Technology Innovation Needs Assessment (TINA)

Nuclear Fission
Summary Report

February 2016

Background to Technology Innovation Needs Assessments (TINA)

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 funding and delivery bodies in the area of 'low carbon innovation'. Its core members (at the time of this document's completion) are the Department of Energy and Climate Change (DECC), the Department of Business, Innovation and Skills (BIS), Scottish Enterprise, the Scottish Government, the Engineering and Physical Sciences Research Council (EPSRC), the Energy Technologies Institute (ETI) and Innovate UK.

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.

This document summarises the Nuclear Fission TINA analysis. 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. Although Scottish Enterprise and the Scottish Government are part of the LCICG they have not been part of the development of this TINA due to the Scottish Government's policy position.

Disclaimer

The TINAs provide an independent analysis of innovation needs and a comparison between technologies. The TINAs' scenarios and associated values provide a framework to inform that analysis and those comparisons. The values are not predictions or targets and are not intended to describe or replace the published policies of any LCICG members. Any statements in the TINA do not necessarily represent the policies of LCICG members (or the UK Government).

The analysis for this report was carried out during 2015 and does not reflect publications, reviews or policy developments since November 2015.

Core members of the Low Carbon Innovation and Coordination Group (LCICG):

Department
for Business
Innovation & Skills

Department
of Energy &
Climate Change

energy
technologies
institute

EPSRC
Engineering and Physical Sciences
Research Council

Innovate UK
Technology Strategy Board

This analysis was prepared for the LCICG by:

CARBON
TRUST

Key findings

Nuclear fission can play a key part in the energy system of the UK having the potential to help the UK replace aging power plants, reduce reliance on gas, and meet greenhouse gas (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 £3.7-13.5 billion (bn)[1] to 2050. Innovation can also help create UK and export based business opportunities that could contribute an estimated cumulative £18.4-33.9bn[2] in discounted Gross Value Added (GVA) by 2050 and support c.50-120k direct jobs in 2050.

Potential role in the UK's energy system	• The UK was a pioneer of global commercial nuclear deployment and still retains world leading expertise in several areas; however no new nuclear has been deployed in Britain since 1995, putting UK capabilities at risk due to retirement and aging of the workforce. • Nuclear could provide between 21% and 65% of the UK's power demands by 2050, up from 18% in 2015, with a central figure of 51% in a decarbonisation scenario assuming 80% GHG emission reductions. • By 2050 the UK could deploy between 16 and 50 gigawatts (GW) of nuclear, of which 16-30GW could be Gen III reactors, 0-10GW Gen IV reactors, and 0-10GW Small Modular Reactors (SMRs), the latter two depending on sufficient investments in innovation and development by the UK, and possibly the establishment of strategic partnerships with other countries (such as France or the United States). • While currently identified sites for large reactors in England and Wales preclude deployment above 40GW, SMRs could potentially be situated in additional sites yet to be identified, pushing the total deployment of nuclear fission in the UK to 50GW.
Cutting costs by innovating	• Current central estimates for Gen III reactor cost are £91/megawatt hour (MWh), based on a First Of A Kind (FOAK) European Pressurised Reactor (EPR). Cost estimates for Gen IV are much more indicative due to the immaturity of the technology and are assumed to be £106/MWh for a FOAK Sodium Cooled Fast Reactor (SFR). SMRs have the potential to be cheaper at FOAK £84/MWh for a light water reactor (LWR), however no commercial SMR prototype exists yet. • Innovation (learning-by-Research & Development) could reduce the existing generation costs by ~<1% (0.1% - 0.3%)[3] by 2025 and ~<1%% (0.5% - 0.7%) by 2050; Gen III costs could be reduced by ~2% (1% - 2%) by 2025 and ~10% (9%-10%) by 2050, Gen IV costs by ~11% (6% - 11%) by 2025 and ~25% (20% - 25%) by 2050, and SMRs by ~3% (1% - 3%) by 2025 and ~15% (14% - 15%) by 2050. • The total cost reduction by 2050 including learning-by-doing could be ~4% (3% - 4%) for existing generation, ~25% (20% -25%) for Gen III, ~29% (25% - 29%) for Gen IV and ~31% (25% - 31%) for SMRs. • The discounted cumulative benefit from reduced cost of deployment for achieving the full R&D cost reduction would be £99m for existing generation, £5.1bn (3.6-5.7) for Gen III, £4.3bn (0-5.3) for Gen IV and £1.8bn (0-2.3) for SMRs.
Green growth opportunity	• Cumulative global discounted turnover for the nuclear sector to 2050 is expected to be £5.9 trillion (5.2-7.6) of which the UK is expected to represent 3.7% (2.9%-4.2%), assuming a deployment of 40GW. • UK potential GVA based on the above global turnover cumulative discounted value to 2050 could be £25.6bn (18.4-33.9).

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[1] Cumulative present discounted values (2015-2050).

[2] Ibid.

[3] All cost reduction scenarios have low and high estimates. In accordance with all other TINAs the "high" cost reduction scenario has been used to estimate cost reduction benefits across the whole study.

The case for UK public sector intervention	• The UK will need strong action by the public sector if it wants to retain and expand its nuclear expertise and regain a seat at the global nuclear table through strategic alliances with other leading nuclear nations. In particular, public investment in innovation is essential to enable the UK to acquire the necessary capabilities to deploy Gen IV and SMRs in the medium term. – Critical market failures affect the back end of the fuel cycle, decommissioning and waste management, due to the very long (60 years+) time horizons involved and lack of incentives for private companies to invest now. Significant failures also affect the front end of the fuel cycle, due to uncertainty over future fuel cycles and the risks connected to proliferation, and the manufacturing of components, due to the high barriers to entry, the lack of competition and the stringency of regulatory requirements. – While the UK could conceivably import a large share of the expertise and technology it needs to develop its new build. Only a renewed domestic R&D push could enable it to develop the capabilities needed to manage the nuclear new build safely and efficiently, while acting as an “expert customer” of foreign technology.
Potential priorities to deliver the greatest benefit to the UK	• Different reactor types are likely to have different needs and priorities for R&D. However, some areas of overlap exist and we have combined different priorities by sub-area for all four reactor types to produce a unitary ranking. • Innovation areas offering the biggest benefit from UK public sector support are: – Components, due to the high innovation benefit and the existence of world-leading UK expertise in relevant niche areas such as behaviour of materials in high temperature settings. – Decommissioning, due to critical market failures and its importance in reducing risk perceptions associated with nuclear. – The front and back end of the Fuel Cycle (Processing, Enriching, Fabricating and Reprocessing, Waste Management) are also very important, the former due to their crucial role in enabling development of Gen IV reactor technology, the risk of losing key UK capabilities, and the potential for them to act as the starting point for the establishment of strategic partnerships with global nuclear vendors. • In the FY 2014/15, LCICG members allocated £117million (m) to nuclear R&D, of which £82m went to research into decommissioning at Sellafield, which is considered out of the scope of this report. • The indicative funding requirements for the identified priority areas are: – In Components, funding in the tens to hundreds of millions of pounds would be needed to develop specific infrastructure and testing facilities, advanced joining techniques, new temperature and radiation resistant materials, and other techniques for nuclear component manufacture. – In Decommissioning, funding in the tens of millions would be needed to develop autonomous robotics and autonomous processes, better thermal technologies to speed up waste decomposition and reduce overall volume, better classification and characterisation of waste, and improved waste packaging and storage. – In the Processing, Fabricating and Enriching, funding in the tens to hundreds of millions would be needed to sustain the development of advanced fuel manufacture for Gen III and Gen IV (such as Accident Tolerant Fuels and Mixed Oxide fuel pellets - MOX), improve capabilities in testing and qualification of material behaviour in very highly irradiated environments, and provide the necessary skill base to re-join international initiatives on advanced reactors. – In Reprocessing and Waste Management funding in the tens of millions would be needed to develop fuel recycling capabilities, immobilisation technologies, and other packing and storing innovations.

Table 1: Nuclear Fission TINA summary

Sub-area	Variant	Value in meeting emissions targets at low cost £bn			Value in business creation £bn						Direct jobs supported in 2025/2050 (central, rounded)		Key needs for UK public sector innovation activity/investment
					Domestic			International					
		Low	Central	High	Low	Central	High	Low	Central	High	2025	2050	
Mining, Processing, Enriching, Fabricating	Existing generation	0.002	0.002	0.002	0.17	0.2	0.2	-	-	-	300	100	• Advanced Fuel manufacture for Gen III and Gen IV including accident and temperature resistant fuels and improved fuel cladding • Exotic fuel cycles • Better testing and qualification of material behaviour in very highly irradiated environments
	Gen III	0.3	0.4	0.4	0.31	0.4	0.5	0.3	0.4	0.5	1,200	2,000	
	Gen IV	-	0.6	0.7	-	0.1	0.1	0.0	0.1	0.1	-	900	
	SMRs	-	0.1	0.1	-	0.1	0.1	0.1	0.1	0.1	-	600	
Capital Expenditure (CAPEX) - Components	Existing generation	-	-	-	-	-	-	-	-	-	-	-	• Materials degradation and resistance to thermal, irradiative and other stress • Ambient pressure cooling • Modelling of materials behaviour at high temperatures • Modularisation • Welding and other joining techniques and surface technology - oxide-dispersion strengthened (ODS) steels
	Gen III	1.2	1.8	2.0	1	2.1	2.4	1.9	2.2	3.1	9,000	14,800	
	Gen IV	-	2.0	2.5	-	0.4	0.5	0.3	0.5	0.8	-	8,000	
	SMRs	-	0.6	0.7	-	0.2	0.3	0.7	0.8	1.5	400	6,500	
CAPEX - Construction Material	Existing generation	-	-	-	-	-	-	-	-	-	-	-	• Waste minimisation. • Reduction of cement content in construction operations • Maximise use of materials such as GGBS (Ground granulated blast-furnace slag) • Maximise offsite construction
	Gen III	0.3	0.5	0.6	2	2.7	3.1	-	-	-	4,200	8,300	
	Gen IV	-	0.3	0.4	-	0.3	0.4	-	-	-	-	2,600	

	SMRs	-	0.2	0.2	-	0.3	0.4	-	-	-	100	1,800	• Onsite verification • Virtual design and advanced simulation • Radio-scanning
CAPEX – Construction/installation and Commissioning	Existing generation	-	-	-	-	-	-	-	-	-	-	-	• NDE/NDT (Non Destructive Examination/Testing) Condition Monitoring • Virtual Reality simulation tools. • Advanced Modelling • Modular construction techniques
	Gen III	1.2	1.8	2.0	4	6.1	7.1	1.8	2.1	2.9	15,100	27,400	
	Gen IV	-	0.6	0.7	-	0.4	0.5	0.1	0.1	0.2	-	4,400	
	SMRs	-	0.8	1.0	-	0.7	0.8	0.3	0.3	0.6	400	6,400	
Operations and maintenance	Existing generation	0.1	0.1	0.1	0.91			0.9	0.9	-	-	-	• Improvement in inspection techniques, monitoring, condition monitoring of new materials and preventative maintenance approaches • Advanced modelling techniques and data mining • Digital Command & Control systems
	Gen III	0.4	0.6	0.6	1.62	2.3	2.7	0.4	0.5	0.7	1,200	2,200	
	Gen IV	-	0.5	0.7	-	0.3	0.3	0.0	0.1	0.1	-	600	
	SMRs	-	0.2	0.2	-	0.2	0.3	0.0	0.0	0.1	-	400	
Decommissioning	Existing generation	0.004	0.004	0.004	0.14	0.1	0.1	0.5	0.5	0.5	1,000	200	• Autonomous robotics and autonomous processes • Thermal technologies to speed up waste decomposition and reduce overall waste volume • Better classification and characterisation of waste such as depth of contamination in structures • Waste packaging and storage
	Gen III	0.0	0.1	0.1	0.18	0.3	0.3	0.4	0.4	0.6	1,000	1,600	
	Gen IV	-	0.2	0.2	-	0.1	0.1	0.1	0.1	0.2	-	800	
	SMRs	-	0.0	0.0	-	0.0	0.0	0.0	0.0	0.1	-	300	
Waste Management, Reprocessing, Storage	Existing generation	0.002	0.002	0.002	0.07	0.1	0.1	0.2	0.2	0.2	1,400	900	• Advanced Qualification of wasteforms

	Gen III	0.0	0.0	0.1	0.07	0.1	0.1	0.1	0.2	0.2	1,000	1,600	• Packing Density • Storage Fluids • Fuel recycling (MOX, aqueous recycling, pyroprocessing) • Fuel Cycle assessment
	Gen IV	-	0.1	0.1	-	0.0	0.0	0.0	0.0	0.1	-	800	
	SMRs	-	0.0	0.0	-	0.0	0.0	0.0	0.0	0.0	-	300	
Total	**Existing generation**	0.1	0.1	0.1	1.3	1.3	1.3	0.7	0.7	0.7	3,000	1,300	
	Gen III	3.6	5.1	5.7	9.9	13.9	16.3	4.9	5.8	8.1	32,600	57,900	
	Gen IV	-	4.3	5.3	-	1.6	1.9	0.5	0.8	1.5	-	18,200	
	SMRs	-	1.9	2.3	-	1.5	1.8	1.1	1.3	2.3	1,000	16,300	
	Total	3.7	11.4	13.5	11.2	18.3	21.3	7.3	8.6	12.6	36,700	93,600	

Benefit of UK public sector activity/investment[4]	High
	Medium
	Low

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[4] Also taking into account the extent of market failure and opportunity to rely on another country. Does not consider costs of the innovation support.

Introduction

As of 2013 there were 441 operating nuclear reactors in the world (including the 48 Japanese reactors which have been in shutdown since 2011), with a net electrical capacity of 377 GW[5]. The UK contributed 9.2 GW, accounting for 19% of UK electrical generation in 2014. Most of this capacity will be decommissioned in the 2020s and early 2030s, unless the licenses of currently operating plants are extended.

While wind has recently overtaken nuclear in total installed capacity, its share of total electricity generation was around 7%, making nuclear the largest low carbon source of electricity in the UK[6].

In addition to its existing capacity, the UK also has 16 reactors and one nuclear reprocessing site (Sellafield) currently undergoing decommissioning, under the supervision of the Nuclear Decommissioning Authority (NDA). NDA expects the total discounted cost of decommissioning (excluding operating reactors) to amount to £65 billion, discounted over the next 120 years. The undiscounted figures range from £90 billion to £220 billion[7]. Considerable opportunities exist for reducing these costs through innovation, and NDA allocates an R&D budget which has already successfully reduced the cost of decommissioning for the reactor sites.

Nonetheless, these costs are currently not included in the Nuclear Fission TINA, because for consistency with the TINA methodology we have only focused on capacity currently generating power and future deployment. It can be expected that investment in decommissioning and waste management R&D could reduce the cost of decommissioning currently underway and that of the new build, bringing substantial benefits to the UK which are not quantified in this study.

Nuclear technology is best understood in terms of generations of reactors. The UK's current fleet of nuclear reactors is mostly Gen II. The new build programme will use Gen III(+) technology; the most likely designs are Areva's European Pressurized Reactor (EPR), Hitachi's Advanced Boiling Water Reactor (ABWR), and Westinghouse's AP1000, 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 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. The UK also has a Gen II Pressurized Water Reactor (PWR) operating potentially to 2055 at Sizewell B.

Generation III – (Gen III) These reactors are advanced versions of light water 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 potential benefits of Gen IV reactors are usually listed 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.

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[5] IAEA Power Reactor Information System, 2015.

[6] DECC, UK Historical Electricity Data 1920 to 2013.

[7] Nuclear Decommissioning Authority, Explaining the Nuclear Provision, February 2015.

- Broader system benefits such as the ability to produce baseload heat for industrial applications or the production of hydrogen.
- Some of the fuel cycles that advanced technologies might use are inherently more proliferation resistant.

A separate type of reactor are **Small Modular Reactors**, which refers to reactors with capacity of up to 300MW built using modular techniques. SMRs could utilise Gen III or Gen IV technology, but the designs closest to commercialisation are Gen III.

In this report, "**existing generation**" will refer to Gen II reactors currently producing electricity in the UK. Gen III will refer to the upcoming new build, with modelling based on cost-data for an **EPR**. **Gen IV** refers to advanced reactors that the UK might choose to deploy following and in parallel to the Gen III new build, with modelling based on the **SFR** design, the closest among the Gen IV designs to commercial maturity[8]. Finally **SMRs** will also be considered, looking at **light water** (Gen III) technology.

In the case of nuclear, innovation is crucial not only to reduce the present and future costs of the Gen III reactors which are expected to be deployed in the short to medium term, but also to allow the development of Gen IV and SMRs. Without sufficient R&D investment to retain and expand UK expertise in key fuel cycle areas, it is unlikely that the country will be able to deploy and manage advanced reactors and SMRs effectively, or enter into any strategic partnerships with other leading nuclear nations to develop joint IP and new technologies.

In particular, development and deployment of Gen IV in the UK is contingent on: 1) considerable state support (in the hundreds of millions of £ very likely), particularly in the form of early R&D and key contributions that would make the UK a valuable partner for a reactor vendor; 2) Gen IV deployment being driven by the choice of a closed fuel cycle, after which decision Gen IV will be deployed despite being more expensive[9] than Gen III(due to its other benefits on fuel use and waste management).

However, other factors beyond mere R&D should be considered when analysing nuclear deployment and potential cost reductions.

- **Cost increases** – nuclear cost reductions have always been contentious, with some studies indicating possible "negative learning-by-doing", resulting in cost increases rather than decreases with additional deployment[10]. This can be partially explained by the increased safety requirements of new reactor models, and can hopefully be ameliorated by advances in passive safety features, thermal efficiency, modularity, and other characteristics of both Gen III+ and potentially Gen IV reactors.
- **Public acceptance** – nuclear power carries a strong stigma in the public mind due to its association with high profile disasters such as Fukushima. Nonetheless nuclear retains majority support in the UK. Effective public relations campaigns stressing the benefits to energy security and GHG emission reductions are very important to ensure that this issue is addressed effectively.
- **International partnerships** – the size and scope of nuclear technology makes it hard for any single nation to pursue entirely on its own without a major commitment by a national government to support it. The UK currently enjoys a position of strong skills and knowledge in key areas that could provide an effective base from which to strike an alliance with another leading nuclear nation to develop jointly new reactor technologies, particularly Gen IV and SMRs. However the window of opportunity is closing rapidly as UK expertise declines due to retirements and

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[8] The Generation IV Forum broadly classifies advanced reactors under six main designs: Sodium Cooled Fast Reactors (SFR), Gas Cooled Fast Reactors (GFRs), Very High Temperature Reactors (VHTR), Super Critical Water Reactors (SCR), Molten Salt Reactors (MSR) and Lead Cooled Fast Reactors (LFR).

[9] Part of the higher cost of Gen IV designs is due to the necessity of building a next generation fuel recycle and recycled fuel manufacturing plant. This cost has been included in the estimates for Gen IV presented here.

[10] Arnulf Grubler, The costs of the French nuclear scale-up: A case of negative learning by doing. Original Research Article, Energy Policy, Volume 38, Issue 9, September 2010, Pages 5174-5188 .

ageing of the workforce and as competitors move forward with their own designs, particularly in the SMR arena. This means a policy decision on whether to pursue advanced reactor technology will need to be taken soon, or at least substantial investment should be made in maintaining existing skills so that a decision can be made at a later stage.

Deployment scenarios

We have created three deployment scenarios based on Energy System Modelling Environment (ESME)[11] modelling, UK stated policy, and literature research (these scenarios aim to capture the full range of feasible deployment scenarios, and are neither forecasts for the UK nor targets for policy makers[12]). Note that they include new deployment only. Existing generation is expected to account for 4.7GW in 2025 and 1.2 GW in 2050[13]:

- **Low scenario** – (8GW 2025, 18GW 2050) this is the basic "replacement plus" scenario, in which existing reactors are replaced with slightly larger Gen III reactors. There is no deployment of Gen IV or SMRs.
- **Central scenario** (10GW by 2025, 40GW by 2050) this is the central scenario being used in this study. It assumes that the full 16GW new build is followed by continued expansion including Gen IV and SMRs.
- **High scenario** (12GW by 2025, 50GW by 2050) It is assumed that the full 40GW of available sites in England & Wales is taken up by large reactors, with a further 10GW of SMRs being deployed in different sites (yet to be identified).

The scenarios have been derived using a combination of energy system modelling with ESME and literature review. ESME determines how much capacity is required across the generation mix to meet energy demand and emissions reduction targets at lowest cost based on the constraints outlined for each scenario above. Technology cost profiles are based on Carbon Trust analysis.

To establish the share of Gen IV reactors we looked at the existing literature. A 2012 study by ETI projected a potential 8GW of Gen IV fast reactors being deployed in the UK by 2050 within a broader 40GW scenario[14]. Further studies indicate that to establish a closed fuel cycle a ratio of at least 25% of Gen IV fast reactor generation to thermal reactor generation should be established[15]. As such, we have modelled 8GW of Gen IV in the medium scenario and 10GW in the high scenario.

On SMRs, we have taken similar figures to those published by the SMR Feasibility Report (NNL, November 2014), estimating 7GW of SMR deployment in the medium scenario and 10GW in the high scenario. The modelling assumes that a FOAK 300MW prototype is expected to be deployed by 2025, with transition to Nth of a Kind (NOAK) beginning in 2030.

Cutting costs by innovating

Current costs

We have estimated the 2015 Levelised Cost of Energy (LCOE) for each different reactor technology based on a variety of different sources[16]. Note that all calculations assume a discount rate of 10%.

Existing generation

- **74 £/MWh.**

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[11] ESME is an energy system model created by the Energy Technology Institute (ETI) to assess different combinations of low carbon energy technologies that can deliver an 80% reduction in CO_2 emissions by 2050; ESME has been used as the primary scenario modelling tool in all the TINAs.

[12] 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.

[13] Our scenarios for existing generation consider that Sizewell B will be operating beyond 2050; while possible this is not an official policy of either DECC or EDF.

[14] ETI, UK Nuclear Fission Technology Roadmap, February 2012.

[15] J. J. Jacobson, G. E. Matthern and S. J. Piet (2011). Assessment of Deployment Scenarios of New Fuel Cycle Technologies, Nuclear Power - Deployment, Operation and Sustainability, Dr. Pavel Tsvetkov (Ed.), ISBN: 978-953-307-474-0, InTech, DOI: 10.5772/17475.

[16] DECC (2013): Electricity Generation Costs, EIA (2013): Updated Capital Cost Estimates for Utility Scale Electricity Generating Plants, EIA (2013): Updated Capital Cost Estimates for Utility Scale Electricity Generating Plants, ICEPT (2012): Cost estimates for nuclear power in the UK, NNL (2014): Small Modular Reactors Feasibility Study.

- Cost assumptions based on DECC Electricity Generation Costs 2013, but reduced based on a “NOAK” assumption – roughly midway between the low NOAK estimate of £70/MWh and central estimate of £80/MWh.
- Fuel and decommissioning costs same as Gen III.
- 75% capacity factor based on UK actual annual capacity factor of existing nuclear reactors from IAEA PRIS (International Atomic Energy Agency Power Reactor Information System).
- Because this is a levelised cost figure it includes estimates for components manufacture and construction costs. However only fuelling, operations and maintenance (O&M), and the back end of the fuel cycle have been considered when estimating benefits to the UK from innovation in existing generation.

Gen III

- **91 £/MWh.**
- Assumed to represent generic PWR, but modelled on EPR.
- Cost assumptions based on DECC Electricity Generating Costs 2013 – central estimate.
- 90% capacity factor (See DECC 2013 Electricity Cost update).
- CAPEX breakdown from EIA “Updated Capital Cost Estimates for Utility Scale Electricity Generating Plants” (2013).

Gen IV

- **106 £/MWh.**
- Sodium-cooled fast reactor.
- Cost assumptions based on modelling work undertaken by the Gen IV International Forum Economics Modelling Working Group (EMWG) using the G4ECONS model, as published in the 2013 Gen IV annual report.
- 80% capacity factor – Carbon Trust assumption.
- CAPEX breakdown also from EMWG.

SMR

- **84 £/MWh.**
- Light water reactor.
- Cost assumptions from the SMR Feasibility Report published in December 2014 by NNL.

We have used the nuclear fuel cycle to break down each technology into 7 main components, illustrated in Table 2.

Table 2: overview of nuclear fission sub-areas – cost attribution **(for sources see footnote 16 on page 8).**

Sub Area	Description	Existing generation	Gen III	Gen IV	SMR
Mining, Processing, Enriching, Fabricating	Full treatment of fuel prior to its use in a reactor, from extraction through to fabrication	6.7%	5.5%	6.4%	6.0%
Capex – Components	Main assemblies of the reactor system – reactor core, heat exchanger, containment vessel, pumps, turbines etc.	25.1%	26.7%	43.9%	26.9%
Capex - construction materials	This refers to the costs of materials, principally steel and concrete, the building frame, and access infrastructure	10.8%	11.5%	14.1%	11.6%
Capex – Construction/installation and Commissioning	This covers the remaining capital costs of the build, including contingency and owner’s fee	38.5%	40.9%	24.9%	41.3%
O&M	Operating costs including fixed costs and maintenance	16.2%	13.2%	9.1%	11.9%
Decommissioning	Defueling and dismantling of the plant and the costs of the full decommissioning process	1.9%	1.5%	1.1%	1.6%
Waste Management, Reprocessing, Storage	Long term waste management	0.8%	0.7%	0.5%	0.7%

Cost savings through learning-by-R&D and learning-by-doing

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 component's development and historical experience) to give a more specific estimate of the impact potential for RD&D[17].

Technologies are assessed according to three main maturity profiles:

- **Emerging**: new technology, little or no deployment. Learning-by-research is prevalent.
- **Evolving**: early stage technology, some deployment. Balanced ratio of learning-by-doing and learning by research.
- **Mature**: established technology, considerable deployment. Learning-by-doing is prevalent.

Learning curves assign a potential cost reduction pathway to a technology based on the number of doublings of deployment. Learning curves for nuclear are based on global, as opposed to simply UK, deployment. This is because the nuclear vendors from which the UK will purchase its reactors (Areva, GE-Hitachi, Westinghouse) are currently building several reactors around the world and should be able to apply some of the learning to the UK deployment as well. For example, there are EPRs under construction in China, France, and Finland. However there might be barriers from different regulatory regimes that force modifications to the basic designs.

Given nuclear energy's historical record there is abundant material on cost reduction pathways. We have used the following cost reduction rates per doubling, depending on the amount of potential cost reduction that its technology area might have, given its maturity and suitability to cost reduction[18]:

- Conservative: 3% cost reduction per doubling.
- Medium: 5% cost reduction per doubling.
- Aggressive: 10% cost reduction per doubling.

Table 3 below illustrates how cost reduction profiles are applied to the various technological components of each reactor type; how maturity profiles determine learning-by-doing vs learning-by-R&D and change overtime as a technology matures. In the case of pre-deployment technologies only learning-by-R&D applies.

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[17] Jamasb, T. (2007). Technical Change Theory and Learning Curves: Patterns of Progress in Energy Technologies. The Energy Journal 28(3): 51-71

[18] Martin Junginger, Paul Lako, Sander Lensink, Wilfried van Sark, Martin Weiss (2008). "Technological learning in the energy sector", Utrecht University, Energy research Centre of the Netherlands ECN.

Table 3: cost reduction pathways by component and technology maturity profiles

Sub Area	Existing generation	Gen III	Gen IV	SMR
Mining, Processing, Enriching, Fabricating	Conservative	Aggressive	Aggressive	Medium
Capex – Components	None	Medium	Medium	Medium
Capex – Construction materials & balance of plant	None	Conservative	Medium	Conservative
Capex – Construction/installation and Commissioning	None	Conservative	Medium	Medium
O&M	Conservative	Conservative	Medium	Conservative
Decommissioning	Conservative	Conservative	Aggressive	Medium
Waste Management, Reprocessing, Storage	Conservative	Medium	Aggressive	Medium

Maturity profile (to 2025)	**Mature**	**Evolving**	**Pre-deployment**	**Pre-deployment**
Maturity profile (2025 – 2040)	**Mature**	**Evolving - maturing**	**Emerging**	**Evolving**
Maturity profile (2040 – 2050)	**Mature**	**Mature**	**Emerging**	**Mature**

Methodology: innovation and maturity profiles have been established using literature research and expert consultation on the most likely innovations to drive costs down in each component area, with the areas with the largest number of likely innovations being assigned an aggressive profile and those with less innovation potential a conservative profile. The key sources consulted include: Martin Junginger, Paul Lako, Sander Lensink, Wilfried van Sark, Martin Weiss (2008). "Technological learning in the energy sector", Utrecht University, Energy research Centre of the Netherlands ECN; Jamasb, Tooraj (2007). "Technical Change Theory and Learning Curves", The Energy Journal 28(3); EIA (2013). "Updated Capital Cost Estimates for Utility Scale Electricity Generating Plants"; Gen IV Forum (2009): GIF R&D Outlook for Generation IV Nuclear Energy Systems, Breakthrough Institute (2014): How to make nuclear cheap, World Nuclear Association (2015) Advanced Nuclear Power Reactors, Generation IV Nuclear Reactors, Small Nuclear Power Reactors (Consulted March 2015, available at: http://world-nuclear.org/info/Nuclear-Fuel-Cycle/Power-Reactors/).

There are several ways in which learning-by-doing and learning-by-R&D can reduce the overall cost of nuclear. In our modelling we have looked at five main components[19]:

1. **General cost reduction**: this represents overall improvements in manufacturing and construction techniques, improved processes, more advanced simulation technologies reducing the risk of error and the need for empirical testing, improved efficiency in the use of materials, etc.
2. **Lifetime extension**: new and more temperature and radiation resistant materials might help extend the expected lifetime of nuclear power plants, spreading the cost over a longer timeframe and thus reducing the LCOE.
3. **Improved fuel and operational efficiency**: better fuelling techniques and improved O&M could reduce downtime and refuelling time, increasing the capacity factor of nuclear reactors.
4. **Reduction in construction times**: construction delays are the main reason behind nuclear cost increases. Advanced modelling and simulation, Non-Destructive Testing, and other innovative technologies can help mitigate the risk of construction delays and overruns. While modular construction techniques can reduce the overall construction time, reducing nuclear costs considerably.
5. **Reduction in the cost of capital**: given the large investments required for nuclear reactors the cost of capital is a key element in the overall cost of nuclear energy. Innovative technologies such as passive safety can decrease the perception of risk and thus lower the effective interest rates, making nuclear cheaper.

The cost reduction curves for each technology are illustrated in Figure 1 to Figure 4. Up to 2025 the curves are based on experts' assessment of the likely potential for cost reduction in that timeframe. From 2025 to 2050 a standard learning cost curve is applied based on the cost reduction ratios mentioned above.

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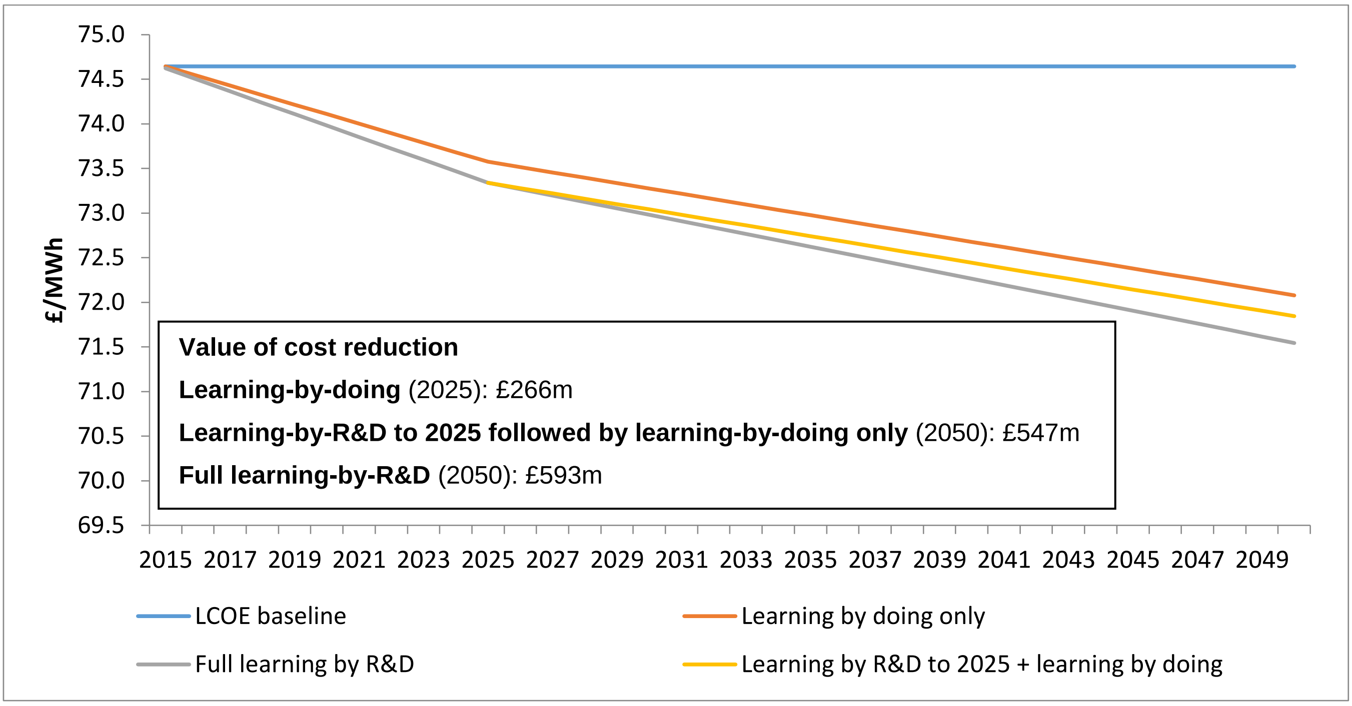
[19] The five components represent the main ways in which cost reductions are likely to be delivered in nuclear. The potential impact that each of the components could have on overall cost reduction has been assessed separately to sense-check the cost reduction results derived from the learning curve methodology. We have looked at up to 20 years life extension (from 60 to 80), up to 10% increase in the capacity factor (from 80% to 90% for Gen IV and SMRs), up to a 1 year reduction in construction time, and up to 2% reduction in the cost of capital.

Figure 1: Unit costs 2015-2050 with learning-by-R&D and learning-by-doing (existing generation)[20]



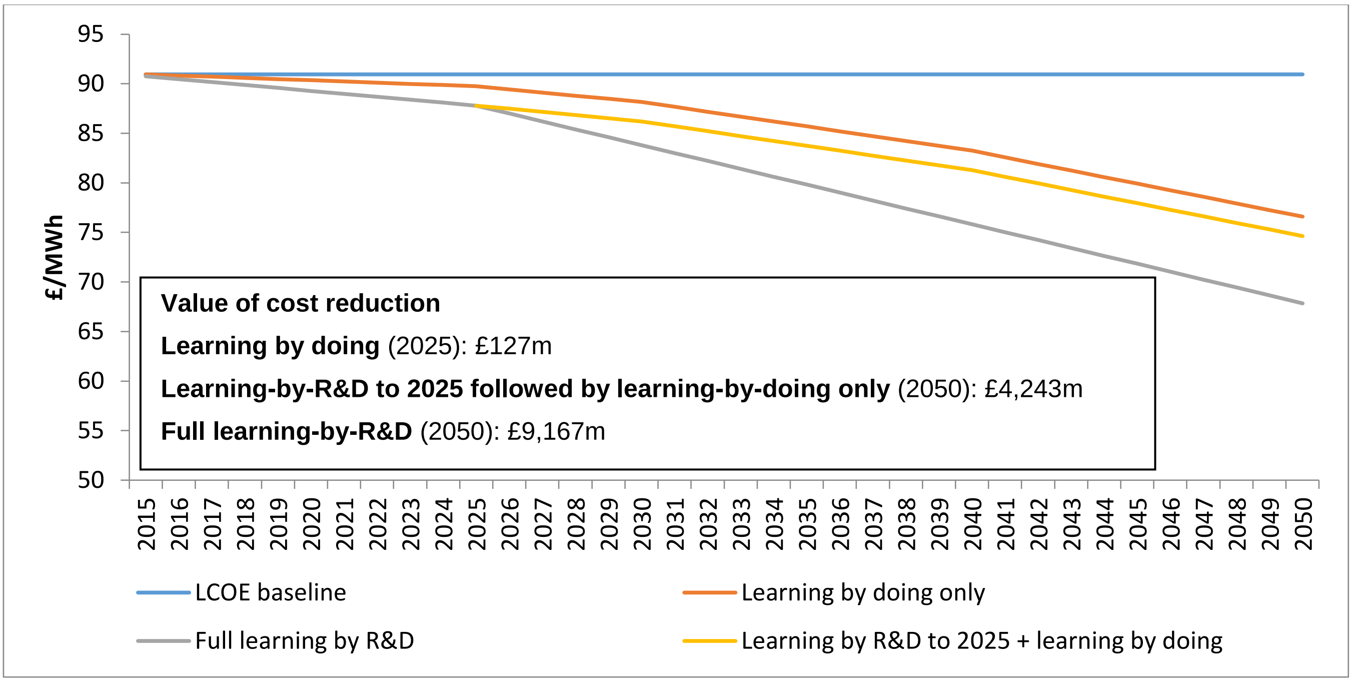
Value of cost reduction

Learning-by-doing (2025): £266m

Learning-by-R&D to 2025 followed by learning-by-doing only (2050): £547m

Full learning-by-R&D (2050): £593m

Figure 2: Unit costs 2015-2050 with learning-by-R&D and learning-by-doing (Gen III)



Value of cost reduction

Learning by doing (2025): £127m

Learning-by-R&D to 2025 followed by learning-by-doing only (2050): £4,243m

Full learning-by-R&D (2050): £9,167m

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[20] Assumes Heysham 1 and Hartlepool operating to 2024, Heysham 2 and Torness to 2030, and Sizewell B to 2055.

Figure 3: Unit costs 2015-2050 with learning-by-R&D and learning-by-doing (Gen IV)

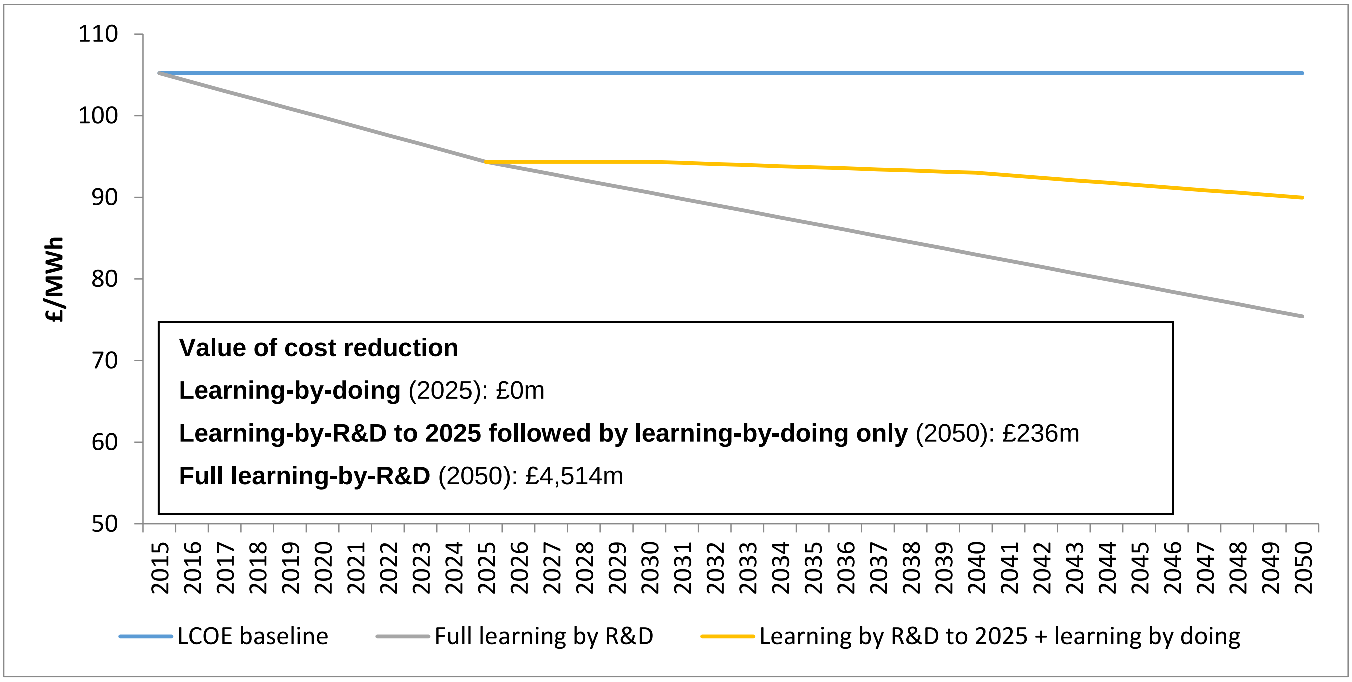
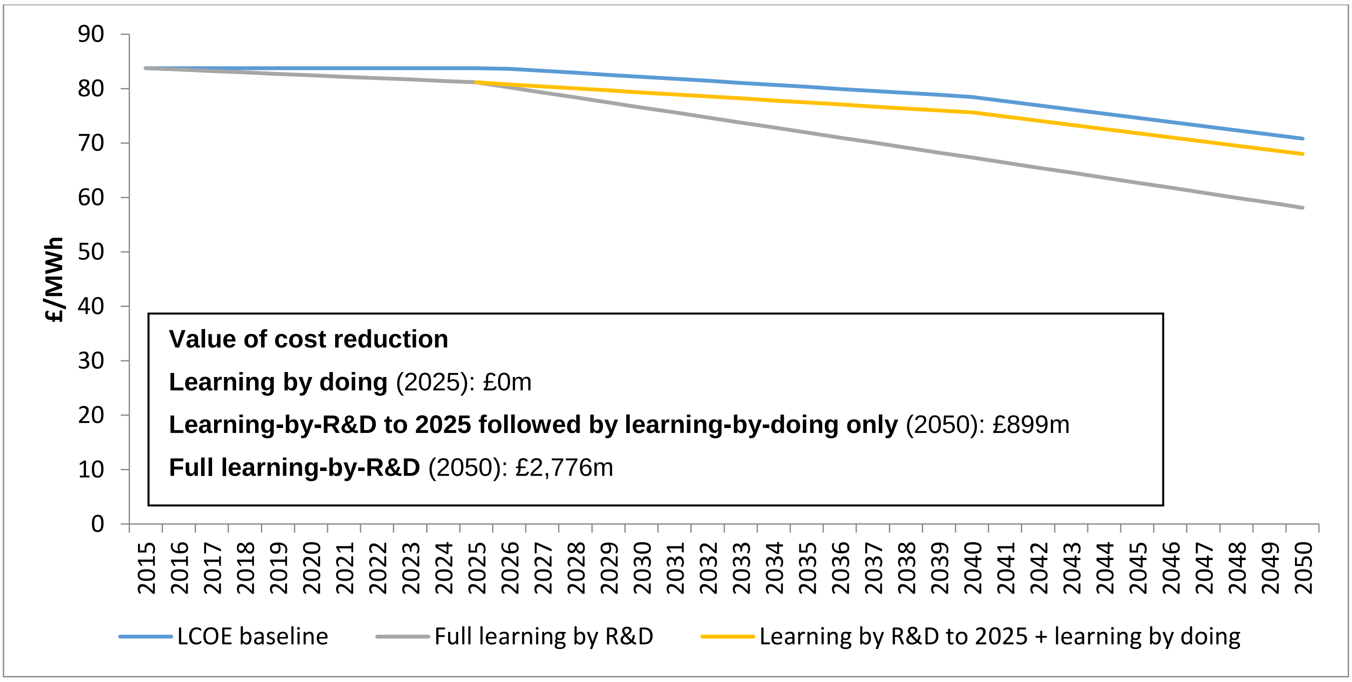


Figure 4: Unit costs 2015-2050 with learning-by-R&D and learning-by-doing (SMR)



Unlike most other low carbon technologies nuclear is characterised by very long lead times between the approval of an investment decision into a new reactor, construction start, and actual connection to the grid. This is due to the requirements of the regulatory approval process, the extremely high level of quality and care that needs to go into preparation work, and the large scale of the project itself. Hinckley Point C, the first plant of the new build, is a £16bn construction project that will probably last for 6 years.

Planning work for the reactor started in 2008, with the Design Acceptance Confirmation for the EPR design being granted by the UK Office for Nuclear Regulation (ONR) in 2012[21].

Once license approval is granted, financial considerations will make major modifications to the design unlikely. As such, innovation in nuclear is unlikely to have a large impact by 2025. Nonetheless, there are a few ancillary processes related to manufacturing of components and of local construction that can be improved. It is also expected that EDF will be able to import some lessons learned from its other EPR projects in France, Finland and China. As such, some cost reduction is expected by 2025, both in terms of learning-by-doing and learning-by-R&D. Broadly speaking, cost reductions to 2025 follow the same curves that extend to 2050, with minor adjustments based on expert opinion and literature research, mainly derived from the previous release of the Nuclear TINA and revised for consistency with the latest understanding of nuclear technology.

In the case of Gen IV, no deployment is expected before 2030. As such the cost reductions to that date are more indicative, showing the pathway that Gen IV could be on if deployment by 2030 were to be achieved. These cost reductions would be derived entirely from R&D that reflects the "enabling value" that R&D in Gen IV would deliver (since without it there would be no deployment of Gen IV at all).

We expect moderate cost reductions for SMRs, entirely from R&D into modularisation techniques and other manufacturing innovations. One of the characteristics of SMRs is the possibility of more rapid learning through manufacturing in batches – that is, while Hinckley C's 3.2 GW of expected capacity would be made up by two very large reactors constructed mostly on site, 1.5GW of SMRs could mean a manufacturing run of 5-30 reactors in a production line setting (assuming 300MW-50MW capacity), allowing for both learning-by-doing and learning-by-R&D in the short term. As such, cost reductions become faster as soon as deployment starts in earnest in the 2030s.

These estimates include maximum innovation potential, combining learning-by-R&D (driven by RD&D spending) and learning-by-doing (achieved through the incremental learning associated with increased deployment alone)[22] – the bottom path in Figure 1. This path is steeper than a base case scenario with only learning-by-doing (without focused R&D activity). The path in-between these in Figure 1 incorporates the maximum innovation opportunities to 2025, followed by learning-by-doing only.

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[21] EDF Energy, Hinkley Point C FAQs, accessed March 2015.

[22] As defined in Jamasb, T. (2007). Technical Change Theory and Learning Curves: Patterns of Progress in Energy Technologies, The Energy Journal, Vol. 28, Issue 3, 45-65.

Table 4: Potential cost savings from innovation (learning-by-doing + learning-by-R&D) by sub-area[23]

Component	**Technology**	**Cost reduction impact by ~2025**[1]	**Cost reduction impact by 2050**	**Innovation needed (source of cost reduction)**
Mining, Processing, Enriching, Fabricating	Existing generation	0%	0%-1%	• Development of advanced fuels for both Gen III and Gen IV reactor technologies • Support the development of advanced reactors utilising exotic fuel cycles • Better testing and qualification of material behaviour in very highly irradiated environments
	Gen III	0%-5%	30%-34%	
	Gen IV	0%-10%	41%-52%	
	SMRs	0%	30%-34%	
Capex – Components	Existing generation	0%	0%	• Research into materials that are more resistant to thermal, irradiative and other stresses • Advanced manufacturing techniques and development of niche capability in areas such as welding and other joining techniques, and surface technology • Modularisation
	Gen III	0%	30%-34%	
	Gen IV	5%-15%	20%-30%	
	SMRs	0%-5%	30%-34%	
Capex - construction materials	Existing generation	0%	0%	• Reduction in cost and energy intensity of materials (mainly cement and steel)
	Gen III	0%-5%	19%-22%	
	Gen IV	0%-5%	14%-19%	
	SMRs	0%	19%-22%	
Capex – Construction, installation and Commissioning	Existing generation	0%	0%	• 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 • Modularisation
	Gen III	0%-5%	19%-22%	
	Gen IV	0%_5%	14%-19%	
	SMRs	0%_5%	30%-34%	
O&M	Existing generation	0%-10%	20%-24%	• Improvement in inspection

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[23] DECC (2013): Electricity Generation Costs, EIA (2013): Updated Capital Cost Estimates for Utility Scale Electricity Generating Plants; Gen IV Forum (2012): Cost Estimation with G4-Econs for Generation IV reactor designs.

	Gen III	0%-5%	19%-22%	techniques, monitoring, condition monitoring of new materials and preventative maintenance approaches • Advanced modelling techniques and data mining • Digital Command & Control systems
	Gen IV	5%-15%	20%-30%	
	SMRs	0%	19%-22%	
Decommissioning	Existing generation	0%-10%	5%-10%	• 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
	Gen III	0%	19%-22%	
	Gen IV	0%-10%	41%-52%	
	SMRs	0%	30%-34%	
Waste Management, Reprocessing, Storage	Existing generation	0%-10%	5%-10%	• Test facility for irradiated waste fuel and Advanced Qualification of wasteforms • Programmes to design and model the behaviour of different fuels and to develop technologies that could use existing UK stock piles, including MOX • New storage techniques
	Gen III	0%	30%-34%	
	Gen IV	10%	41%-52%	
	SMRs	0%	30%-34%	
Total	**Existing generation**	**~0%-2%**	**~4% (3%-4%**	
	Gen III	**~0%-4 %**	**~2% (20%-25%)**	
	Gen IV	**~5%-10%**	**~29% (25%-29%)**	
	SMRs	**~0%-4%**	**~31% (25%-31%)**	

[1] All cost reduction scenarios have low and high estimates. In accordance with all other TINAs the “high” cost reduction scenario has been used to estimate cost reduction benefits across the whole study.

Sources: see Table 3.

Value in meeting emissions targets at lowest cost

Using the cost reduction curves and estimates presented in the preceding section we estimate the total innovation benefit to the UK. We define the innovation benefit as the difference in the cost of deployment, as expressed by the LCOE, between the various deployment scenarios at full cost and at reduced cost. We calculate the full benefit from both learning-by-doing and learning-by-R&D, but only use the learning-by-R&D figure as the innovation benefit used by the TINA methodology to prioritise UK public innovation spending.

This benefit is represented by the “wedge” or difference between the “learning-by-doing” curve and the “full learning” curve in Figure 1 to Figure 4.

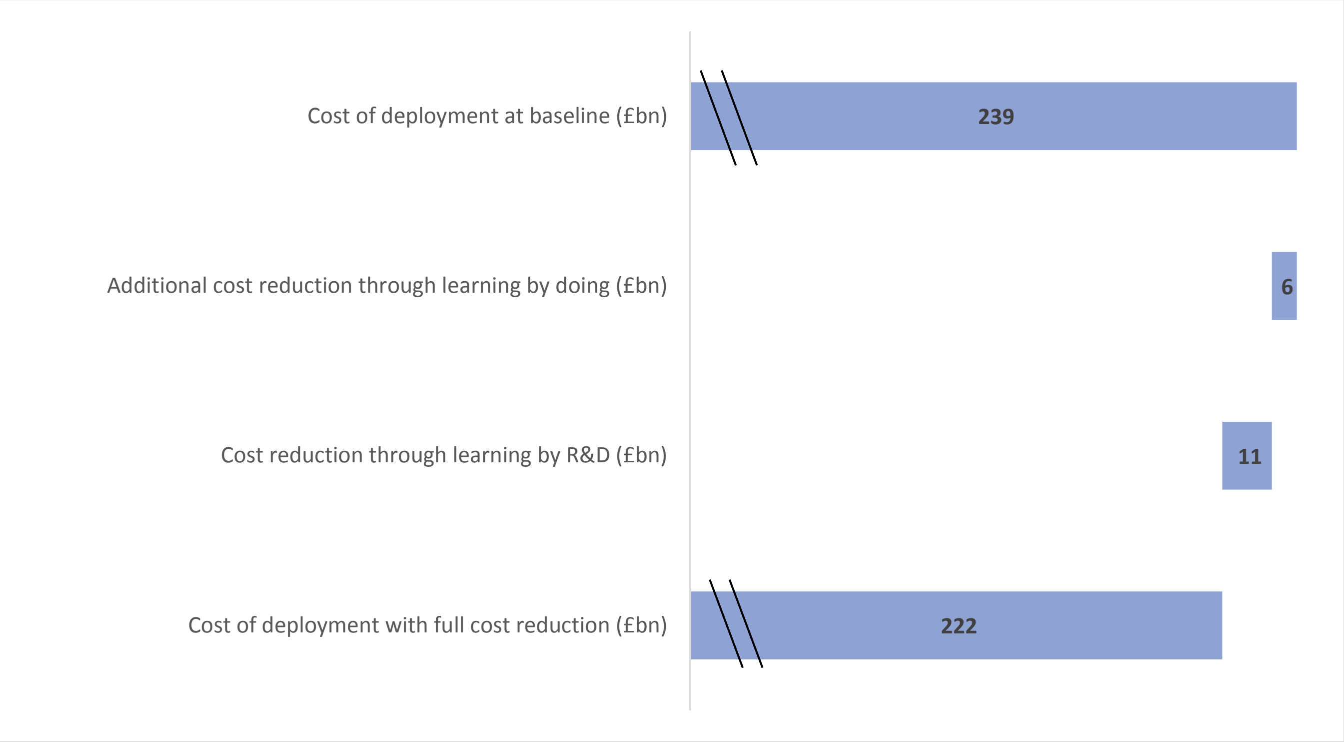
For nuclear energy in the central 40GW scenario, the total innovation benefit to 2050 is £17bn. Of this, £11bn is due to R&D and £6bn is due to learning-by-doing. It is the £11bn figure that we consider the “innovation benefit” for nuclear (Figure 5).

The benefit to 2025 is much smaller owing to lower deployment and the prevalence of mature existing generation in the deployment scenario, with £393m from learning-by-doing and £248m from learning-by-R&D.

Based on our estimates for cost and efficiency improvements and our scenarios for deployment (taking into account emissions constraints), we calculate the potential savings in energy system costs through innovation.

These savings estimates use an ‘inflexible deployment’ counterfactual, i.e. the deployment costs for this technology without cost reduction are compared with the deployment costs with cost reduction without considering any feedback between costs and deployment.

Figure 5: Potential cost savings from 2015 to 2050 – assuming inflexible deployment

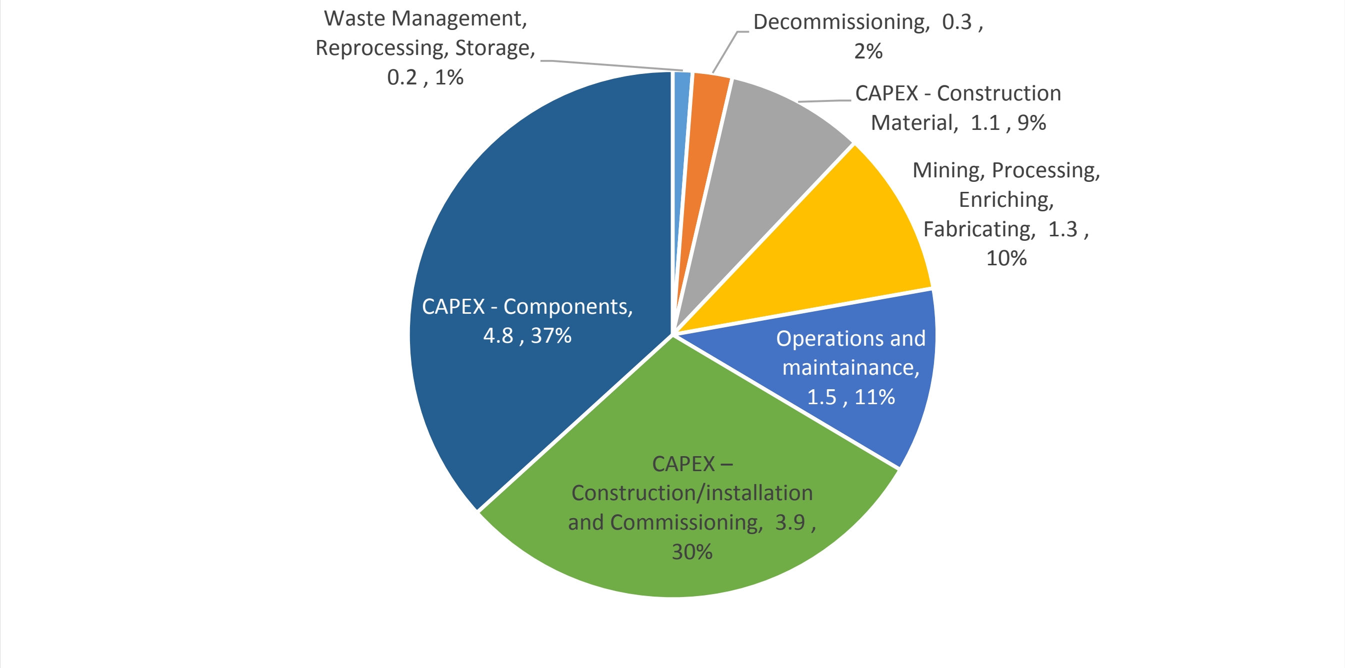


Note: deployment costs are cumulative unit costs installed between 2015-2050 discounted to 2015 using the social discount rate, 3.5% to 2045 and 3.0% 2045-2050.

The savings opportunity can be further broken down by each sub-area, as shown in

Figure 6. The greatest cost savings are from Components, Construction, and O&M.

Figure 6: Potential R&D cost savings from 2015 to 2050 by sub-area (medium deployment scenario, £bn)



Green growth opportunity

Global nuclear fission market

We have used the International Energy Agency's (IEA) 2014 Energy Technology Perspectives (ETP) report to estimate the deployment of nuclear technology out to 2050. The ETP provides three main scenarios based on expected future temperature changes driven by climate change: 6 degrees, 4 degrees, and 2 degrees. We have used these as respectively our low, medium and high scenarios.

IEA only provides figures for total nuclear capacity without giving a breakdown by technology. As such we have assumed similar ratios of SMRs to large reactors and thermal to fast reactors for the UK.

Finally, we have estimated the existing generation drawdown curve based on the age of each reactor currently operating in the world (as of 2015) and a projected maximum lifetime of 45 years, using data from the International Atomic Energy Agency (IAEA)[24].

- **Low scenario** (474GW by 2025, 435GW by 2050) The 6°C Scenario (6DS) is largely an extension of current trends. By 2050, energy use grows by more than two-thirds (compared with 2011) and total GHG emissions rise even more. In the absence of efforts to stabilise atmospheric concentrations of GHGs, average global temperature rise is projected to be at least 6 degrees C in the long term. In this case new nuclear deployment barely keeps capacity level with current numbers (377GW in 2015).
- **Medium scenario** (512GW by 2025, 595GW by 2050) The 4°C Scenario (4DS) takes into account recent pledges made by countries to limit emissions and step up efforts to improve energy efficiency. It serves as the primary benchmark in ETP 2014 when comparisons are made among scenarios and projects a long-term temperature rise of 4˚C. In many respects, this is already an ambitious scenario that requires significant changes in policy and technologies compared with the 6DS. Capping the temperature increase at 4˚C requires significant additional cuts in emissions in the period after 2050, yet still potentially brings forth drastic climate impacts.
- **High scenario** (575GW by 2020, 907GW by 2050) the 2°C Scenario (2DS) is the main focus of ETP 2014. It describes an energy system consistent with an emissions trajectory that recent climate

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[24] IAEA, Power Reactor International Statistics, 2015.

science research indicates would give at least a 50% chance of limiting average global temperature increase to 2˚C. The 2DS also identifies changes that help ensure a secure and affordable energy system in the long run. It sets the target of cutting energy- and process-related CO_2 emissions by more than half in 2050 (compared with 2011) and ensuring that they continue to fall thereafter. Importantly, the 2DS acknowledges that transforming the energy sector is vital, but not the sole solution: the goal can be achieved only provided that CO_2 and GHG emissions in non-energy sectors are also reduced.

- Across the low-medium-high scenarios, the cumulative, discounted global market turnover by 2050 could grow to £5.2tn–£7.6tn (£5.9tn in the medium scenario).

The UK's position in the Global Market

While the UK retains world leading expertise in several areas, its role as a top tier nuclear nation has been reduced since the last British reactor was connected to the grid at Sizewell in 1995. Depending on its competitiveness in the different areas, the UK could capture market niches ranging in value from 2% to 9% of the global market.

We have relied on expert consultation and a literature review[25], including an analysis of the main UK companies and institutions active in each area, to establish UK competitive advantage.

The UK has a medium-high competitive advantage in the following areas:

- **Decommissioning** - The UK has a large nuclear legacy in need of decommissioning, currently absorbing £3bn a year in government funding (including Waste Management activities). Several private companies operate in the sector and with support from the government have been able to export their expertise to other countries, such as Japan.
- **Operations & Maintenance** - The UK has good expertise in the operation of AGR and PWR reactors thanks to the existing fleet, and some of this expertise could be applicable to advanced reactors. The UK also has strong R&D skills in niche areas such as monitoring and modelling.
- **Waste Management, Reprocessing and Storage** - The size and uniqueness of the UK waste legacy has incentivised the development of advanced capabilities (see also under Decommissioning). The UK was also one of the few countries to carry out a full scale reprocessing programme However, there is a strong risk of losing capability and expertise in the medium term due to the planned shutdown of key facilities.

In the front end of the fuel cycle the UK is considered to have medium competitiveness:

- **Mining, Processing, Enriching, Fabricating** - The UK was a pioneer nation in the front end of the fuel cycle, developing enrichment centrifuges at Urenco and full fuel manufacturing facilities at Springfields. Expertise and R&D capabilities still exist but are at risk of disappearing in the short term. Countries with leading nuclear vendors will drive the decision over future fuel cycle technology.

In the remaining areas, the UK is considered to have low-medium competitiveness:

- **CAPEX – Components** - No strong capabilities in the nuclear island and other specific manufacturing areas. China and India are investing heavily in manufacturing capability and will likely dominate the market, while established players like Japan and France will be hard to dislodge.
- **CAPEX – Materials** – this sub-area is expected to be entirely domestic due to the low value, high bulk nature of the materials involved.
- **CAPEX – Construction, Installation & Commissioning** - The UK has not been present in the nuclear construction arena for more than 15 years. This market likely to be dominated by established nuclear vendors.

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[25] TSB (2008): A Review of the UK'sNuclear R&D Capability, Oxford Economics (2013): The economic benefit of improving the UK's nuclear supply chain capabilities, House of Lords (2012): Nuclear Research and Development Capabilities, NIA (2012): Capability Of The UK Nuclear New Build Supply Chain.

£18.4-33.9bn contribution to the UK economy

If the UK successfully competes in a global market to achieve the market share above, then nuclear fission could contribute c.25.6bn in the medium scenario (£18.4 low –33.9bn high) in cumulative discounted GVA by 2050.

It may be appropriate to apply an additional displacement effect since part of the value created in the nuclear fission sector 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%. This factor is already included in the numbers above. Of the GVA listed above, £18.3bn (11.2 – 21.3) would be from domestic activities and £8.6bn (7.3-12.6) from export activities, together supporting a total of 36,700 jobs in 2025 and 93,600 in 2050.

Figure 7: cumulative 2050 discounted GVA (domestic + international) by sub-area, £bn

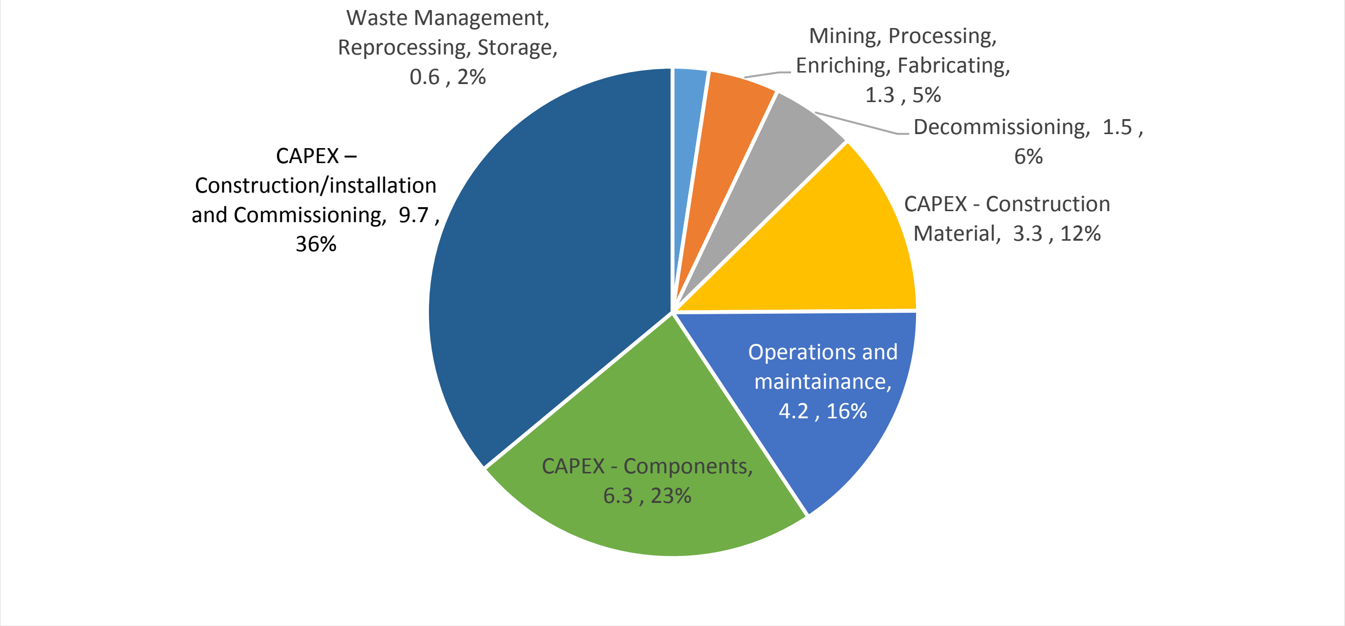
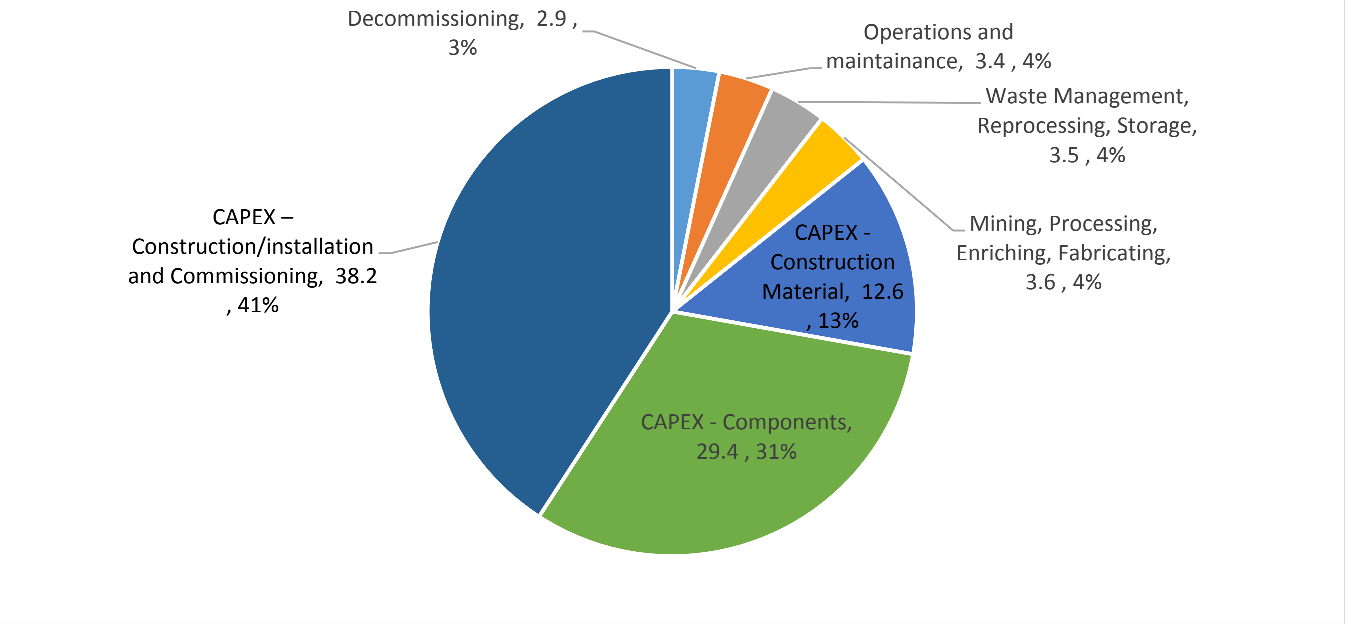


Figure 8: direct jobs supported by 2050 by sub-area, '000



The case for UK public sector intervention

Public sector activity/support is required to unlock this opportunity – both the c£11bn reduction in the costs to the energy system to 2050 from learning-by-R&D and the c£25.6bn net contribution to UK GDP from new business creation.

Market failures impeding innovation

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.

A number of overall market failures inhibit innovation in nuclear fission, creating critical failures in market demand conditions: uncertainty over future governmental commitment to nuclear (especially following Fukushima), large number of reactor designs, and uncertainty over the path to follow for Gen IV reactors (especially over the fuel cycle e.g. thorium and waste management).

Within the value chain, the critical market failures have most impact on:

- Decommissioning.
- Waste Management, Reprocessing, and Storage.

These are further detailed in Table 5 below.

Ability of the UK to rely on others

For a number of areas of nuclear fission technology, the UK can wait and rely on other countries to intervene in tackling these market failures and in driving innovation. This would support cost reductions in deployment at no cost to the UK, but would mean that the UK would not own IP and thus not be able to generate value from exports.

These include fuel cycle technologies, where several countries including France, the US, Russia, China, India, and South Korea 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 other markets can be easily imported given the UK's different approach to regulation and safety cases.

Furthermore, in the case of nuclear power the ability to rely on others is compounded by the opportunity of creating strategic partnerships with leading nuclear nations, which could enable the UK to develop IP in a few key areas and gain a larger share of the benefit of new reactor designs without having to sustain the entire cost by itself. In this case a degree of R&D investment would be warranted even in areas where the UK could technically entirely rely on others.

Finally, nuclear technology requires a higher degree of expertise and local knowledge to be managed safely and securely, even when most of the technology is being imported from abroad. Again, this requirement would make it necessary to continue investing in nuclear R&D, with the purpose of maintaining skills and expertise, even in areas where reliance on other countries was a definite possibility.

In general, the UK would be able to rely on others for the following areas:

- **CAPEX – Components** - particularly as it applies to nuclear island components which are being manufactured in industrial parks of countries such as China and Japan.
- **Construction, Installation and Commissioning** – as the UK will import reactor designs from international nuclear vendors, it is conceivable that most innovation in construction techniques and the design of those reactors will be undertaken by the vendors and imported to the UK. Nonetheless, the UK would still have a strong interest in developing capabilities in this area to capture more of the GVA. For SMRs, this might not be an area where the UK would want to rely on others, but rather join up as a strategic partner.
- **CAPEX – Construction materials** – it should be easier to import less sensitive innovations around improved use of cement and steel in nuclear construction without incurring the same problems represented by other more sensitive technological areas.

The UK would be able to partially rely on others for the following areas:

- **Mining, Processing, Enriching and Fabricating** – other nations are researching across a range of advanced reactor technologies but the UK has expertise in the areas which it needs to retain to both be able to strike partnerships with other countries and to manage its new nuclear deployment effectively.
- **O&M** - China aims to drive operating costs down 10% by 2020 on reactors similar to the UK new build but the UK regulatory system may make international innovation difficult to apply.

Finally, we expect the UK to not be able to rely on others for the following areas:

- **Decommissioning** – the UK has a specific and imminent decommissioning requirement. While in the long term innovations could be imported from other countries, the decommissioning needs of even just the current generation should be enough for the UK to have a clear need to retain and expand R&D capabilities in this area.
- **Waste Management, Reprocessing and Storage** - the requirements are very specific and safety regulations constitute a significant barrier to entry.

Table 5: Market failures 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 reactor’s lifetime (e.g. nuclear island) again pushing profitability for innovation to the longer term.	Significant failure
Capex – Construction Material	• Lack of alternatives 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.	Minor failure
O&M	• Overall the development of industry best practice and sharing of O&M learning is achieved under the responsibility of the World Association of Nuclear Operators. • The necessary skilled workforce requires a long time to reach maturity and is vulnerable to high turnover rates and obsolescence, requiring	Moderate failure

	constant investment even during loss-making periods. • Subsidised electricity markets can reduce the incentive to reduce operating costs. • There are barriers to entry particularly for SMEs trying to bring in innovative solution, which require government support to be addressed; as such while there can be said to be minor or no failures in terms of operation of existing plants, R&D in this area still faces a degree of market barriers.	🟨
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 no 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

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). The LCICG has identified and prioritised these innovation areas.

Innovation areas with the biggest relative benefit from UK public sector activity/investment

The LCICG has identified the areas of innovation with the highest relative benefit from UK public sector activity/investment[26].

These have been prioritised by identifying those areas that best meet the following criteria:

1. value in meeting emissions targets at lowest cost;
2. value in business creation;
3. extent of market failure;
4. opportunity to rely on another country; and
5. strategic importance.

While the first 4 criteria are common across all TINAs, the fifth is specific to nuclear. We define strategic importance as the role that a specific technology sub-area can play in enabling the development of the reactor type as a whole, and thus in enabling a successful UK nuclear new build.

For example in the case of SMRs, modularisation of components is an area of key strategic importance. In Gen IV innovative fuel cycles play a similar role.

This indicator includes elements such as the importance for the UK to be able to effectively and efficiently manage the nuclear new build, particularly when acquiring nuclear expertise from abroad, and the role that investment in specific technology sub-areas can play in helping the UK establish strategic partnerships with other countries.

The strategic importance also reflects the existence of UK capabilities at risk of being lost in the absence of investment, and what would be required for the UK to gain a seat at the “top nuclear table” in order to be able to steer decisions on new technologies in directions that could be more beneficial to the UK.

A detailed assessment of the strategic importance of each sub-area by reactor technology is presented in Table 6 . The table shows the relative importance of each sub-area within each reactor type, which is why it varies.

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[26] Without considering costs – these are considered in the final prioritisation.

Table 6: strategic importance by reactor technology

Sub-area	Existing generation	Gen III	Gen IV	SMRs
Mining, Processing, Enriching, Fabricating	Low	High	High	Medium
Capex – Components	N/A	Low	Low	High
Capex - construction materials	N/A	Low	Low	Low
Capex – Construction/installation and Commissioning	N/A	High	Medium	Medium
O&M	Medium	Low	Low	Low
Decommissioning	High	High	High	Medium
Waste Management, Reprocessing, Storage	High	High	High	Medium

Using the data presented in the previous section for each of the four technology types we have created a prioritisation by sub-area and reactor technology. We then combined this prioritisation to obtain a single overall ranking, which is shown in Table 7. Of course, prioritisation within each reactor technology would be different from the overall ranking.

Components has the highest priority, as a key enabling technology with a high value potential both in terms of innovation benefit and GVA. Decommissioning is also high priority, driven by the absolute need for public sector intervention due to critical market failures and the relevance of its innovations across all reactor types.

The fuel cycle, both front (fuelling, processing, and fabrication) and back (reprocessing, waste management) have medium-high priority, due to their high strategic importance as enabling technologies, particularly for Gen IV.

Table 7: Prioritisation of UK public sector activity/investment by sub-area and technology type (central scenario)

Sub-area	Innovation benefit (£m)	Export potential (£m)	Domestic GVA (£m)	Jobs (2050)	Market failure	Rely on others	Strategic importance	Final ranking	Rationale
Mining, Processing, Enriching, Fabricating	1,072	734	522	3,600	Significant	Partially	High	Medium - high	• Overall innovation benefit and GVA is smaller than other areas • High strategic importance for Gen IV and to a lesser degree Gen III • Important area for strategic partnership
Capex – Components	4,337	2,762	4,337	29,300	Significant	Yes	Medium	High	• High innovation benefit and GVA • UK expertise in key niche areas which could underpin international partnerships • Essential for SMRs
Capex - construction materials	976	3,296	976	12,700	Moderate	Yes	Low	Low	• Low innovation benefit, medium GVA, and no export potential • Less strategically important
Capex – Construction/installation and Commissioning	3,205	7,165	3,205	38,200	Moderate	Yes	Medium	Medium	• Private sector has a strong incentive to achieve cost reductions on its own • Less essential as enabling technology, particularly to advanced reactors and SMRs
O&M	1,348	3,680	1,348	3,300	Moderate	Partially	Low	Medium	• Less need for public sector intervention as operators are strongly incentivised to act on their own • Support needed for R&D and SMEs
Decommissioning	289	468	289	2,900	Critical	No	High	High	• High strategic importance through de-risking • Good export potential • Critical market failures
Waste Management, Reprocessing, Storage	145	195	145	3,600	Critical	No.	High	Medium-high	• UK-specific requirement due to peculiarity of UK legacy waste • Critical market failures

Existing innovation support

The UK is supporting many of the areas highlighted above. This is through a combination of policies to incentivise demand, supply-side innovation programmes to 'push' technology, and support for enablers (Table 8).

Table 8: Summary of current/recent UK public sector support

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 Electricity Market Reform* **Carbon Floor Price** –improves nuclear economics against fossil fuels as it is a tax on carbon **Contracts for Difference** – a type of Feed in Tariff to support low carbon generation including nuclear	**R&D Spending** **Nuclear Decommissioning Authority (NDA)** **Direct spend of c.£7m 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 **InnovateUK -** £7.15m **BIS** - £1.9m to Nuclear Advanced Manufacturing Research Centre (NAMRC) **R&D grants** **Research Councils (£19m)** – supports R&D on Gen III and IV, and waste and decommissioning, e.g. New Nuclear Manufacturing (NNUMAN) programme **EPSRC - a**dvanced materials for nuclear fission (£4M)**, c**ollaboration with S Korea (MSIP) in nuclear (£2.0M)	**NIRAB –** sector based advisory body of experts helping government assess nuclear innovation priorities **NIRO –** NIRAB's secretariat **NDA's Research Board** **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 **National Nuclear Fuel Centre for Excellence** **National Nuclear User Facility** **Committee on Radioactive Waste Management** **Universities**

Sources: consultation, LCICG members' websites

Potential priorities for public sector innovation support

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

High priority

- **CAPEX – Components** – this area has a high innovation benefit and aligns with UK priorities. The UK government has stated its preference for investing in high value manufacturing activities. Investment in R&D in this area would also give the UK a very strong card to play in the establishment of any strategic partnerships with international reactor vendors, particularly for Gen IV (France's ASTRID) and SMRs. The UK already has key facilities in place, such as the Nuclear Advanced Manufacturing Research Centre, from which these capabilities could be further developed.
- **Decommissioning** – investment in decommissioning innovation could play a crucial part in reducing risk perceptions associated with nuclear, particularly in light of the recent increases in the decommissioning costs of legacy UK nuclear facilities such as Sellafield. Innovations emerging from both the research currently being undertaken by NDA for its estate and from new lines of research could be applied to both Gen III and Gen IV reactors. Critical market failures apply in this area, making public intervention all the more important. Finally, the UK already enjoys a strong competitive advantage in this area, leading to high export opportunities.

Medium-high priority

- **Mining, Processing, Enriching and Fabricating** - this area is of particular importance to Gen IV, but also affects Gen III and SMRs. The UK still possesses world leading capabilities in this area, being entirely self-sufficient in terms of fuel processing, enrichment, and fabrication (although the processing plant is on long lease to Westinghouse) and having established expertise in fuel for gas cooled reactors which could be applicable to some future Gen IV reactor designs. Renewed investment in R&D

The NIRAB Annual Report 2014

As a result of the 2012 Beddington Review and the publication of the Nuclear Industrial Strategy by the UK government the Nuclear Innovation and Research Advisory Board (NIRAB) was created to provide advice to government on nuclear innovation.

The first NIRAB annual report was published in February 2015 and contained a wide ranging number of recommendations, focussed on actions that would enable the UK to eventually deploy advanced reactors and SMRs.

While the TINA study was conducted independently of NIRAB, we maintained close contact with Nuclear Innovation and Research Office (NIRO), NIRAB's secretariat. We believe that our recommendations are broadly aligned with those made by NIRO, particularly as they concern Gen IV reactors. Below we provide a brief summary of NIRAB's key recommendations and how they overlap with this report.

Mining, Processing, Enriching and Fabricating

Several of NIRAB's recommendations are categorised under *Fuel fabrication*, including accident tolerant fuels, improved fuel cladding, and fuel for advanced reactor. This is a similar set of interventions to those listed in our report. We assign a **medium-high priority** to this area.

CAPEX - Components

NIRAB's recommendations on *Advanced Reactor Development* include the development of component manufacturing capabilities, as stated in this report. We assign this area a **high priority**.

Waste Management, Reprocessing and Storage

In the annual report NIRAB details the innovations required to develop UK capabilities in *Fuel Recycling and Waste Management*. These are particularly important both for dealing with the current UK nuclear legacy, particularly plutonium, and for enabling technologies for advanced reactors. We assign this area a **medium-high priority.**

in this area would help retain and expand capabilities that are otherwise at risk of being lost.

- **Waste Management, Reprocessing and Storage –** R&D in this area would have benefit across multiple reactor technologies. For future generation, reprocessing is essential if the decision is made to pursue a closed fuel cycle using Gen IV technology. The UK was an early pioneer in this area with the Dounreay Fast Reactor, and still retains considerable capabilities in reprocessing. Furthermore, innovations in this area would help deal with the plutonium stockpile produced by the UK’s early nuclear weapons programme.

Table 9 outlines how the potential innovation priorities align against each technology sub-area, the scale of public funding needed for programmes for each sub-area, the current activities/investment in each area and potential future activities.

System characteristics of central nuclear deployment scenario

The nuclear fission TINA’s central deployment scenario is derived primarily from ESME modelling, with external sources used to establish the breakdown of the overall deployment between Gen III, Gen IV, and SMRs.

The 40GW scenario envisages a UK electricity system which has about 120GW of overall installed electricity capacity by 2050. The main other low carbon technologies in this system are CCGT with CCS, and offshore and onshore wind in roughly equal proportions. Due to its high load factor nuclear provides roughly 50% of total electricity generation, as baseload

The 40GW would be located in sites that already have nuclear power plants, plus a few additional sites which have already been identified but will need licensing approval from the ONR. This could be facilitated by SMRs. In this case nuclear would not require massive investment in new grid connection capacity. However, the other renewables in this scenario, particularly wind, might.

Table 9: Potential nuclear fission innovation priorities and support

Sub area	Potential innovation priorities	Estimated cost/time[1]	Current public sector activities/investments	Future example potential activities
Mining, Processing, Enriching, Fabricating	• Advanced Fuel manufacture for Gen III and Gen IV • Exotic fuel cycles • Better testing and qualification of material behaviour in very highly irradiated environments • Accident and temperature resistant fuels • Improved fuel cladding	10s to 100s of £m	• NNL – Fuel and Reactors programme (fuel design through 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 degradation and resistance to thermal, irradiative and other stress • Ambient pressure cooling • Modelling of materials behaviour at high temperatures • Modularisation • Welding and other joining techniques and surface technology - oxide dispersion, ODS steels	10s to 100s of £m	• Dalton – Materials. • NAMRC – Welding, Non Destructive Evaluation. • New Nuclear Manufacturing (NNUMAN) - Research activities	• 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 materials	• Reduction in cost and energy intensity of materials (mainly cement and steel)	<10£m	• None	• Waste minimisation • Reduction of cement content in construction operations • Maximise use of materials

				such as GGBS (Ground granulated blast-furnace slag) • Maximise offsite construction • Onsite verification • Virtual design and advanced simulation • Radio-scanning
Capex – Construction, installation, commissioning	• NDE/NDT (Non Destructive Examination/Testing) Condition Monitoring • Virtual Reality simulation tools • Advanced Modelling • Modular construction techniques	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 for 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	• Digital C2 systems • Improvement in inspection techniques, monitoring, condition monitoring of new materials and preventative maintenance approaches, leading to increased safe operating time and reduced downtime • Advanced modelling techniques and data mining to better understand risk	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	- Autonomous robotics and autonomous processes - 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 - Waste packaging and storage	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	- Advanced Qualification of wasteforms - Packing Density - Storage Fluids - Fuel recycling (MOX, aqueous recycling, pyroprocessing) - Fuel Cycle assessment	10s 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: Gen IV Forum (2009): GIF R&D Outlook for Generation IV Nuclear Energy Systems, Expert interviews, HM Government (2012): A Review of the Civil Nuclear R&D Landscape in the UK, House of Lords (2012): Nuclear Research and Development Capabilities, NNL (2014): Small Modular Reactors Feasibility Study, TSB (2008): A Review of the UK's Nuclear R&D Capability, NIRAB (2015) 2014 Annual Report, 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.

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