone will not drive the structural changes that are necessary for a successful UK nuclear industry, capable of realising the economic, high value skills and commercial opportunities that are on offer. The need for a coherent approach to the use of UK plutonium as MOX provides an ideal test case of what is required.

1 House of Lords Select Committee on Science and Technology, Nuclear Research and Development Capabilities, November 2011
2 Government Response to the House Of Lords Science And Technology Select Committee Report: "Nuclear Research And Development Capabilities", February 2012

Conclusions

Long term strategy

The UK has decided that the decarbonisation agenda and ensuring security of supply of low carbon energy sources will be best served by having nuclear power as part of a balanced energy mix. This study has examined two important parts of the UK's nuclear landscape: the future delivery of low carbon energy using a low carbon energy mix including new nuclear power generation, and the more immediate imperative of dealing with the UK's legacy nuclear materials, principally the inventory of 100 tonnes of plutonium.

Examination of the history of nuclear power in the UK reveals a litany of 'goes', 'stops', changes of direction and changes of emphasis at a regular frequency of much less than a decade. For an industry characterised by long technology development and implementation timescales, the wonder is not that the industry is in sub-optimal state, but that it is there at all.

Although the present proposals for new nuclear power stations will be sufficient to replace the existing nuclear fleet, this would only result in nuclear's contribution to a reduced carbon intensive economy effectively standing still. Substantial additional decarbonisation will require a new set of policies and actions, in nuclear and in other low carbon energy markets. In particular, if there is a successful global decarbonisation, development will be needed on new reactor systems and fuel cycles, especially in the light of competing demands on uranium resources or if economically retrievable uranium becomes more scarce.

It was very clear from our stakeholder consultation that the current UK nuclear industry, and future UK nuclear capability, is fundamentally dependent on the development of a long term strategy that gives industry the confidence to invest on a long term basis. Of particular note, the perceived fractured policy landscape of the nuclear energy sector is seen to hold back realising the maximum economic and high value skills opportunities which are required to reach the Government's objective of safe and secure energy, free of carbon by 2050.

Given that we are serious about increased decarbonisation, the need for substantial increases in non-carbon sources, including nuclear, is such that new reactor systems and fuel cycles become a strategic necessity which introduces an additional step change in the UK's technology and research base which should be combined with a strategic view of UK industry's role in the ongoing nuclear journey. This requires independent strategic advice, both on the desired role and the path to its achievement. The establishment of an independent strategic advisory body seems mandatory in these circumstances.

As an example of how long term strategic direction could be provided, a House of Lords Science and Technology Select Committee Report[1] recommended a body (which was suggested to be called the Nuclear R&D Board: "the Board") be established with both advisory and executive functions to oversee nuclear research and development in the UK. The Government's Response[2] proposed that an Advisory Board be established under the auspices of the the Government Chief Scientific Adviser. Such an Advisory Board is to be welcomed, but would seem to be aimed at a much more limited remit than the need for an overall strategic direction which has been identified in this study. Improved UK nuclear R&D capability alone will not drive the structural changes that are necessary for a successful UK nuclear industry, capable of realising the economic, high value skills and commercial opportunities that are on offer.

One issue where such a strategic approach is apparently missing is the immediate imperative of dealing with the UK's legacy nuclear materials, in particular the UK's plutonium stocks. Our study has concluded that the Government's declared intent that the vast majority of the stockpile should be made into MOX fuel for re-use in new build reactors is likely to remain the most economically favourable option for the UK taxpayer. Issues have been identified around the relative equity of the positions of 'MOX seller' and 'MOX buyer', together with some recommendations for further study around fuel fabrication technology options, commercial models, including fuel leasing, and institutional frameworks, Introducing a more coherent approach to the use of UK plutonium stocks would usefully provide and ideal 'case study' for the overall strategic direction which has been advocated.

In summary, the main conclusions from the report are:

- If the UK is going to go down the decarbonisation route there is an enormous challenge in meeting the electricity demand particularly with the increased use of electricity in transport and possibly heating. At present the current proposals for new nuclear reactors will be no more than sufficient in replacing the current fleet. ***Substantial additional decarbonisation will require clear policies and levers to make it happen, in nuclear and other low carbon energy markets.***
- If the UK is serious about developing a world leading capability in low carbon energy supply, we need to develop a long term strategy encompassing both nuclear reactors and the nuclear fuel cycle. This should be based upon the likely long term challenges and a realistic assessment of the opportunities the UK can harness from its involvement in a civil nuclear programme. ***A long term strategy for civil nuclear power is required.***
- Uranium resources are currently not problematic, however they could rapidly become so, should decarbonisation of the world's power supplies gain momentum. As Chapter 3 of the report has shown, any use of nuclear power which is significant in meeting the global warming challenges will require either much higher uranium reserves than are currently identified, or a change of fuel cycle to minimise uranium use. ***We do stress there needs to be a much clearer view of those options and how strategy should be pursued in a UK and international context in order to provide the strategic underpinning of long term nuclear investment in the UK.***
- If the fabrication of MOX fuel in a new MOX Plant is to proceed, it should be as part of an overall strategic plan to maximise the benefit to the UK from the burning of UK plutonium in UK reactors. The UK must become 'intelligent purchasers' of the optimum technology and intelligent sellers' of the UK's plutonium asset. The present model - essentially asking potential suppliers and customers for their views- is reactive rather than proactive – and is not a model likely to deliver value for money to the UK taxpayer. ***The development of fuel leasing as identified in requires further investigation as every 10% decrease in costs and increase in prices will save the UK some £0.5B, which could eventually save over £3bn from the public purse.***
- Fundamentally and strategically, the current structure of the UK nuclear industry is aligned more towards the 'no nuclear' stance of 2003 than the 'new build' stance of 2012. The need for a long term nuclear strategy is imperative, but there is currently no organisation which carries more than a proportion of the necessary remit. There is no mechanism to develop a 'UK view' on any given proposal, and this has been glaringly obvious even in the last few months. ***There must be some form of independent body with the mission to evaluate and impartially advise on long term nuclear strategy, R&D and structural options for the industry. What it is can be debated elsewhere, that it is required seems to be self-evident.***

[1] House of Lords Select Committee on Science and Technology, Nuclear Research and Development Capabilities, November 2011
[2] Government Response to the House Of Lords Science And Technology Select Committee Report: "Nuclear Research And Development Capabilities", February 2012

Assumptions for the demand scenarios:

Business-As-Usual

Domestic passenger transport	In 2050, individuals travel 9% further than today. No noticeable modal shift.
Transport electrification	By 2050, 20% plug in hybrid electric cars; 2.5% zero emission cars.
Domestic freight	By 2050, 130% passengers increase; 50% more fuel use
Average temperature of homes	Average room temperature increases to 20°C (a 2.5°C increase on 2007)
Home insulation	Over 7m homes insulated, average thermal HLC falls by 25%
Domestic lighting, appliances, and cooking	European Union
	Energy demand for domestic lights and appliances increases by 20% (relative to 2007)
Growth in industry	No electrification of processes, little improvement in energy intensity
Commercial heating and cooling	Space heating demand increases by 50%, hot water demand by 60%, cooling demand by 250%
Commercial lighting, appliances, and catering	Energy demand for lights & appliances increases by 33%. Energy for cooking is stable
Energy Efficiency & Electrification	
Domestic passenger transport	In 2050, individuals travel the same distance as today. Signficant shift to public transport.
	Nuclear Installations Inspectorate
Transport electrification	By 2050 100% zero emission vehiclesl; all passenger trains electrified; 50% bus electrified
	Pressurised Water Reactors
Domestic freight	Road modal share falls to half, significant hybridisation, all rail electrified
	Sellafield Ltd is a Nuclear Site Licence company
Average temperature of homes	Average room temperature decreases to 16°C (a 1.5°C decrease on 2007)
	Tonnes of Heavy Metal
Home insulation	Over 24m homes insulated, average thermal HLC decreases by 50%
	Terrawatt-Hours
Domestic lighting, appliances, and cooking	Energy demand for domestic lights and appliances decreases by 60%

Energy intensity of industry	High electrification; CCS captures 48% of emissions; process emissions reduced
Commercial heating and cooling	Space heating demand drops by 25%, hot water demand by 10%, cooling demand by 60%; The proportion of non-domestic heat supplied using electricity is 80-100%
Commercial lighting, appliances, and catering	Energy demand for lights & appliances decreases by 5%; decreases by 20% for cooking

Notional LWR reactor and uranium usage

The current majority world 'technology and fuel cycle of choice' is once-through burning of low-enriched uranium fuel in light water thermal reactors. For example, of the 2011 world total nuclear operating capacity of 374 GWe, the LWR total was 305GWe, or 81% of the total[1].

A notional 1GWe PWR reactor has been assumed for this study, and the main parameters used are shown in Table 1 below.

Reactor	*Assumed lifetime*	*Capacity (MWth)*	*Efficiency (%)*	*Capacity (MWe)*	*Load Factor(%)*	*Average Burnup (thermal) (MWd/teHM)*	*Electrical Output GWy*	*Electrical Output TWh*	*Initial Charge (teHM)*	*Fuel usage per annum (teHM)*	*Uranium Usage per annum*	*Uranium usage - assumed life*	*Pu Generation per annum*	*Years per FR startup*	*U usage per GW-y*	*U usage per TWh*
1GWe	*60*	*2933*	*34.10*	*1000*	*90*	*50,000*	*0.900*	*7.89*	*81.20*	*19.28*	*180*	*10,800*	*0.23*	*51.00*	*200*	*22.82*

Table 1. Notional LWR Reactor

The calculations have assumed a 4.9% ^{235}U fuel and a feed factor of 9.34. The simplifying assumptions make no correction for initial core or final core changes. These numbers will change depending on the thermal efficiency and load factor of the actual reactors, the enrichment and burnup of the fuel.

The relative costs of uranium as uranium hexafluoride (UF6) and enrichment (as cost per Kg Separative Work, SWU) will also affect the Optimum Tails Assay, which is the 235U content in the tails which minimises the overall cost of Low Enriched Uranium (LEU).

This is illustrated in the figures below.

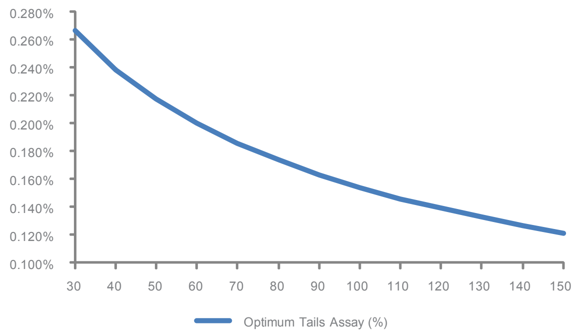


Figure A1. Optimum Tails Assay versus Uranium Price

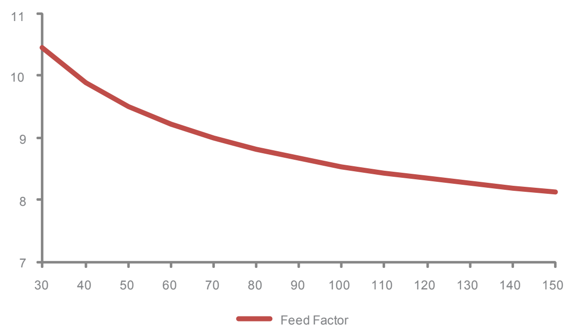


Figure A2. Feed Factor versus Uranium Price

In figure A1, the uranium price is varied from $30/lbU3O8 to $150/lbU3O8 while keeping the conversion and enrichment costs constant at $12/kgU and $130/kgSWU respectively. This is seen to vary the Optimum Tails Assay from over 0.26% to around 0.12% ^{235}U, while in Figure A2 the Feed Factor is seen to reduce from 10.45 to 8.12. As shown in Figures A3 and A4, this also raises the proportion of LEUF6 cost attributed to uranium from around 43% to 68% (of a total LEUF6 cost from under $2,000/kg to over $4,600/kg), and reduces the amount of uranium used to fuel the notional 1GWe reactor from 201teU/s to 157teU/a.

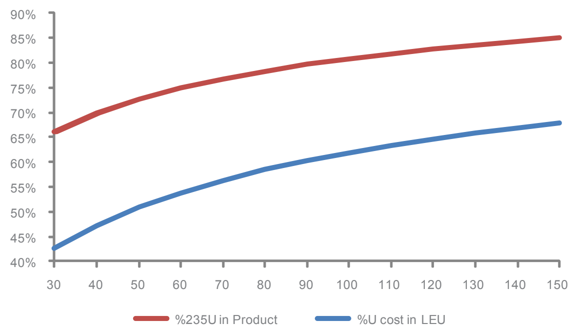


Figure A3. % of 235U in LEU product and notional Uranium cost as % of LEU cost factor

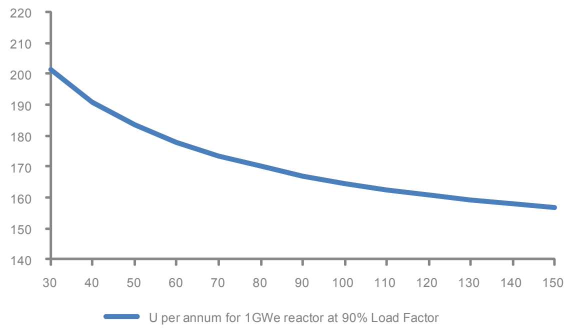


Figure A4. Annual uranium usage for 1GWe reactor at 90% Load

Figure A3 also shows that the proportion of the 235U in the mined uranium which goes into the product (and hence fuels the reactor) rises from 66% to 85% as uranium price rises and OTA falls. The 180teU/a uranium use assumed in the main report for the notional 1GWe PWR corresponds to uranium prices around $50-60/lb U3O8, which compares with end-2011 spot prices around $55/lbU3O8[2], and an EU average of 61.68/kgU during 2010[3].

The 180teU/a for the notional reactor corresponds to about 22.8teU per TWh output.

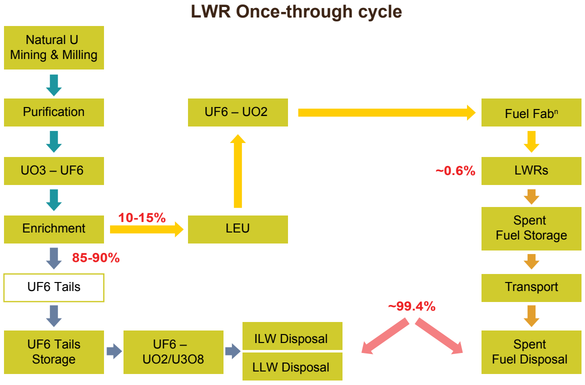
BOX - Nuclear Fuel Cycles

Of the 374GWe of nuclear electrical capacity in the world, some 81% of the total is made up of Light Water Reactors (LWRs), making this currently the world's dominant reactor technology. The reactors use water to slow the neutrons produced during fission ('thermal neutrons'), which makes them much more effective at producing further fissions, but means nearly all the power produced is from the U-235 isotope. In many countries (e.g. USA, South Korea, Spain, UK, Sweden) these reactors are used with a 'once through' cycle – where the spent fuel is stored and ultimately disposed of as waste in a geological disposal facility.

- Natural uranium as mined has 0.71% of the U-235 isotope
- LWRs use uranium oxide fuel enriched up to 3-5% in the U-235, and made into fuel with sintered UO2 pellets in zirconium alloy tubes.

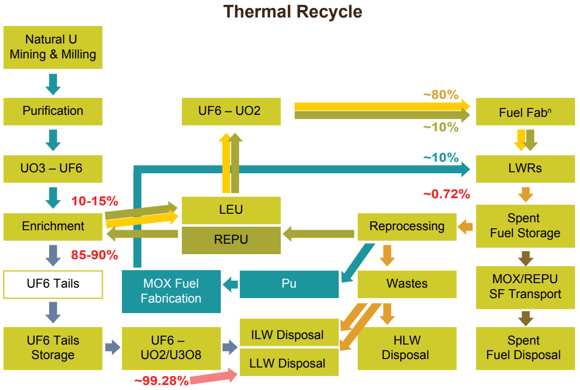
- The enrichment process gives around 10-15% of the enriched product, with the other 85-90% as 'UF6 tails' with a U-235 content generally between 0.2% and 0.3%.
- LWR fuel typically stays in a reactor for 3-5 years, burns around 5% of the uranium atoms – which represent only about 0.6% of the original mined uranium.

LWR Once-through cycle



Alternatively, some countries (notably France and Japan) reprocess the spent fuel, allowing the plutonium (which has been produced from uranium in the fuel while in the reactor) and the remaining uranium to be separated and recycled as new fuel. This is known as 'thermal recycle'

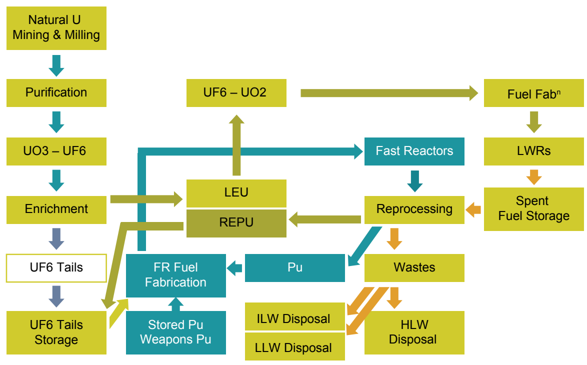
Thermal Recycle



- The spent fuel is reprocessed, separating out the plutonium and unused uranium from the fission product waste and fuel cladding etc.
- The plutonium is fabricated into MOX fuel (UO2 containing 5-10% Pu) and re-used in LWRs
- The recovered uranium is re-enriched, fabricated into fuel and re-used in LWRs
- In general this recycle is only done once, with spent MOX and recycled uranium fuel disposed of as waste.
- The recycled MOX and uranium fuel can save around 20% of the natural uranium and increasing the amount of the original uranium burnt by 20% to around 0.72%

Countries such as Russia, France, Japan, India and China are actively pursuing research into an alternative reactor concept, the fast reactor. The fast reactor does not slow down the neutrons, and while they are less effective in causing fission, the number of isotopes which can be fissioned increases well beyond U-235. This means, in effect, that all the mined uranium, not just the 0.71% U-235, can produce power. In practice, the length of time that fuel can stay in the reactor is limited by the need to remove the waste products, but with reprocessing and recycle as new fuel, the fast reactor fuel cycle can essentially burn all the uranium which is mined (including the 99.28% U-238), and this leads to an increase in the amount of power from a given amount of uranium of a factor of 50 or 60.

Fast Reactor



- Fast reactors have an initial fuel charge of enriched uranium or uranium-plutonium
- The plutonium can be derived from the reprocessing of spent LWR fuel
- The fast reactor can produce more plutonium than the uranium or plutonium it consumes – allowing additional fast reactors to be started up

- The plutonium from reprocessed fast reactor fuel is mixed with more uranium, fabricated into fuel and again produces power, and more plutonium
- The fast reactor is effectively burning the 99.28% U-238 – giving a 50-60 times increase in power per tonne of uranium as compared to an LWR.

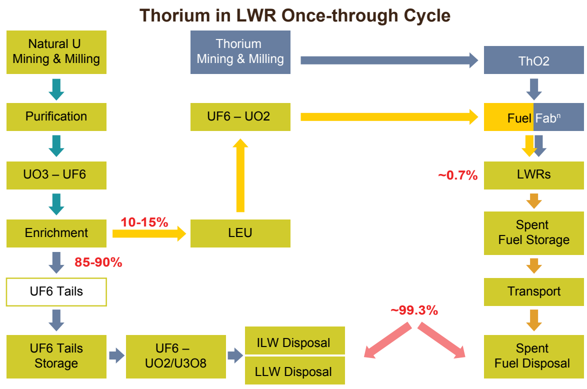
Thorium is a metal which was discovered in 1828 by the Swedish chemist Jons Jakob Berzelius, and is around four times as abundant as uranium. In nature, it consists almost entirely of the Th-232 isotope, which decays very slowly (its half-life is about three times the age of the Earth). The decay chains of natural thorium and uranium give rise to minute traces of Th-228, Th-230 and Th-234, but the presence of these in mass terms is negligible. Th-232 is not fissile, but can capture neutrons and transform to U-233, which is fissile. Fission of U-233 produces energy, so in principle the potential energy from thorium is very large indeed.

Thorium is very effective at capturing neutrons, so once a neutron source is provided (which could be, for example, from a U-235 fission reaction or a plutonium fission reaction), it is possible for a number of reactor systems, including LWRs, to produce more fissionable U-233 than the fissionable material being consumed. Thus given a 'starter' of fissionable material, it is possible in principle to convert all the thorium into U-233 and thence into energy. Of course, such 'total conversion' of thorium cannot be achieved in a single cycle of fuel – fission product wastes build up in the fuel and must be removed, with the unburned thorium and U-233 recycled into new fuel.

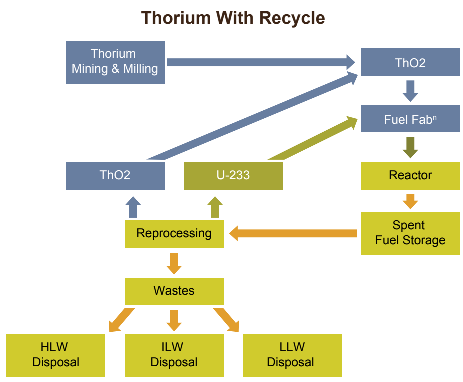
Thorium fuel proposals split into two main groups:

- Concepts which use the generation of U-233 to produce once-though fuels that produce more power from less uranium (or plutonium) than conventional uranium or plutonium fuels, and
- Concepts which recycle fuel, periodically removing the fission product wastes and recycling the thorium and U-233, essentially 'burning' all the thorium as U-233.

These concepts are illustrated below.



- Thorium introduced as part of a composite fuel element with thorium oxide and UO2 (enriched in U235 or U-233) or MOX
- The UO2 (or MOX) starts the nuclear reaction
- Thorium breeds U-233 which fissions and produces power
- The overall effect is to produce power from thorium in addition to that from U-235 and Pu



- This could save around 10% of the uranium input to an LWR once-through fuel cycle
- The reactor and fuel can be set up so that more U-233 is produced than U-235 (or U-233, or Pu) is burnt
- In the thorium recycle concept, an initial charge including U-235, U-233 or plutonium (not shown) is required
- The thorium-U-233 fuel (oxide is shown, but could

be nitrides, carbides, or molten salt) produces more U-233 (either in situ or with a thorium-only 'blanket' round the reactor core)

- Reprocessing separates the U-233 and unused thorium from the fission product wastes
- The wastes are conditioned and disposed
- The U-233 is fabricated with more thorium into new fuel

Used in the recycle mode, the energy from thorium could be around 40 times that from the same amount of uranium used for making LWR fuel.

[1] IAEA PRIS Databases, http://www.iaea.org/programmes/a2/, 21.06.2011
[2] www.uxc.com/review/uxc_Prices.aspx, 02 January 2012
[3] Euratom Average Uranium prices for 2010 at http://ec.europa.eu/euratom/observatory_price.html

Stakeholder engagement

Which organisations did we seek to consult with?

Allderdale Borough Council
All Party Parliamentary Group on Nuclear Energy
Areva UK
British Chamber of Commerce
Cabinet Office
Confederation of British Industry
Centrica plc
Committee on Radioactive Waste Management
Copeland Borough Council
Costain Ltd
Cumbria County Council
Cumbria Opposed to Radioactive Environment (CORE)
Dalton Institute, University of Manchester
Department for Business, Innovation & Skills
Department for Energy and Climate Change
Department for Environment, Food and Rural Affairs
Department of Energy – US
Department of Energy – South Africa
EDF Energy
Energy and Climate Change Committee
Energy Institute
Environment Agency
Energy Research Council
Engineering and Physical Sciences Research Council
European Energy Commissioner
FORATOM
French Embassy (UK)
Friends of the Earth
General Electric
Greenpeace
GMB
Health & Safety Executive
Horizon Nuclear Power Ltd
House of Commons Science & Technology Select Committee
House of Lords Science & Technology Select Committee
HM Treasury
Imperial College London
Institute of Physics
Institution of Engineering and Technology
International Atomic Energy Agency
International Framework for Nuclear Energy Co-operation
International Nuclear Services
KPMG
Lloyds
MCM Consulting
Ministry of Defence
MIT
MPs
National Nuclear Lab
National Skills Academy for Nuclear
Nuclear Decommissioning Authority
Nuclear Industry Association
Nuclear Installations Inspectorate
NuGen
Oxford Martin School, University of Oxford
PriceWaterhouseCoopers
Prospect
Rolls-Royce Nuclear
Royal Academy of Engineering
The Royal Society
Royal Society of Chemistry
Russell Group
Sellafield Ltd
Shareholder Executive
Sheffield Forgemasters Engineering Ltd
UK Energy Research Centre
UK Pugwash
University of Central Lancashire
University of Manchester
US Academy of Sciences
Westinghouse
World Association of Nuclear Operators
World Institute for Nuclear Security
World Nuclear Association

Acronyms

AGR	Advanced Gas Reactors
Bau	Business as usual
BNFL	British Nuclear Fuels Ltd
CAPEX	Capital expenditure
CCS	Carbon Capture and Storage
DECC	Department of Energy and Climate Change
EU	European Union
EPR	A type of Pressurised Water Reactor
GDF	Geological Disposal Facility
GW	Gigawatts
HSE	Health and Safety Executive
Magnox	A type of nuclear reactor
MOX	Mixed Oxide Fuel
LWR	Light Water Reactor
NDA	Nuclear Decommissioning Authority
NII	Nuclear Installations Inspectorate
NPS	National Policy Statements
NRC	Nuclear Regulatory Commission
ONR	Office of Nuclear Regulation
PRISM	Power Reactor Innovative Small Module
PSER	Preapplication Safety Evaluation Report
REPU	Reprocessed Uranium
SBR	Short Binderless Route
Sellafield Ltd	Sellafield Ltd is a Nuclear Site Licence company
SGHWR	Steam Generating Heavy Water Reactor (SGHWR)
teHM	Tonnes of Heavy Metal
THORP	Thermal Oxide Reprocessing Plant
TWh	Terrawatt-Hours
UKAEA	United Kingdom Atomic Energy Authority