Technology Innovation Needs Assessment (TINA)

Nuclear Fission
Summary Report

April 2013

Background to Technology Innovation Needs Assessments

The TINAs are a collaborative effort of the Low Carbon Innovation Co-ordination Group (LCICG), which is the coordination vehicle for the UK's major public sector backed organisations in the area of 'low carbon innovation'. Its core members are the Department of Energy and Climate Change (DECC), the Department for Business, Innovation and Skills (BIS), the Engineering and Physical Sciences Research Council (EPSRC), the Energy Technologies Institute (ETI), the Technology Strategy Board (TSB), the Scottish Government, Scottish Enterprise, and the Carbon Trust. The LCICG also has a number of associate members, including the Governments of Wales and Northern Ireland, Ofgem, the Crown Estate, UKTI, the Department for Transport, the Department for Communities and Local Government, the Ministry of Defence, and the Department for Environment, Food and Rural Affairs.

The TINAs aim to identify and value the key innovation needs of specific low carbon technology families to inform the prioritisation of public sector investment in low carbon innovation. Beyond innovation there are other barriers and opportunities in planning, the supply chain, related infrastructure and finance. These are not explicitly considered in the TINA's conclusion since they are the focus of other Government initiatives, in particular those from the Office of Renewable Energy Deployment in DECC and from BIS.

This document summarises the Nuclear Fission TINA analysis and draws on a much more detailed TINA analysis pack which will be published separately.

The TINAs apply a consistent methodology across a diverse range of technologies, and a comparison of relative values across the different TINAs is as important as the examination of absolute values within each TINA.

The TINA analytical framework was developed and implemented by the Carbon Trust with contributions from all core LCICG members as well as input from numerous other expert individuals and organisations.

DEPARTMENT OF ENERGY & CLIMATE CHANGE

BIS Department for Business Innovation & Skills

Research Councils UK Energy For a Low Carbon Future

CARBON TRUST

energy technologies institute

Technology Strategy Board Driving Innovation

Key findings

Nuclear fission can play a key part in the energy system of the UK and has the potential to help the UK replace aging power plants, reduce reliance on gas, and meet GHG emissions and low carbon energy targets. Innovation can reduce the costs of deploying, operating and decommissioning nuclear capacity, and is also important in reducing the perceived risks of investing in, for example, the UK's new build programme. We assess that innovation has the potential to deliver benefits worth £2-14bn[1] to 2050 and £3-34bn[1] to 2100. Innovation can also help create UK based business opportunities that could contribute an estimated £1.5-13bn to GDP by 2050.

Potential role in the UK's electricity system	• The UK has considerable experience in nuclear power and a history of world leading technology development. • The UK new build programme based on Gen III technology could be followed by the deployment of Gen IV technologies. These would reduce the need for storage of waste and some advanced reactors could also reduce proliferation risk, among other benefits. • In 2011, 19% of the UK's electricity was produced by nuclear power. By 2050 nuclear has the potential to provide up to 60% of the UK's electricity based on DECC 2050 Pathways.
Cutting costs by innovating	• Innovation also has the potential to reduce the costs of nuclear[2] – potentially bringing down the overall cost of operating and decommissioning the UK's existing nuclear stock by 5% and the levelised cost of energy from new Gen III plants by ~20% and Gen IV plants by more than 35% between now and 2050[3]. This is achieved by not only reducing CAPEX and OPEX, but also reducing risk (both nuclear risk and the associated cost of capital), avoiding construction delays, increasing capacity factors and extending plant lifetime. • Development and deployment of Gen IV technologies depends on innovation. The strongest arguments for the deployment of Gen IV may be about the benefits to waste management, fuel efficiency, and mitigation of fuel scarcity risk. • The overall innovation benefit is in the range £2-14bn by 2050 and £3-34bn by 2100 – the large range being driven by the different deployment scenarios used.
Green growth opportunity	• The UK has the opportunity to exploit leading expertise in niches, for example, decommissioning. The potential cumulative gross value-added available to the UK is likely to be in the low billions (£1.5-13 bn) to 2050 – depending on global deployment scenarios.
The case for UK public sector intervention	• Market failures that are preventing innovation exist in all sub areas. In many cases the UK could choose to rely on others to innovate in areas of nuclear power – there are ambitious RD&D plans in China for example and the UK will also have the opportunity to purchase finished technology on the global market. That said there are still strong arguments for public sector R&D support in a number of areas, decommissioning in particular. • Additionally, it is essential that the UK retain world leading regulatory capability and the ability to act at the very least as a well-informed customer of nuclear technology and a safe operator of the plants that get built. There is a very strong strategic case for innovation and RD&D programmes in fuel cycle technologies (e.g. enrichment) to support this. • Furthermore, there is also a strong case to retain UK expertise in enrichment, fuel fabrication and uranium conversion technologies in anticipation of the value of such skills and expertise becoming ever more important in a potentially resource constrained nuclear sector.
Potential priorities to deliver the greatest benefit to the UK	• Innovation that supports the successful and timely – or lower cost - delivery of the new build programme should be a priority for the UK but making the case for public investment may require a 'partnering' approach. • Decommissioning is also an area offering considerable opportunity to the UK. Whilst offering relatively low innovation benefit, decommissioning could be a considerable business value creation opportunity for the UK. Between 2016 and 2026, 200 reactors are currently scheduled to close around the world, costing a total of £35-65bn. Innovation in decommissioning will contribute to the UK accessing this market. The UK also has a unique and pressing decommissioning and waste legacy requirement that needs to be dealt with domestically. • There are large benefits from innovation in Gen IV and re-joining the international Gen IV programme, but they need to be assessed against costs through a cost/benefit analysis. • Supporting all of the UK's priority innovation areas is likely to require hundreds of millions of GBP over the next 5-10 years (potentially leveraging 3-4 times that in private sector funding). The UK is addressing some of these innovation areas, but there is scope to expand this activity. • Innovation can also benefit the existing British nuclear fleet, especially in terms of life extension (through O&M innovation) and decommissioning.

1 Cumulative (2010-2050) present discounted values for low-high scenarios based on learning by RD&D only.
2 It should be stressed that while important no cost reductions should come at the expense of nuclear safety and security.
3 Cost reduction percentages include both learning by doing and learning by RD&D.

Chart 1 Nuclear fission TINA summary to 2050

Sub-area	Value in meeting emissions targets at low cost (£bn[4])			Value in business creation £bn[5]	Key needs for public sector innovation activity/investment
	Gen III	Gen IV	Total		
Front End of the Fuel Cycle	0.3 (0.1 - 0.4)	~0.3 (0-2.6)	~0.5 (0.1-2.8)	~0.1 (0-0.2)	• Participation in international programmes via the establishment of UK programme to re-join the international Gen IV programme – for example the Jules Horowitz European Research Reactor. • Retention of existing capabilities.
Components	~1 (0.5-1.1)	~0.2 (0-2.2)	~1.2 (0.4-3.3)	~0.4 (0.1-0.8)	• Specific infrastructure and testing facilities – irradiation facilities. • Modelling of materials behaviour and qualification of materials at very high temperature and dose for fission and fusion programmes. • Advanced manufacturing techniques and development of niche capability in areas such as welding and other joining techniques.
Construction material	~0.6 (0.3-0.7)	~0 (0-0.2)	~0.6 (0.3-0.8)	~0 (0-0.06)	• Better quality of materials and more consistent techniques eg. for large concrete pouring.
Construction, Installation and Commissioning	~2 (0.9-2.2)	~0.3 (0-2.3)	~2.1 (0.9-3.5)	~0.6 (0.1-1.2)	• Reduction in build time. • Support the use of modular construction techniques. • Better systems for the qualification of components. • Structural Integrity and programmes to analyse the condition of components and sub components in nuclear reactors.
O&M	~0.5 (0.2-0.5)	0.1 (0-1.1)	~0.8 (0.4-2.1)	~3.0 (0.6-5.7)	• Advanced modelling techniques and data mining to better understand risk. • NDE programmes to reduce inspection times and associated outages. • Condition monitoring. • Digital C2 systems and greater automation.
Decommissioning	~0.1 (0-0.1)	~0 (0-0.1)	~0.3 (0.1-0.6)	~2.2 (0.5-4)	• Autonomous processes. • Different chemical processes for decommissioning. • Remote handling technologies.
Waste Management, Reprocessing, Storage	~0.1 (0-0.1)	~0.1 (0-1)	~0.2 (0.2-1.1)	~0.5 (0.1-0.9)	• Test facility for irradiated waste fuel. • Programmes to design and model the behaviour of different fuels and to develop technologies that could use existing UK stockpiles. • Linked to Fuel Cycle programmes, the development of longer term waste management approaches. • Encasement materials for GDF.
General Opportunities					• SMR programme to develop IP, including marine propulsion. • Partnering with nations growing nuclear capability from a low base. • Delivery capability - project delivery expertise (delivering large construction projects currently in decommissioning and also if new build goes ahead). • Technology enablers – advanced modelling and simulation. • Process innovation – especially regulatory processes and nuclear safety.
Total	**~4.7 (2.1-5.3)**	**~1 (0-9.3)**	**~5.7 (2-14.5)**	**~7.2 (1.5-13)**	

Benefit of UK public sector activity/investment[6]	
	High
	Medium
	Low

Source: CT Analysis

[4] We analysed four scenarios: Low, Medium I (no Gen IV) Medium II (some Gen IV), High. Figures shown are for the Medium II scenario. Figures for the UK Low and High are shown in brackets.

[5] 2010-2050 with displacement.

[6] Also taking into account the extent of market failure and opportunity to rely on another country but without considering costs of the innovation support.

Overview

The UK has had the capacity to generate electricity from nuclear power since 1956. At its peak in 1997, a quarter of the UK's electricity was generated this way. Whilst the plans of India and China in particular have caught the eye globally, the UK remains a major nuclear nation, particularly when considered in the context of the rest of Europe and North America.

There are a number of challenges ahead for the UK.

First, the UK has to continue to operate, and then decommission, its current fleet of reactors. Innovation in this area could reduce operating costs of the existing stock, extend plant life (of AGRs in particular) and thus accrue additional benefit from electricity production, and reduce the costs of decommissioning.

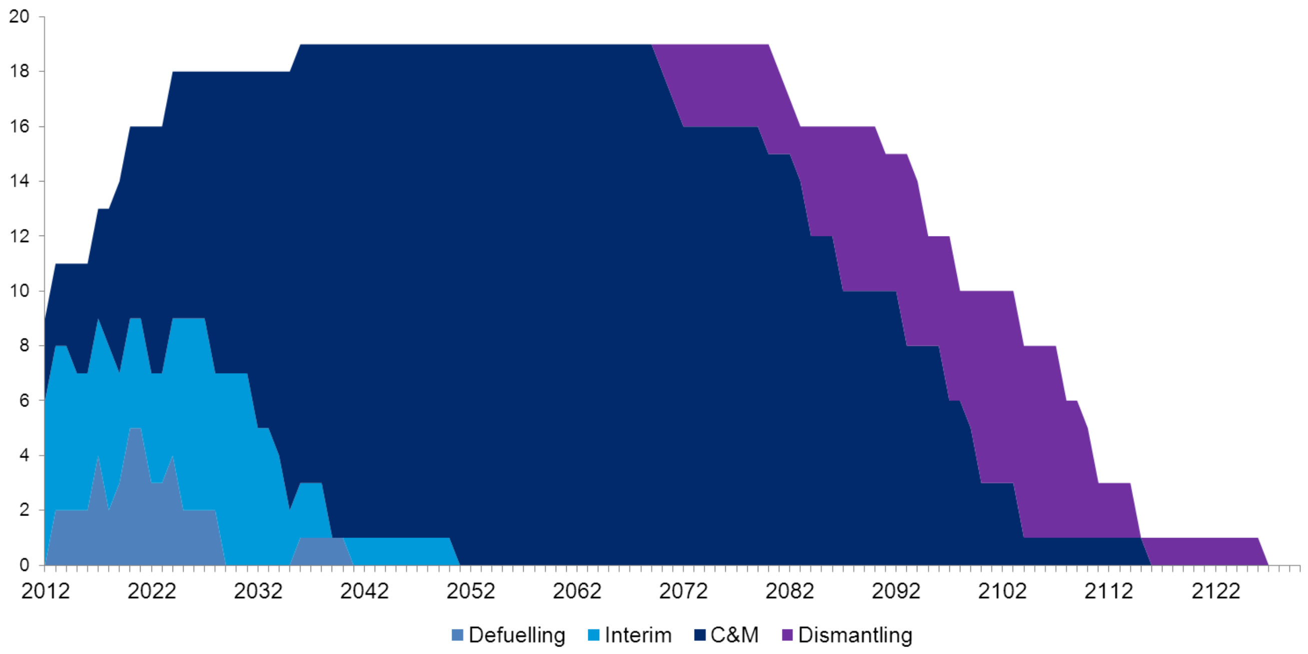
The full decommissioning financial liability is assessed yearly in the HMT Whole of Government Accounts, however the estimates remain uncertain. Chart 2 shows the number of reactors that will be going through the various stages of decommissioning. This requirement will be in place irrespective of what additional nuclear capacity the UK decides to deploy.

Second, after a lull in the construction of new reactors, utilities in the UK are about to embark on an ambitious new build programme that – as currently planned – will replace the UKs current fleet of reactors with up to 16GW of new capacity by around 2025. Innovation could deliver benefits here in terms of reducing the costs of deployment, improving capacity factor, and reducing the perceived risks of investing in the new build programme. This latter area is particularly significant, as are the potential savings if the reactors constructed under the new build programme can be built ahead of time.

The analysis presented in this report is focussed on the potential innovation benefits to the new build programme.

Third, the UK needs to think what will come after the reactors are built in the new build programme. These Advanced or Gen IV reactors will be based on prototypes available from 2025 onwards. They include thermal reactors such as Very High Temperature Reactors, and Fast or Breeder reactors, such as Gas, Sodium or Lead Cooled Fast Reactors, each with different advantages, and the international community has yet to settle on a specific technology. There has already been substantial research in Gen IV reactors, including in the UK where a prototype Very High Temperature Reactor (the Dragon reactor) was in operation until 1976.

***Chart 2: UK existing fleet and legacy decommissioning requirement – Numbers of reactors in each stage of the process*[7]**



[7] The generic stages of the UK decommissioning process have been modelled as follows. Defuelling – 5 years, Interim – 10 years, Care and Maintenance 65 years, Dismantling 10 years. This is an approximation based on NDA forecasts, CT analysis and consultation with industry.

Understanding Nuclear Technology

Nuclear technology is best understood in terms of generations of reactors. The UK's current fleet of nuclear reactors is Gen II. The new build programme will use Gen III(+) technology; the most likely designs are Areva's EPR, and Hitachi's Advanced BWR, subject to regulatory approval. Gen IV reactors could be deployed from about 2030. A more detailed classification is as follows:

Generation I – (Gen I) Early prototypes of nuclear reactors. In the UK, MAGNOX reactors are classified as Generation I, with one still operational at Wylfa.

Generation II – (Gen II) This classification refers to plants built up until the 1990s. In the UK this mainly refers to Advanced Gas Cooled reactors (AGR), using Graphite as the moderator. EDF, the AGR operator, is currently seeking life extensions which could see them operating into the late 2020s.

Generation III – (Gen III) These reactors are advanced versions of Gen II designs, which typically have improved fuel technology, superior thermal efficiency, passive safety systems and standardized design for reduced maintenance and capital costs. Gen III+ reactors are similar in design but have more advanced safety systems.

Generation IV or Advanced Reactor technologies. (Gen IV) These reactors are being researched and are expected to be ready for prototyping from around 2025-2030. While some of the designs are based on existing research and prototypes that were developed in the '50s and '60s, Gen IV reactors are expected to be "revolutionary" in design as opposed to "evolutionary", and as such qualify as a new technology. The claimed benefits of Gen IV reactors are usually listed[8] as:

- High level waste is radioactive for a period of time measureable in hundreds, rather than thousands, of years.
- Energy yield from the same amount of fuel improves up to 300 times.
- Gen II and III spent fuel can be used as new fuel in Gen IV reactors, turning a liability into an asset
- Improved passive safety design.
- Broader system benefits such as the ability to produce baseload heat for industrial applications or the production of hydrogen.[9]
- Some of the fuel cycles that advanced technologies might use are inherently more proliferation resistant.

Discussions of the value of developing Gen IV technologies are often focussed on its benefits to waste management – Gen IV fast reactors would be able to consume the current UK nuclear stockpile as fuel, producing a much smaller quantity of waste material that would last for a much shorter amount of time.

Other type of reactors, such as Very High Temperature Reactors, could have substantial side benefits such as high quality waste heat for hydrogen production.

A separate type of reactor are **Small Modular Reactors**, which refers to reactors under 300-500MW which have been built using modular techniques. SMR could utilise Gen III or Gen IV technology.

Nuclear fission has an important role to play in the UK energy system

Nuclear fission has the potential to provide up to 60%[10] of the UK's electricity, depending on the actual cost of deployment. While innovation will play a role in ensuring nuclear fission is deployed at large scale, the overall capacity installed also depends on key "exogenous" factors, especially the cost of alternative generation technologies, the degree of public acceptability for nuclear technology, the (relative) technical success of CCS, the availability of biomass for energy use, the overall electricity demand, and the success of energy efficiency/demand reduction measures.

Political support also plays a role, as the post-Fukushima decision by the German government to reverse its policy position and cancel the planned life extension of the existing nuclear fleet shows. Thus, there is a high level of uncertainty built into the analysis.

We have considered 3 indicative deployment levels of nuclear fission. These scenarios aim to capture a range of feasible deployment scenarios, and are neither forecasts for the UK nor targets[11]:

- **Low scenario** (16GW by 2050). Current UK nuclear fleet is replaced with up to 16GW of Generation III capacity by 2030. The scenario represents the current UK new build programme including the Horizon project (recently purchased by Hitachi).
- **Medium scenario** I (40GW by 2050) UK deploys 40 GW of Generation III capacity.
- **Medium scenario II.** UK also builds 40 GW of nuclear by 2050, but uses Advanced Reactor (Gen IV) technology for 80% of new reactors above 30GW of total installed capacity.
- **High scenario.** (75GW by 2050) As set out in the Carbon Plan - UK builds 75GW by 2050, with 80% of new reactors being Gen IV reactors above a total installed capacity of 30GW.

[8] The first bullet applies to actinide burners and the second and third bullets to fast neutron systems (including actinide burners) with a closed nuclear fuel cycle.

[9] These benefits are only relevant if one makes some fairly broad assumptions about the type of energy system the UK might have in the future – but they are included for completeness.

10 AEA, Pathways to 2050 – Key results, 2011

[11] By trying to capture the full range of uncertainty over the mid to long term to inform innovation policy, these indicative deployment levels were not precisely aligned with UK government short and mid-term targets.

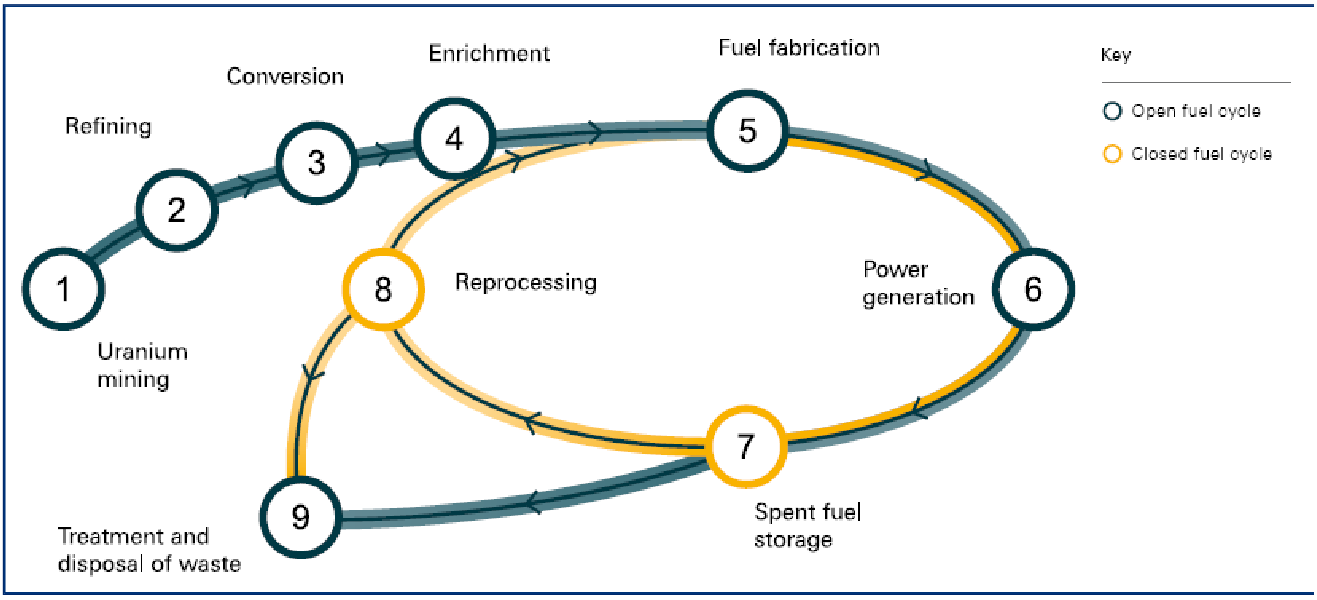
Cutting costs by innovating

Current costs

The latest government-commissioned reports have estimated the cost of nuclear technology at circa £3.8m/MW[12]. We have used Levelised Cost of Energy (LCOE) in our cost model and have calculated innovation benefits using as the starting point an LCOE based on Parsons Brinkerhoff's 'Cost of Electricity Generation', completed for DECC in late 2012. The central LCOE figure is £81/MWh[13]. This figure was chosen to be consistent with the most recent DECC low carbon energy scenarios; however, a high degree of uncertainty remains around nuclear energy costs, and as such this figure should not be intended to be definitive.

Based on the Fuel Cycle, we have split out the LCOE of nuclear fission systems into seven major cost sub-areas. These are shown on Chart 3[14] along with the contribution that they make to the overall LCOE of nuclear fission.

Chart 3 Overview of nuclear fission sub-areas – the Fuel Cycle



Source: http://royalsociety.org/uploadedFiles/Royal_Society_Content/policy/projects/nuclear-non-proliferation/FuelCycleStewardshipNuclearRenaissance.pdf

Chart 4 Overview of nuclear fission sub-areas – cost attribution

Sub-area	Descriptions	% LCOE
Mining, Processing, Enriching, Fabricating	Full treatment of fuel prior to its use in a reactor.	**15%**
Capex – Components	The main assemblies of the reactor system – reactor core, heat exchanger, containment vessel, pumps, turbines etc.	**20%**
Capex – Construction material	The costs of materials, principally steel and concrete.	**11%**
Capex – Construction/installation and Commissioning	The remaining capital costs of the build.	**28%**
O&M	Operating costs including fixed costs and maintenance.	**15%**
Decommissioning	Defuelling, cooling and dismantling of the plant.	**5%**
Waste Management, Reprocessing, Storage	Typical costs for the back end of the fuel cycle.	**5%**

[12] Based on the Parsons Brinkerhoff estimated EPC cost for nuclear of £3823/KW. This is based on a reactor with a 60 year operating lifetime and 90% capacity factor.

[13] This represents the cost of a generic reactor at a 10% discount rate, and is the middle figure in a range that goes from 73 to 93 £/MWh, as per DECC's Electricity Cost Update, October 2012.

[14] This analysis is based on Gen II and Gen III costs. We have also applied it to our analysis of Gen IV costs in the absence of any other information. The breakdown is derived from analysis by the International Atomic Energy Agency (IAEA) and the OECD Nuclear Energy Agency.

Cost savings through economies of scale and innovation

We calculate total potential savings in energy system costs through innovation based on our cost and efficiency improvements, and our scenarios for deployment (taking into account emissions and energy security constraints). This represents the maximum innovation potential, combining "learning by research" (driven by RD&D spending) and "learning by doing" (achieved through the incremental learning associated with increased deployment alone). In our calculation, we separate out "learning by doing" from "learning by research" (based on the stage of each components development and historical experience) to give a more specific estimate of the impact potential for RD&D.

We base our breakdown of learning by doing and learning by RD&D on methodological work common to all the TINAs; as such, the LCOE numbers produced differ from the First of a Kind (FOAK) and Nth of a Kind (NOAK) power plants in the Parsons Brickenhoff (PB) report.

We have analysed UK nuclear capacity in terms of existing capacity and legacy, Gen III new build, and Gen IV new build. We have divided the benefits derived from learning by doing and learning by RD&D based on the level of maturity of nuclear technology.

For existing nuclear capacity most of the benefits derive from learning by doing, chiefly in O&M and the back end of the fuel cycle.

For Gen III cost savings from learning by RD&D are counted from an N^{th} of a kind (NOAK), assumed to start construction in 2020, yielding c. £4.5bn to 2050 as shown in Chart 2. Learning by doing still has an overall larger share of the total benefits for Gen III than learning by RD&D, yielding c. £15bn to 2050[15].

Gen IV is considered a newer technology and as such is more reliant on learning by RD&D, yielding c. £1bn from deployment in 2030 up to 2050, compared to c. £0.6bn from learning by doing[16].

Benefits for the UK's current nuclear fleet

RD&D has the potential to deliver benefits in a number of ways. Our analysis modelled the impact of innovation on the existing nuclear fleet; roughly a quarter of a billion, as shown in the table below.

Table 1 - cost reductions from innovation to UK existing fleet, cumulative to 2050, discounted

Sub-area	£m
Mining, Processing, Enriching, Fabricating	4
CAPEX - Components	0
CAPEX - Construction materials	0
CAPEX - Construction, Installation and Commissioning	0
O&M	191
Decommissioning	28
Waste Management, Reprocessing, Storage	28
Total	**251**

However, extending the lifetime of the current nuclear fleet could also deliver large indirect benefits to the UK economy:

- Current existing nuclear plants have already paid off their capital costs, and are now generating electricity at a very low price. Keeping them in operation for longer avoids the cost of having to build new power plants, possibly keeping electricity prices at a lower level than they would otherwise be.
- Additional revenue from electricity generation. This would accrue largely to the owner of the plants.

While important, we do not expect life extension and O&M innovation in existing reactors to be a priority for public sector investment, as the operators have a sufficient incentive to act on their own. However, they would benefit from increased coordination and cooperation between the nuclear research sector, industry and government. The existing reactor fleet is likely to benefit from process and other cross-cutting innovations as well.

[15] The cost reductions have been calculated by modelling two different cost reduction curves, for R&D and learning by doing, and applying them to the deployment scenarios. The ratio of learning by doing to R&D is derived from Jamasb, Tooraj (2007). "Technical Change Theory and Learning Curves", The Energy Journal 28(3)

[16] See above.

Benefits for the New Build Programme

If the UK completes the new build programme as currently planned, then there are considerable potential benefits from innovation. These benefits are the focus of the analysis and the figures presented describe the potential benefits of innovation to the development, deployment, operation and decommissioning of nuclear capacity built from 2011 onwards. The figures also include the reduction in operating costs for the current fleet.

There are a number of ways in which innovation might deliver benefits:

- Cost reduction.
- Capacity factor improvement.
- Life extension. Of all the levers, this is least impactful because its benefits are heavily discounted.
- Reduction in the cost of capital. The cost of capital will come down if the perceived risks of investing in nuclear can be reduced. Our analysis suggests that this is crucial because of the effect on levelised cost. We assume this reduction will derive from improved passive safety technology, innovative construction techniques (such as modular construction) and other innovations which will help de-risk the technology and lower the cost of finance.
- Avoiding build-time over-run.

Innovation Benefits to Gen IV deployment

Innovation is required simply to develop Gen IV technology. That said if the UK decides to deploy Gen IV technologies in the future there will be benefits from innovation that will act in the same generic way as described above.

Whilst the cost levers may potentially be similar, our understanding of their effect and of what constitutes potential improvement is less well developed than for Gen III technologies on which the new build programme will be based.

For that reason our figures for the innovation benefits of Gen IV technologies should be regarded as more indicative than those for Gen III.

Cost of Generation IV

Further to the point made above, due to the early stage of development of Gen IV technology, no reliable and consistent cost information exist in the public domain. After consultation with industry and academia we have decided to apply a 20% mark up to Gen III costs to simulate the potential cost of a FOAK Gen IV nuclear power plant. This gives a levelised cost figure for Gen IV of ~£100/MWh. This is just a modelling assumption and Gen IV benefits should be regarded as highly speculative estimates.

Assessing the potential benefits of innovation

Innovation benefit is based on a bottom-up assessment of reasonable levels of improvement in each of the fuel cycle sub-areas – shown in Chart 5. Gen III figures are shown with Gen IV figures included in brackets where they differ.

The cost reduction and other improvements figures have been derived from extensive consultation with nuclear experts from industry, government and academia. However there is a high level of uncertainty and variation in quantitative estimates of nuclear industry costs and in forecasts of potential cost reductions from innovation programmes. As such all this figures should be regarded as estimates with potentially large ranges.

Overall Innovation benefit for Gen III and Gen IV

The Medium II 40GW by 2050 scenario (assuming the HIGH level of cost reduction for Gen III) is used as the central scenario for the following analyses.

On the basis of the improvement potential by sub area and cost lever set out in Chart 5, we have assessed the amount of potential benefit associated with each of these levers and sub areas. In separating out innovation benefit by sub area and by cost lever, we are able to understand where innovation has the potential to deliver greatest benefit, and which of the cost levers and sub areas are most important.

Chart 5 - Potential cost savings from innovation by sub-area - Generation III and (Generation IV)

Sub-area	% of LCOE	Reasonable foreseeable innovation potential Gen III (Gen IV if different)					Remarks
		Cost reduction[1]	Reduction in construction time[2]	Capacity factor Improvement[3]	Lifetime improvement[4]	Reduction in cost of capital[5]	
Mining, Processing, Enriching, Fabricating	15%	0-5%(10%)	0	1%(5%)	0 (2.5)	0%(0.50%)	Fuel cycle technology has the potential to deliver greater benefit to Gen IV deployments – particularly in terms of reducing the perceived risk of investment.
Capex – Components	20%	5-10%(15%)	0	1%(3%)	3.5 yrs (2.5)	0.25%	Advanced manufacturing techniques and other innovation could reduce component cost for both Gen III and Gen IV reactors.
Capex – Construction material	11%	5-10%(5%)	0	0%	0	0.25%(0%)	There is some scope for cost reduction through innovation and innovation in this area (helping build times for example) may also reduce the perceived risk of investment.
Capex – Construction/installation and Commissioning	28%	0-5%(5%)	1	0%	3 yrs (2.5)	0.50%(0.50%)	The prospect of a successful build programme (on time and budget) is a very important lever in reducing perceived risks.
O&M	15%	5-10%(15%)	0	1%(2%)	3.5 yrs (2.5)	0%	O&M innovation can deliver benefit across the cost levers but is not a factor for risk reduction in Gen IV deployments.
Decommissioning	5%	5-10%(10%)	0	0%	0	0%	Main impact of innovation benefit is in terms of cost reduction, from schedule improvements and safety improvements – e.g. reducing C&M period
Waste Management, Reprocessing, Storage	5%	5-10%(10%)	0	0%	0	0%(0.50%)	Innovation may lead to cost reductions through novel technologies e.g. waste minimisation
TOTALS		3-8%[3] (10%)	1	+3% (+10%)	+10 yrs (10)	1%(1.75%)	

Source: Carbon Trust analysis, consultation

[1] Gen III cost reduction figures are shown as a range. The core analysis in this report has been done using the HIGH figure for cost reduction as per standard TINA methodology. Gen IV improvement is shown as single and more indicative figure in brackets.

[2] Base construction time for a Gen III or Gen IV power plant is 6 years. We assume a possible reduction of one year. It is worth noting that a construction overrun of one year or more as could result in significant cost increases

[3] Capacity factor improvement is expressed here in terms of improvement in the average capacity factor over the lifetime of the plant. There is a certain lead time between a nuclear plant's commissioning and the moment it reaches maximum capacity; innovation reduces this lead time, allowing the average capacity factor to increase. We assume an average capacity factor of 90% for Gen III, based on the PB report, and 75% for Gen IV, as desk research indicates the average capacity factor of a newly deployed nuclear design is in the mid-70s, based on historical experience.

[4] We assume both Gen III and Gen IV reactors to have a 60 year operating lifetime at commissioning, based on the PB report.

[5] We assume a starting cost of capital equal to the discount factor of 10%, based on the PB report. The reduction assumes the cost of capital decreases by the stated percentage point.

Gen III versus Gen IV

At larger scales of deployment, and over a longer time frame, the potential deployment of Gen IV reactors becomes more important.

Chart 6 shows the overall benefit associated with Gen III and Gen IV innovation for each of our scenarios and out to 2050 and 2100. As previously stated, the potential innovation benefits for Gen IV technologies are indicative.

This may be simply a function of the greater number of advanced reactors deployed, but there is also value in deploying these types of reactors as opposed to 'traditional' Gen III technology.

Generation IV should also deliver additional indirect benefits to other areas of the nuclear fuel cycle. For example it should reduce waste management costs. While this particular effect is already partially accounted for in our modelling, there are extra system benefits to be derived from the interaction between Gen III and Gen IV, specifically the possibility for the latter of using the waste of the former as fuel, thus transforming a liability into an asset. This type of benefit has not been modelled.

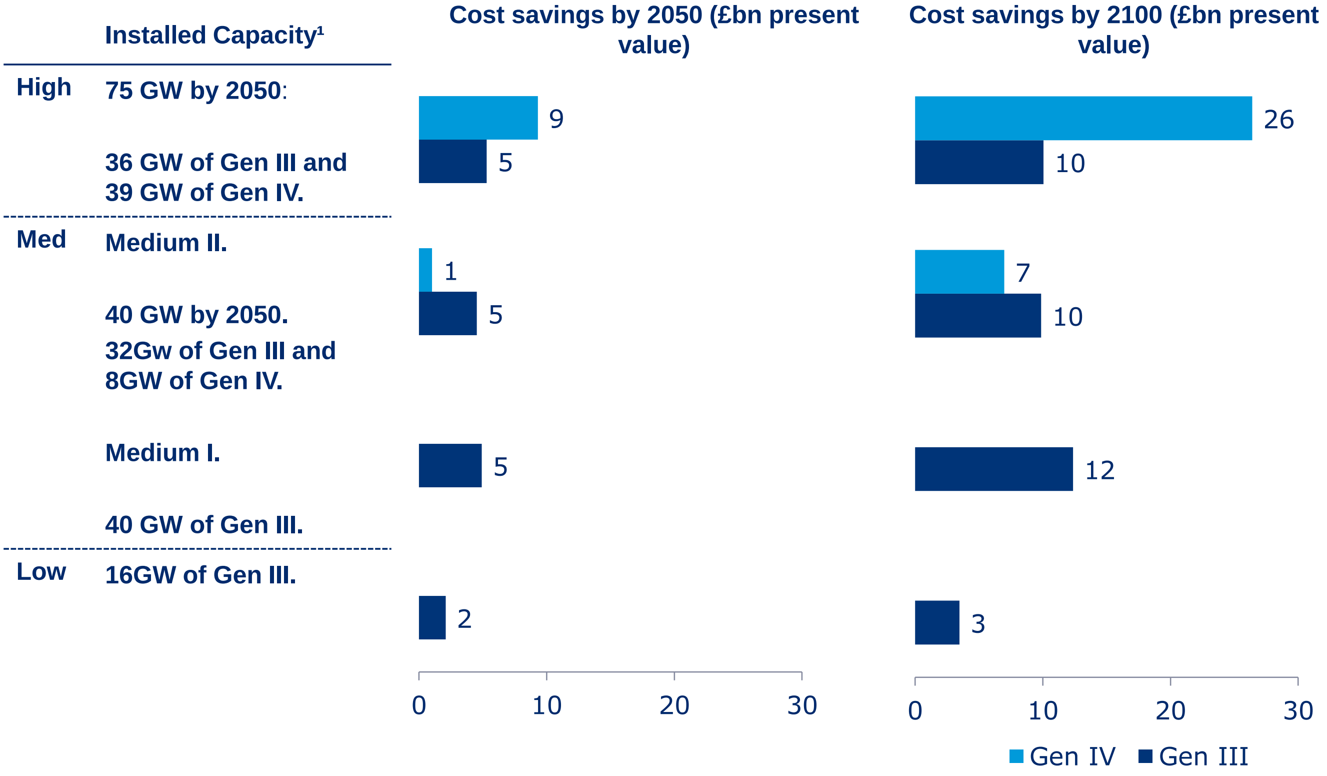
Some specific types of Gen IV reactors would produce hydrogen as a by-product, and others could be used for district heating. These indirect benefits have not been quantified in this analysis and are not included in the calculations below, but they could be the main drivers behind the decision to pursue Gen IV technologies, and as such might warrant additional analysis.

Our analysis allows us to model the contribution of innovation in each sub area to the overall innovation benefit – the results for both the Gen III and Gen IV are shown in Chart 7. This shows that the relative importance of the contributions of innovation in different sub areas varies from Gen III to Gen IV.

The key points from this analysis are:

- The marked importance of innovation in Construction, Installation and Commissioning for Gen III. Approximately a third of this benefit is itself due to the effects of building reactors in 5 years instead of 6 as currently planned, but even accounting for this it is clear that in terms of innovation benefit, Construction should be an area of priority.
- The increasing importance of Front End of the Fuel Cycle innovation for Gen IV technology.

Chart 6 – How Gen IV becomes more important at greater scales of deployment and timeframe



1 Excludes legacy

Source: Carbon Trust analysis

2050 versus 2100

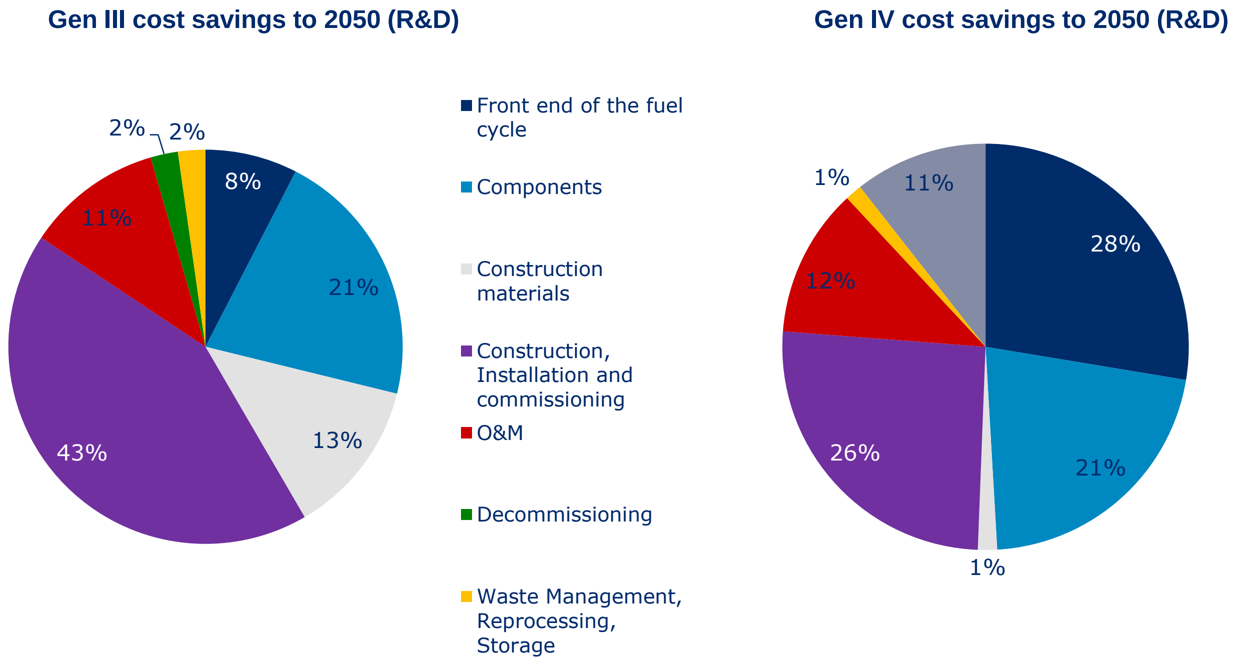
Overall innovation benefit depends primarily on the scale of deployment. Chart 7 shows how the relative importance of innovation in different sub areas changes with technology. Chart 8 shows how this contribution varies with timescale.

The transition from a wholly Gen III fleet to one dominated (as it is in our High scenario) by Gen IV technologies shows how this shift in the relative importance of innovation in the different sub areas affects the contribution of those sub areas to overall innovation benefit.

Again, a notable example of a change in relative importance is the Front End of the Fuel Cycle. At low levels of deployment, innovation in this sub area contributes less than 10% of the overall innovation benefit. At higher levels of deployment – where more if the installed capacity is likely to be Gen IV technology, this benefit increases disproportionately to, for example, O&M innovation.

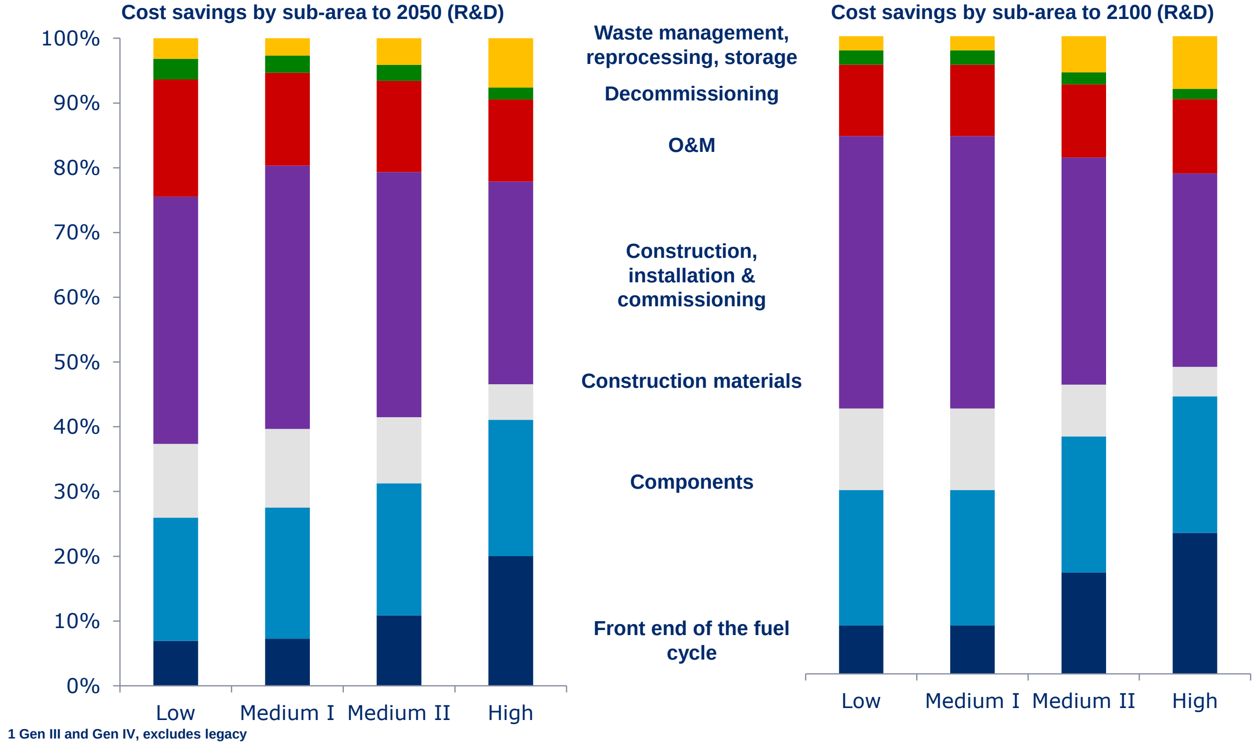
	Low	Med I	Med II	High
Gen III	16GW	40GW	32GW	36GW
Gen IV	0	0	8GW	39GW

Chart 7 – How the relative importance of innovation in different sub areas varies for Gen III and Gen IV technologies.



1 Excludes legacy

Chart 8 – How percentage contribution to overall innovation benefit changes with deployment scenario out to 2050 and 2100.



Source: CT analysis

Other benefits from innovation

In addition to the modelled benefits resulting from learning by RD&D there are other advantages that are less quantifiable but nonetheless important.

For example, it could be argued that some degree of investment in nuclear innovation is necessary to maintain the key strategic capabilities that would enable the UK to import and operate safely nuclear technology developed by international actors.

Additionally, wider societal issues weigh in the consideration of nuclear innovation. Novel fuel cycles might have the potential to change the way in which the technology is perceived by the public, which might unlock larger deployments than are typically envisaged today, where the unlikelihood of further development sites becoming available is seen as a constraint on the construction of reactors at any site that is not already a nuclear facility. Conversely, this could have adverse effects if the public is not properly engaged and made aware of the benefits and security of new technologies.

Finally, by directly fostering and supporting innovation in nuclear technology the UK government can contribute to the growth of the domestic nuclear supply chain and the emergence of new companies, especially if the innovation process helps to ameliorate the high barriers to entry that prevent new companies from becoming established in the nuclear market.

Green growth opportunity

A large global nuclear fission market

A large amount of nuclear fission power is likely to be required globally as well as in the UK, with IEA estimates ranging from around 500GW to almost 2,000GW by 2050:

- **Low scenario** (482GW by 2050). This is based on the IEA Baseline scenario.
- **Medium scenario** (1,223GW by 2050). Based on the IEA Bluemap scenario in which the world keeps on a 2 degrees path and there are few constraints on nuclear (and CCS).
- **High scenario** (1,973GW by 2050) Based on the IEA HiNuc scenario.

Across the low-medium-high scenario, the global market turnover by 2050 could grow to £286bn – £2,485bn (£1,348bn in medium scenario) (discounted).

The UK is unlikely to be a market leader but there are niche opportunities available

The UK is not currently a nuclear vendor and also has a relatively modest nuclear RD&D spend as a proportion of overall energy RD&D spending when compared to leading nuclear nations such as the USA and France. The UK market share in nuclear markets is likely to be low-medium, between 2% and 9% depending on the sub area. There are niche opportunities in most sub areas, but those in component manufacture and decommissioning represent perhaps the best opportunity for the UK.

£1.5-13 bn net contribution to the UK economy

If the UK successfully competes in a global market to achieve the market share above, then nuclear fission could make a cumulative contribution[17] of c. £7bn (£1.5–13bn) by 2050. This includes the application of a displacement effect since part of the value created in the export market will be due to a shift of resources and thus partly cancelled out by loss of value in other sectors. Expert opinion has roughly assessed this effect to be between 25% and 75%, so we have applied a flat 50%[18].

It should also be noted that standard TINA methodology does not quantify the additional benefit that could be achieved by the UK if innovation helped increase the local content of the new build supply chain by making UK companies more competitive. For example, this would entail capturing a larger share of the £20bn that Hitachi/Horizon is expected to invest in building the Wylfa and Oldbury complexes.

The case for UK public sector intervention

Public sector activity may be required to unlock this opportunity – both the reduction in the costs to the energy system from learning by research, and the net contribution to UK GDP from new business creation.

Market failures impeding innovation

A number of overall market failures and barriers inhibit innovation in nuclear fission. We use the term “market failure” in a very broad sense, including not only failures that arise from the structure of the market system, such as externalities, but also barriers that are created by the nature of nuclear technology itself, for example long decommissioning and waste management time horizons.

Within the sub areas of nuclear technology, the critical market failures have most impact on decommissioning, with significant market failures also affecting both the Front and back End of the Fuel Cycle, Component Manufacture, and Construction, Installation and Commissioning. These are further detailed in Chart 9 below.

In a number of areas, the UK can rely on other countries to drive innovation with the required focus and pace

For a number of areas of nuclear fission technology, the UK can wait and just rely on other countries to intervene in tackling these market failures, and in driving innovation with the focus, and at the pace required for UK value creation.

These include fuel cycle technologies, where several countries including Russia, China and India are currently carrying out the RD&D necessary to develop advanced reactors. That said there are questions as to whether technology and approaches developed in the Chinese market can be easily imported given the UK’s different approach to regulation and safety cases.

But there are areas where the UK cannot rely on others

The UK has specific needs in the technology sub-areas:

- Front End of the Fuel Cycle – Fuel Cycle research could be more important if the UK decided to engage actively with the international Generation IV programme, as this area is essential to the development of Gen IV. At present the UK has valuable expertise in fuel enrichment, fabrication and conversion that will be lost unless specific investments in the area are made.

[17] Discounted at 3.5% to 2040, and 3.0% between 2041 and 2050, in line with HMT guidelines

[18] The 50% value has been used across all TINA reports and is currently considered the “best estimate” out of extensive consultations and workshops with economists.

- Decommissioning – The UK has a specific decommissioning requirement based on its legacy nuclear sites. Innovation can reduce the cost of this programme and is not an area where the UK could largely rely on others, especially due to specificities of the UK decommissioning requirement.
- Back End of the Fuel Cycle – Waste management and disposal. The UK has a significant and unique spent fuel challenge – and while exchange programmes with other countries exist, the UK requirements are fairly unique and would be better served by development of domestic capability.

Chart 9 - Market failures and economic barriers in nuclear fission innovation areas.

Sub-area	What market failures exist?	Assessment
Mining, Processing, Enriching, Fabricating	• Uncertainty over future fuel cycles. • The risk of proliferation prevents the global expansion of enrichment facilities. • High capital costs act as a barrier to entry for innovative players.	Significant failure
Capex – Components	• Limited number of nuclear vendors with advanced manufacturing capabilities, low competition and high barriers to entry due to the need for costly testing facilities such as particle accelerators. • Stringent safety requirements and long certification times prevent innovation from being profitable in the short term – new systems need to log in hundreds of hours of operating time before being allowed to reach commercial stage. • Some components are not replaced during a reactors lifetime (e.g. nuclear island) again pushing profitability for innovation to the longer term.	Significant failure
Capex – Construction Material	• Lack of alternatives also discourages innovation. • Traditionally seen as an area in which it is difficult to innovate. • Safety case requirement also limits opportunities to use new materials.	Moderate failure
Capex – Construction/installation and Commissioning	• Insufficient sharing of array performance data due to perceived risks of losing competitive advantage (i.e. positive externalities/coordination failures). • Site-specific certification needed, slowing the process of innovation adoption and preventing economies of scale.	Significant failure
O&M	• Commercial developments discourage data pooling and the development of cross industry best practice. • Coordination failures (positive externalities) including a lack of monitoring and pooling of reliability data. • The necessary skilled workforce requires a long time to reach maturity and is vulnerable to high turnover rates and obsolescence, requiring constant investment even during lossmaking periods. • Subsidised electricity markets can reduce the incentive to reduce operating costs. • That said, industry's view is that it is currently well incentivised to reduce cost.	Moderate failure
Decommissioning	• Decommissioning takes place in the far future and as such heavily discounted, which means there is little incentive to innovate to reduce cost. • There is not guarantee that the innovator will receive the decommissioning contract 40 years in the future, reducing the incentive to present innovation. • Meeting current decommissioning may be complicated by regulators preference for established methods over innovative processes.	Critical failure
Waste Management, Reprocessing, Storage	• Until government policy on waste management and reprocessing is clear the market does not have a strong incentive to innovate. • Revenues from waste management and storage services are relatively small and far off in the future. • Reprocessing capabilities are limited by proliferation concerns.	Critical failure

Source: Expert interviews, Carbon Trust analysis.

Potential priorities to deliver the greatest benefit to the UK

The UK needs to focus its resources on the areas of innovation with the biggest relative benefit to the UK and where there are not existing or planned initiatives (both in the UK and abroad). We have attempted to identify and prioritise these innovation areas.

The results of our analysis are shown below.

Innovation priorities have been assessed using the following criteria:

- Value in terms of innovation benefit – this is a purely quantitative evaluation derived from modelling potential cost reductions across the technology sub-areas and scaling them up to the expected deployment scenario, thus resulting in a monetary figure.
- Value in terms of business creation – this is a quantitative evaluation based on a series of factors:
  - The expected size of the global market, modelled after deployment scenarios from the IEA.
  - The amount of that market which we expect to be tradable, e.g. accessible to UK exports, by sub-area. This is derived from our analysis assessing tradable shares of global markets across industries that are similar to nuclear, such as aerospace.
  - The amount of the tradable market that we expect the UK to be able to access, again based on an assessment of UK global market share in comparable industries and of UK competitive advantage in specific nuclear technologies.
  - Displacement effect, estimated at 50% (see description on page 15).
  - Gross Value Added, again derived from an analysis of comparable industries.
- Extent of market failure – this is a qualitative estimate based on workshops and consultation with nuclear industry experts.
- Opportunity to rely on others to innovate.
- Broader strategic value to the UK – this is a qualitative estimate based on a series of factors, and derived from extensive consultation with nuclear industry experts. It includes considerations on what the UK needs to remain in the first tier of global nuclear nations and maintain engagement with international nuclear forums such as the Generation IV forum; the needs of the current UK nuclear deployment and expected future liabilities; and the needs of the UK nuclear industry in terms of supply chain development and skill retention.

Our analysis is based on our assessment of the current state of the nuclear sector.

Chart 10 - Benefit of UK public sector activity/investment by sub-area and technology type

Sub-area	Potential innovation benefit to 2050 £bn[1]			Value in business creation	Extent of market failure	Opportunity to rely on others	Strategic Importance	Benefit of UK public sector activity/investment (without considering costs)
	Gen III	Gen IV	Total	£bn[2]				
Mining, Processing, Enriching, Fabricating	0.3 (0.1 - 0.4)	~0.3 (0-2.6)	~0.5 (0.1-2.8)	~0.1 (0-0.2)	Significant	Yes – in the short term.	High	**Medium** – Direct innovation benefit is limited and the UK can also rely to a large extent on others – but expertise has strategic importance especially if there is interest for rejoining the Gen IV international development effort. Additionally, there is high potential value in retaining the UK's fuel cycle capabilities.
Capex – Components	~1 (0.5-1.1)	~0.2 (0-2.2)	~1.2 (0.4-3.3)	~0.4 (0.1-0.8)	Significant	Yes	Low	**Medium –** High level of potential innovation benefit but this is an area where the UK can rely on others – European utilities and China in particular. However, there are niche areas where the UK has strong expertise, such as behavior of materials in high temperature settings.
Capex – Construction material	~0.6 (0.3-0.7)	~0 (0-0.2)	~0.6 (0.3-0.8)	~0 (0-0.06)	Moderate	Yes.	Low	**Low** - Opportunities to innovate are limited because of the nature of the materials and the constraints of safety cases – and improvements are focused on quality assurance rather than technological innovation.
Capex – Construction/installation/Commissioning	~2 (0.9-2.2)	~0.3 (0-2.3)	~2.1 (0.9-3.5)	~0.6 (0.1-1.2)	Significant	Partially – the UK retains a major stake in the success of the new build	High	**High** – Essential for delivery of new build and for UK companies to acquire expertise to operate on global markets. UK can become a key partner of global nuclear vendors. Additionally, skills developed in this area will remain in the UK. There is potential for specific R&D programs for example to develop modular construction capabilities.
O&M	~0.5 (0.2-0.5)	0.1 (0-1.1)	~0.8 (0.4-2.1)	~3.0 (0.6-5.7)	Moderate.	Partially, but negative impact on UK skills	Medium	**Medium –** Reasonable innovation benefit and business value creation, and although many innovation opportunities exist, private sector is reasonably well incentivised to innovate to cut operating cost.
Decommissioning	~0.1 (0-0.1)	~0 (0-0.1)	~0.3 (0.1-0.6)	~2.2 (0.5-4)	Critical	No	Medium	**High** – The UK specific legacy requirement means reliance on others in the short-medium term at least is unlikely. Discounting means there is scarce incentive to invest and thus a major market failure. Finally there is a large opportunity for global exports.
Waste Management, Reprocessing, Storage	~0.1 (0-0.1)	~0.1 (0-1)	~0.2 (0.2-1.1)	~0.5 (0.1-0.9)	Critical	No.	High	**Medium - High.** Clear requirement for the UK but not certain that innovation here will be applicable to a broader market – national waste management issues may be very specific.
TOTAL	**~4.7 (2.1-5.3)**	**~1 (0-9.3)**	**~5.7 (2-14.5)**	**~7.2 (1.5-13)**				***1 Medium ll value to 2050 (Low-High)*** ***2 After displacement effects.***

Source: Consultation, Carbon Trust analysis

Potential priorities for public sector innovation support

In the sections above, we identified the generic innovation needs in nuclear fission and the market barriers hindering these innovations. This analysis points to a number of priorities for public sector innovation support:

- **Front End Fuel Cycle: medium priority** – a potential driver for investment in this area could be renewed involvement in international Gen IV programmes via the establishment of innovation programmes that contribute to global research on advanced reactors. This need not be the development of a novel fuel; it could be a materials programme looking at, for example, the development of different fuel cladding materials. This will have utility because such programmes allow the UK to access other Gen IV research, have obvious applications to both Gen III and Gen IV technologies, and may also be useful in terms of the fusion programme. However a more in-depth cost/benefit analysis is needed before a clear choice can be made regarding the value of Gen IV research to the UK. Furthermore, the UK currently has extensive expertise in enrichment (Urenco), uranium conversion and fuel fabrication (Springfields). All these capabilities are at risk of being lost in the coming years – for example the facility at Springfields, owned by Westinghouse, is scheduled for closure in 2018, with no planned replacement. There is high potential value in retaining these capabilities.

- **Components: medium priority** – There is a case for the continued development of niche manufacturing processes that can allow UK firms to gain access to the new build supply chain and – subsequently – develop innovative and widely applicable techniques (for example joining techniques and welding) that can be sold into a global market. There is a wealth of expertise from the AGR fleet and Sellafield that are fairly unique to the UK and have the potential to be both transferable to other nuclear designs and exportable on the global market. However these are all relatively small niches and are not as essential to new nuclear in the UK as other areas.

- **Construction, Installation and Commissioning: high priority** - this is one of the most important areas for successful delivery of the new build programme. If the UK is able to deliver the first new build power plants on time and to budget it will have effectively demonstrated its nuclear expertise and will have improved its chances of being a global exporter of nuclear technology. UK companies have the *capacity* to deliver a substantial portion of the supply chain, but need to prove their *capability* to satisfy the quality and time requirements of nuclear, and their competitiveness against international companies. The new build also represents an opportunity for creating strategic partnerships with global nuclear vendors, which could function as an effective vehicle for accessing the international market. In addition to supporting innovation in this area the public sector could help provide technical assistance and coordination to help align basic RD&D with the private sector and international markets, and give companies the certainty they need to invest in capacity and capability improvements.

- **O&M: medium priority** – private companies are generally well incentivised to reduce cost; the public sector should take more of a coordination role, making sure the proper incentives are in place and barriers are removed for the relevant actors to deliver cost reductions through learning by doing and RD&D, while also creating opportunities for exporting UK know-how to emerging nuclear nations. There should therefore be two approaches in this area – first ensure that the market mechanisms agreed for the new build programme incentivise operating cost reduction, and second; focus on those programmes which will be in demand internationally as well as having a potential cost reducing impact in the UK.

- **Decommissioning: high priority** – this is a high priority area for public intervention as the private sector has relatively little incentive to act on its own, due to the extremely long time horizon and the effect of discounting. In addition to innovation programmes the government could also help sell nuclear decommissioning expertise abroad, as this is currently outside the remit of the Nuclear Decommissioning Authority. Another issue is the focus on single projects, and decommissioning plants at the lowest possible cost, which is not conducive to broader investments into innovation that could help improve decommissioning capabilities in the future but present an element of risk and costs increases in the near term.

- **Waste Management, reprocessing and storage: medium-high priority** – as with decommissioning, there is also a strong market failure due to the long time horizon. In addition the UK already has a substantial waste stockpile, especially plutonium, which represents a considerable liability, making cost reductions through innovation a strong priority. The UK also has existing expertise, chiefly in MOX fuel reprocessing (which links with the front end of the fuel cycle) that could be retained and expanded, providing both a solution to the waste issue and a potential avenue for export. The latter however is dependent on the fuel cycle choices taken in the international arena.

- **Knowledge sharing and cooperation** - for example measurement and sharing of data and the funding of incentives to share and/or coordinate. This is mainly about enabling processes rather than technological innovation but the main interventions that would help here are a shared platform for the exchange of research and a clear set of RD&D priorities which the nuclear community could use to prioritise and design innovation programmes. This would include the provision of active facilities such as a National Nuclear User Facility providing a venue where industry and academia could carry out R&D.

- **Cross-cutting technologies** – some technologies might deliver benefits across several component areas, or are needed as enablers of innovation across the whole nuclear spectrum. These include advanced materials research, advanced simulation tools, modelling for resistance to radiative and temperature stress and for life assessment, and condition monitoring. On the process side the public sector should make sure that regulatory processes are able to quickly integrate new technologies into the safety assessment procedures, so that the regulator does not hamper the rapid adoption of innovation. Finally, there is a need for improved communication with the public to allay fears of nuclear technology and manage the perception of risk.

Existing innovation support

The UK is supporting some of the areas highlighted above. This is summarised in Chart 11.

Chart 11 - Summary of existing UK public sector activity/investments

Market pull (demand side)	**Technology push** (supply side)	**Enablers**
National Policy Statements – assessment of potential new build sites **Office for Nuclear Development** – focuses on removing potential barriers to investment, and signals to the industry the intention of government to push forward on nuclear new build **Office for Nuclear Regulation** – regulatory reform and streamlining on safety and O&M **Manufacturing Advisory Service** – supports British based suppliers for the civil nuclear industry **Nuclear forums** – run by DECC, they help ensure maximum stakeholder involvement and knowledge sharing across the nuclear sector *Indirect support from the proposed Electricity Market Reform* **Carbon Floor Price** – could potentially improve nuclear economics against fossil fuels if the price is sufficiently high to act as a tax on carbon tax **Contracts for Difference** – a type of Feed in Tariff to support low carbon generation including nuclear	**R&D Spending** **Nuclear Decommissioning Authority** **Directly c.£10m per year –** R&D on waste management and decommissioning **And via the Site Licencing Companies a further c.£110m per year.** This spending is accounted for primarily by Sellafield Ltd and is spent on a range of discrete decommissioning projects. **R&D grants** **Research Councils (£7.5m for fission, £3.7m for waste and decommissioning, and £34m for fusion)** – supports R&D on Gen III and IV, and waste and decommissioning **NDA/TSB/DECC/EPSRC** R&D call – £15m	**National Nuclear Laboratory (£1m from NDA) –** R&D on fuel cycle, focused on waste management **Culham Centre for Fusion Energy –** fusion research with crossover to fission **Nuclear Advanced Manufacturing Research Centre (£25m) –** Applied near market research **Dalton Nuclear Institute** - research facilities focusing on radiochemistry materials performance, modelling and simulation and nuclear physics **National Skills Academy for Nuclear** – works with existing training providers to develop training and qualifications and maintain and increase the UK nuclear skills base **Universities**

Conclusion - Designing innovation programmes

Chart 12 outlines how potential innovation priorities align against each technology sub-area, the indicative scale of public funding for each, the current activities/investment in each area and potential, future activities.

To realise the full benefit from innovation to 2050 will require on-going support to existing areas, as well as adding a prioritised set of new programmes.

Supporting *all* the prioritised innovations would require a significant increase in the current UK funding of RD&D in nuclear fission and is therefore unlikely. However, targeted investment is justified in several areas, especially:

- In construction, for example by supporting the development of modular construction techniques
- In decommissioning, to address the critical market failures and specific UK needs in the area
- In the front end of the fuel cycle, if the decision is made to re-engage with the international Gen IV forum

Whatever the specifics of the costs, the public sector investment required however is likely to be a small fraction of the value that nuclear fission innovation could bring to the UK economy, through innovation benefit and value add creation to UK GDP.

Irrespective of these benefits, there is also a case for continued nuclear RD&D to preserve the skills that allow the UK to buy and operate nuclear technology safely. A key aspect of this is the ability to regulate – there is value in preserving the skills needed to do this well.

As well as supporting innovation in each of the individual areas above, public intervention can help collaboration and integration across them. It can also facilitate the commercialisation of innovative concepts created by research institutes and small companies through entrepreneurial support programmes (generally across many technology areas). Finally, it can join up innovation programmes with supply chain and infrastructure development where there are co-location benefits. The Nuclear Advanced Manufacturing Centre is an excellent example of this.

There are a number of discrete opportunities for the UK that we have not covered in our analysis – either because they do not fit into the framework or because they lie outside the traditional scope of technology led innovation. That said, they represent important opportunities for the UK and are worthy of further investigation. They are shown in the call out box below.

Discrete opportunities for the UK

Small and Modular Reactors

Small Modular Reactors (SMRs) represent a discrete area of nuclear technology that could provide significant business opportunities for the UK, but was not considered in scope for the present analysis. SMRs are expected to be cheaper, easier and quicker to build and thus to finance. Larger power plants could be assembled by adding up several SMRs as demand increased or finance became available.

The UK could base an SMR development programme off the back of its nuclear submarine expertise; UK manufacturers would be able to assemble most of the components for an SMR, due to their smaller size compared to a full scale reactor. As such, the accessible share of the global market in SMRs components would be potentially larger than the assumption for full scale reactors in this study.

SMRs are being currently investigated in a number of countries. There is relevant activity in the US, China, Russia, South Korea, Japan and India. The US for example recently announced funding for the Babcock & Wilcox' SMR design. Research is divided between light water reactors, high-temperature gas cooled reactors, fast neutron reactors and molten salt reactors, or a mix of Gen III and Gen IV technology.

This technology area holds great potential and we recommend that the relevant stakeholders undertake a more in-depth analysis of its benefits and costs to the UK and the British nuclear industry.

Sharing the UK's approach to regulation

Additionally, UK expertise in regulation is globally renowned, and there is no doubt that consulting on regulatory and safety frameworks is a potentially important area of business for the UK in the next few decades. Innovation programmes in nuclear fission support the preservation of this capability, albeit sometimes indirectly.

Helping nuclear 'first timers'

There are a number of countries likely to be developing nuclear programmes from a very low base in the next few decades. Saudi Arabia is an obvious example, and there is a potential opportunity for the UK to offer a coherent package of skills expertise and services, including nuclear safety regulation that might help such a nation. The world class reputation required to access this sort of opportunity is at least partly underpinned by a well-resourced innovation programme – so innovation in the areas described in this report might be important in the longer term to giving the UK access to this sort of opportunity.

Chart 12 - Potential nuclear fission innovation priorities and support. Programmes that would focus on support to the development of Gen IV technologies are marked with an asterisk (*).

Sub area	Potential innovation priorities	Estimated cost/time[1]	Current public sector activities/investments	Future example potential activities
Mining, Processing, Enriching, Fabricating	• Development of advanced fuels for both Gen III and Gen IV reactor technologies. • Retention and development of enriching facilities. • Support the development of advanced reactors utilising exotic fuel cycles. • Better testing and qualification of material behaviour in very highly irradiated environments.	10s to 100s of m	• NNL – Fuel and Reactors programme (fuel design thru irradiation) • Dalton – Modelling and simulation • C-NET. Gen III+ and advanced reactors	• Re-join the international advanced reactor programme via the development of, for example, a materials programme that will have utility for both Gen III and Gen IV technologies. Support Jules Horowitz etc.* • Advanced fuel manufacturing processes to improve efficiency and fuel performance
Capex – Components	• Materials programmes that support both fission and fusion development. • Innovation to support UK access to the new build supply chain. • Development of new techniques that may have global application (welding etc)	10s to 100s of m	• Dalton – Materials. • NAMRC – Welding, Non Destructive Evaluation .	• Specific infrastructure and testing facilities – Irradiation facility. • Modelling of materials behaviour and qualification of materials at very high temperature and dose for fission and fusion programmes.* • Advanced manufacturing techniques and development of niche capability in areas such as welding and other joining techniques.
Capex – Construction/installation/ Commissioning	• Development of techniques that will support the streamlining of processes in the construction of reactors leading to cost reduction and the avoidance of overruns. • Developing approaches that design in iterative lifetime extensions.	10s of m	• NAMRC - Provides training and skill support for the nuclear supply chain	• Streamlined construction techniques and better qualification of, for example, large concrete pouring. • Support to the use of modular construction techniques. • Virtual Reality, modelling and 3D visualisation to support construction and installation . • Structural Integrity. Programmes to analyse the condition of components and sub components in nuclear reactors.
O&M	• Development of less disruptive techniques that minimise the impact of O&M leading to higher utilisation. • Better understanding of risk which is used to underpin a more rigorous and less disruptive O&M regime.	10s of m	• Dalton C-NET (Centre for Nuclear Energy Technology) – Instrumentation.	• Advanced modelling techniques and data mining to better understand risk. • NDE programmes to reduce inspection times and associated outages. • Condition monitoring. • Digital C2 systems. And increased automation.
Decommissioning	• The development of technology and techniques that reduce the cost of decommissioning and the human involvement on the process, minimising the risk and waste profiles of the decommissioning process. • Better qualification of contaminated materials and much more specific treatment of waste to reduce volumes of ILW in particular.	10s of m	• NDA. Materials Characterisation, Plant Termination, Site Restoration programmes.	• Waste treatment –Thermal technologies to speed up waste decomposition and reduce overall waste volume. • Better classification and characterisation of waste - for example, depth of contamination in structures. • Land quality work. Dealing with the volumes of contaminated land or water. • Autonomous processes and robotics.
Waste Management, Reprocessing, Storage	• Development of technologies that underpin a UK waste management programme and that have potential application globally.	10s to 100s of m	• NNL – Waste and decommissioning, waste immobilising, Spent Fuel and nuclear materials. • NDA – Waste processing and Management of Strategic Nuclear materials.	• Test facility for irradiated waste fuel • Programmes to design and model the behaviour of different fuels and to develop technologies that could use existing UK stockpiles.* • Linked to Fuel Cycle programmes, the development of longer term waste management approaches including Fuel Recycling (Plutonium as thermal MOX) • Encasement materials for GDF.

Source: Expert interviews, Carbon Trust analysis. [1]Provides an order of magnitude perspective on the scale of public funding (existing and future) potentially required over the next 5 to 10 years to address each need.