carbon
Connect

STORAGE
SOLAR
BIOENERGY
NUCLEAR
INTERCONNECTION
MARINE
WIND
COAL
OIL
NATURAL GAS
HYDRO

Future Electricity Series

Part 3:
Power from Nuclear

A report by
Carbon Connect

Written by Fabrice Leveque and Andrew Robertson

March 2014

> *‘Nuclear energy has a long history of controversy, but the UK has made important progress since 2007, when new nuclear was put back on the table, to today when we have broad political consensus behind new nuclear.’*

Baroness Worthington and Charles Hendry MP, Future Electricity Series Co-Chairs

CONTENTS

FOREWORD

Nuclear energy has a long history of controversy, but the UK has made important progress since 2007, when new nuclear was put back on the table, to today when we have broad political consensus behind new nuclear. The development of the nuclear option and many other changes taking place in the power sector are rightly attracting discussion and debate, but only *constructive* debate will move us forward. This report guides people towards constructive debate in what we will look back on as a defining decade in UK energy policy.

The nuclear energy available per atom is around one million times bigger than the chemical energy released in burning each atom in fossil fuels. Consequently, nuclear energy is a potentially huge resource and the comparatively small amount of fuel that goes in and waste that comes out of nuclear power stations are major benefits. Nuclear has been important in diversifying our energy mix and providing low carbon electricity for several decades, but the UK has not built a new reactor since the privatisation of the electricity sector. The Electricity Market Reform package is being introduced with broad political support, and includes plans for a policy framework supporting the private sector to build new nuclear power. It can be challenging to formulate a new regime which strikes the right balance between public and private involvement, to encourage competition and protect consumers and taxpayers. But getting the balance right is critical for maintaining a broad political consensus. As this report highlights, consensus is vital for pursuing nuclear alongside renewables and CCS as we transition away from unabated fossil fuels. If nuclear is to keep its place in this portfolio of low carbon options however, it must buck the trend of delays and remain competitive.

The first chapter of this report highlights key strategic opportunities and challenges for nuclear power in the UK. One of the most immediate challenges is obtaining approval from the European Commission on the package of support measures for Hinkley Point C. The report examines the expected cost and developer returns on what could be the first nuclear power station built in the UK for two decades, although it is too early to conclude on value for money. The future of the UK’s plutonium stockpile has implications for several strategic national priorities and it is crucial that we see this pursued with more urgency and the best of ‘joined-up government’ thinking. After a promising initial response to the Beddington review, the UK needs to follow through with actions to ensure that research and development best reflects the potentially significant strategic value to the UK of nuclear technology developments. Building on this, we want to see more consideration given to the role of the UK in developing and demonstrating the next generation of nuclear technologies.

Understanding the nuclear lifecycle, current and future technologies and the chronology of nuclear power in the UK are important context for the key opportunities and challenges highlighted in Chapter 1. Chapter 2 outlines these and ends with a look to the future, showing the substantial and potentially growing contribution that nuclear power could make in the UK, including development of next generation nuclear technologies and fuel cycles.

Chapter 3 examines the key role that nuclear plays in providing low carbon baseload electricity, and its wider implications for system and fuel security. We highlight the system security challenges around 2019/20 and 2023/24 when a substantial number of coal, gas and nuclear power stations could close, but which is currently uncertain. These will all need to be considered in implementing the capacity mechanism, which will still be a relatively new policy tool during this period. The mix of technologies and dynamics of the electricity system are likely to change dramatically over coming decades, but we do not yet know exactly how. This could be crucial in determining the role of nuclear, and is something that policy makers will need to consider more and more. Keeping nuclear as part our energy mix will continue to help diversify the security and affordability risks that fossil fuels pose to consumers.

The numerous elements of affordability are examined in Chapter 4, and are particularly important for a technology with a history of delays and budget over-runs. The Government has taken steps to address past drivers of cost escalation, such as introducing the Generic Design Assessment process, and it is now important that industry achieve delivery to time and budget. Uncertain technology cost reductions and fossil fuel and carbon prices means that we do not know which generation technologies will be cheapest in future. On this basis supporting a broad mix of generation technologies today – including nuclear power – is sensible, although deciding if and how to begin narrowing down this portfolio could be challenging. Nuclear may also provide substantial economic opportunities for the UK if we can extend our base of expertise and secure more business in supply chains and nuclear industry at home and abroad.

Chapter 5 considers the carbon and wider environmental impacts of nuclear power on a life cycle basis, finding that it is amongst the lowest carbon forms of electricity generation. The long lived nature of some radioactive nuclear waste, and the dual use potential of nuclear technology for civil and military applications, creates unique social and economic sustainability challenges. The UK is a world leader in managing these risks, but it is important that Government continues to pursue with urgency the work on implementing long term solutions, such as finding a site for and building a long-term underground store for intermediate and high level nuclear waste.

Energy is a high stakes game, with consequences for every household, every business and every region in the UK. It is central to our economy, our security and our efforts to tackle climate change. For these reasons, government will always hold the reins on energy, even when the private sector is charged with delivery. Energy, and especially its price, will remain a critical issue for politicians as the next general election comes into view. Rhetoric has frequently sought to exploit political divides, often ignoring areas of consensus, which has created political uncertainty. This uncertainty has far-reaching consequences in a sector where infrastructure is built and operated by companies, often with international investment opportunities. Consensus amongst politicians and parties is therefore particularly important in keeping investment flowing and the costs of finance down. We are supporting the *Future Electricity Series* and Carbon Connect because they recognise this important point. *Power from Nuclear* completes a series of three reports, and joins previous publications, *Power from Fossil Fuels* and *Power from Renewables,* in providing a high quality and accessible guide for everyone involved in debating and making energy policy.

We have thoroughly enjoyed the series, and would like to thank everyone who participated and generously gave their expertise during its course. We would also like to thank the esteemed steering group members for their hard work. Finally, we thank the Institution of Gas Engineers and Managers for their kind sponsorship of the *Future Electricity Series*, Costain whose sponsorship also made this report possible, and Andrew Robertson and Fabrice Leveque at Carbon Connect for compiling the report.

Future Electricity Series Co-Chairs

Charles Hendry MP

Baroness Bryony Worthington

EXECUTIVE SUMMARY

This report begins with an overview of the key strategic opportunities and challenges for the UK related to civil nuclear energy (Chapter 1). They are of immediate relevance to politicians, policy makers, industry and academics and rise out of the more detailed discussion about the current and potential future contribution of nuclear power towards energy policy objectives (Chapters 3-5). Having an understanding of the technologies involved in civil nuclear power, today and in the future, and of the chronology of nuclear power (Chapter 2) are also important context for considering these cross-cutting strategic issues.

KEY FINDING 1

Nuclear power benefits enormously from the political consensus in the UK on its continuing importance. Political consensus is particularly critical because the development and construction of power stations often spans two to three political cycles, and because political risk can have a material impact on the cost of nuclear power.

KEY FINDING 2

The broad political consensus behind new nuclear power in the UK is predicated on agreement over the relative roles of the public and private sector. It is important that politicians work together to maintain consensus whilst agreeing with the European Commission a regime for pursuing new nuclear power.

KEY FINDING 3

There is potential for the UK to be constructing multiple nuclear power stations alongside a substantial amount of other infrastructure. Part of the Government's portfolio management should include making sure that there is an adequately sized and skilled workforce to avoid increasing the cost or slowing the deployment of all new infrastructure, not just nuclear.

KEY FINDING 4

The UK has amassed a large stock of long-lived nuclear waste from 60 years of nuclear weapons development and power generation at 39 reactors. Although the Government has developed a long term strategy for managing this waste, efforts to identify a site for a Geological Disposal Facility have failed to date. Having stalled, the Government must urgently revisit the process for resolving a crucially important challenge.

KEY FINDING 5

Assessing options and finding a solution for managing the UK's plutonium stockpile needs to be pursued with more urgency and better coordination given its implications for several national strategic priorities (nuclear non-proliferation, technology development, waste and power generation). Setting clear criteria against which to assess potential solutions and identifying budgetary requirements for supporting the development and deployment of solutions would help expedite the process.

KEY FINDING 6

Good progress has been made in reorganising the UK's nuclear research and development activity and spending to reflect long term ambitions for nuclear energy. More could be done, however, to engage in advanced fission reactor and advanced and alternative fuel cycle research, capitalising on UK expertise and reflecting the strategic value of these technologies.

KEY FINDING 7

Introducing competition into the process of awarding revenue support for new nuclear power will be a substantial challenge for policy makers over the coming two decades. In particular, it is not yet clear how the Government's goal of technology neutral auctions for revenue support contracts in the 2020s will be realised given the fundamental differences between low carbon generation technologies and the vastly different arrangements for renewables and nuclear currently.

KEY FINDING 8

The deployment of nuclear power is likely to be influenced more by the economics of system balancing than technical system balancing challenges, which can be met with greater deployment of existing balancing tools. The cost of maintaining system security is likely to mean that the UK maintains at least some baseload capacity, such as nuclear power, to limit system costs. High nuclear deployment could be constrained by system costs, although uncertainty over future demand profiles, supply mix and the cost of balancing tools means that this is currently difficult to assess.

KEY FINDING 9

It is not yet clear which generation technologies will be cheapest in the 2020s, including gas power, because of substantial uncertainty over technology costs, fossil fuel prices and carbon prices. This is the main reason for supporting a broad mix of generation technologies today, including nuclear power.

KEY FINDING 10

The environmental impacts of nuclear power are comparable to some generation technologies and favourable to others, although the long lived nature of some radioactive nuclear waste and the dual use potential of nuclear technology for civil and military applications create unique but manageable challenges for social and economic sustainability.

Strategic landscape

Following a programme of state-developed nuclear power spanning several decades and culminating with the commissioning of Sizewell B in 1995, the UK is on the cusp of beginning a new build programme led by the private sector. It has taken time and effort to get here, since nuclear was first proposed as one of the solutions to diversify and decarbonise the future power sector by the Labour Government in 2007. The UK strategy is broadly to facilitate deployment of current nuclear technologies up to 2030 whilst supporting reactor and fuel cycle innovations which could unlock new technologies to compete for deployment beyond 2030. This is in the context of modelling which suggest that between 23 and 55 gigawatts of nuclear could help the UK to decarbonise most cheaply (current deployment is around 10 gigawatts).

A major part of Electricity Market Reform is putting in place a policy framework to support the construction of new nuclear power stations by the private sector. It has proved a great challenge to formulate a new regime which strikes the right balance between public and private involvement and protecting market competition, consumers and taxpayers. Getting the right balance is also important for maintaining political consensus behind nuclear power.

Nuclear power benefits from a broad consensus between the main political parties on its continuing importance. This is crucial in any regulated market that wishes to attract private investment, because it provides longer term confidence in the credibility of policy. It is particularly crucial in the energy sector, and especially for nuclear power, where investments are large and can take many years to complete. Perceived political risk has a significant impact on the affordability of nuclear power and the political consensus that the UK has been established will contribute to making new nuclear power stations more affordable.

One of the most immediate challenges facing the Government's reforms is obtaining approval from the European Commission on the package of electricity market support measures, particularly the investment contract for Hinkley Point C. The Commission has specifically questioned the balance of risk and return expected on the Hinkley Point C contract and this is discussed further below. Changing this support package would not be an impossible task if made necessary and politicians should work together to maintain consensus whilst agreeing with the European Commission a regime for pursuing new nuclear power.

Significant delay to the new build programme could have important implications for security of supply, affordability and decarbonisation objectives in the medium term, underlining the importance of reaching agreement with the European Commission on the package of support for new nuclear. Considerations include capitalising on the expertise of the UK's aging nuclear workforce, the costs and risks of pursuing decarbonisation without nuclear and the potential costs of reviving the UK's nuclear infrastructure at a later date if needed. Finally, delays could exacerbate energy security challenges in the 2020s, when a large volume of existing power station capacity will close. The timing of life extensions and of new nuclear power stations could both be important for maintaining energy security in the period 2019-2024. There are a number of significant uncertainties in this timeframe regarding closure of old coal, gas and nuclear power stations which need to be considered in implementing the capacity mechanism, which will still be a relatively new policy tool during this period.

Having enough suitably skilled and experienced workers will be important for delivering new build projects on time and to budget, and delivering wider economic benefits for the UK. There are economic opportunities as well as challenges in ensuring these needs are met alongside the delivery of a major nationwide infrastructure pipeline. Strengthening the UK workforce in particular areas could boost the wider economic benefits captured by the UK through jobs and export opportunities. Nuclear power stations also require a skilled workforce to operate them. There is a particular need to train a new generation of workers for these roles, as much of the incumbent workforce is likely to retire within the next decade.

Public acceptance is a crucial factor in energy policy. In addition to securing planning permission, national support is important given the scale of potential deployment, the cost of supporting new nuclear power through electricity bills, and the safety and proliferation risks associated with radioactive nuclear materials. Public support for nuclear power has increased over the last few years, although the public remains divided, with roughly equal numbers of people in support, in opposition and undecided. Support increases from around 30 to 50 per cent when nuclear is framed as one of several options to tackle climate change and improve energy security, or is placed in the context of an overall mix that also includes renewable energy. Public opinion of nuclear power and a Geological Disposal Facility is generally more favourable in communities that have a history of a nuclear industry.

Nuclear power currently benefits from having already approved sites with a history of holding nuclear facilities, which tend to have more favourable public acceptance, and which could hold up to around 23 gigawatts of new capacity. Waste management and safety in the event of an accident are also key public concerns, which underline the importance of the Government pressing forward with its strategy to find a site for a long term waste disposal facility. This is crucial considering past failures to implement this strategy, most recently in Cumbria where the County Council rejected a proposal despite strong community and national level support in January 2013.

The large quantity of separated plutonium, currently being held in storage, is a key strategic issue for nuclear power in the UK. As well being a security and proliferation risk, there is a significant opportunity for plutonium to be used as fuel, and pursuing a solution for this could align well with the UK re-engaging in the development of alternative and advanced reactor designs. The strategy adopted for plutonium will impact on future power generation, the development of advanced reactors and fuel cycles and the management of high level wastes in future. Assessing options and finding a solution for managing this stockpile needs to be pursued with more urgency and better coordination. Setting clear criteria to assess options and establishing a means of supporting deployment would expediate the process.

Research and development into new fission reactors and into advanced and alternative fuel cycles, such as thorium, could offer many benefits to the UK and others, particularly if high nuclear deployment emerges as favourable for cost effective decarbonisation or if uranium prices rise substantially. Despite the return of new nuclear power to Government plans for power sector investment since 2007, a 2013 review by the Government's then Chief Scientific Advisor (Sir John Beddington) found that the UK's research and development activities were focused on on-going activities, such as decommissioning and waste, and fusion technology for the very long term future, with a gap in-between. The Government's initial response to the Beddington review has however been promising. Several major international initiatives, such as the Generation IV International Forum, are coordinating national research and development activities into new reactors and fuel cycles and the UK is now re-joining this 'top table' in international collaboration on nuclear research and development. The Government has also established the Nuclear Innovation Research Advisory Board and Nuclear Innovation Research Office to help define a national programme of nuclear energy research and development. More could be done, however, to engage in advanced fission reactor and advanced and alternative fuel cycle research, capitalising on unique UK expertise and reflecting the strategic value of these technologies.

Some commentators, particularly supporters of renewables technologies, have argued that pursuing nuclear power as part of the UK's low carbon strategy will have an adverse overall impact on achieving policy objectives, although evidence to assess this is thin. Chapter 2 discusses three such arguments relating to competition for a limited pot of funding, the higher opportunity cost of nuclear power and tension between supporting both centralised and decentralised energy technologies.

Security

System security

The economics of current nuclear power technology mean that power stations generate electricity whenever possible. In addition, nuclear power is comparatively reliable, meaning that newer power stations could generate up to around 90 per cent of the time on average. For technical reasons, current designs take several days to be turned on and off, and once on, output can only be varied at a relatively slow rate compared to other thermal power stations. such as unabated coal and gas.

These characteristics define the contribution of nuclear power to system balancing over the three broad timeframes on which system security is managed. Over the short term (up to an hour) nuclear does not contribute reserve services but the large size of reactors does pose risks. National Grid contracts reserves to manage the risk of large generating units failing unexpectedly. Sizewell B nuclear power station currently has the largest generating unit of 1.1 gigawatts, but the planned power station at Hinkley Point C will add two reactors of 1.6 gigawatts, and as a result more reserves will need contracting to manage risks in the event of an unexpected reactor outage, with an impact on costs.

Over the medium term (hours to days), nuclear power is best suited to supplying a portion of 'baseload' demand, rather than load-following to meet mid-merit or peak demand. Baseload is the level of demand that remains constant throughout the year. For example, in 2011 demand was at least 20 gigawatts 90 per cent of the time. Around 69 per cent of annual electricity consumption falls within this baseload demand. Nuclear is well suited to meeting this because of its high reliability and availability, and is the main low carbon baseload option with current potential for deployment at scale. However, fossil fuels with carbon capture and storage, biomass power, geothermal or (to a lesser extent) varying renewables in conjunction with energy storage could contend with nuclear in the future.

Over the long term (seasons to years), nuclear power's high average availability and low variability around this average means that it helps strengthen capacity adequacy. In contrast, a system with a lot of varying renewables in the mix would require more grid balancing tools to maintain capacity adequacy. The Government is introducing a capacity mechanism to address capacity adequacy risks in the future. Whilst still a relatively new policy tool, implementation of the capacity mechanism will need to meet challenges arising from potentially major, but uncertain, power station closures around 2019/20 and 2023/24, including many existing coal, gas and nuclear power stations. Possible life extensions for existing nuclear power stations are one source of uncertainty, further compounded by the risk of delays in the construction of new nuclear power stations.

System compatibility

Major changes are expected to the UK's energy system over coming decades, driven primarily by decarbonisation and the availability of new technologies such as smart grids. These mean that the dynamics and features of the future power system are very unclear. General trends suggest that there will likely be an increase in assets driving greater variation in supply and demand, but will probably be accompanied by deployment of measures that enable greater manipulation and flattening of supply and demand. A system with high baseload demand could be favourable for deployment of nuclear power, highlighting the synergies between nuclear power and measures such as storage, demand side response and interconnection. A system with low baseload demand or high penetration of varying renewables, or both, could be less favourable for high deployment of nuclear power, as nuclear could struggle to sell enough of its electricity to keep it economic. New nuclear technologies, such as small modular reactors, could offer nuclear power but with different economic and technical characteristics.

Fuel security

The current UK electricity mix is dominated by fossil fuels and so increasing the share of nuclear would help diversify the UK's fuel security risk (at least initially). Fuel costs make up a far smaller proportion of the cost of nuclear power than for coal or gas power, meaning that increasing the amount of nuclear in the mix would also reduce the UK's exposure to fuel price risk overall (both upside and downside risk).

Were nuclear to become the dominant source of electricity for the UK, fuel security risk from nuclear would become more pressing. Although uncertain, there are thought to be adequate uranium resources around the world to meet current demand for around 100 years. The UK has significant volumes of separated uranium and plutonium which could be used as a fuel in the future, for example if Generation IV reactors which use a more closed fuel cycle can be developed, shown to be economic and deployed. There are also alternative nuclear fuel cycles not based on uranium or plutonium, such as thorium which is more abundant than uranium. Thorium could diversify fuel security and be used in both current and future generation reactors, if research and development on thorium fuel cycles continues. New extraction techniques and improved fuel efficiency could also extend the potential for nuclear power.

FINDING 8

Nuclear power stations currently have an inflexible electrical output for economic, rather than technical reasons. Although they could be operated more flexibly in future, it is likely that other technologies could provide system flexibility at lower cost.

FINDING 9

In the context of the current UK electricity system, nuclear power has a lower impact on system-wide costs than varying renewables. It has a slightly higher impact than conventional thermal generation due to the large size of planned new power stations.

FINDING 10

Around 2019/20 and 2023/24 a substantial volume of coal, gas and nuclear power stations could close, but this is currently uncertain. These uncertainties and possible delays to the commissioning of new nuclear reactors will need to be considered in implementing the capacity mechanism, which will still be a relatively new policy tool during this period.

FINDING 11

The deployment of nuclear power is likely to be influenced more by the economics of system balancing than technical system balancing challenges, which can be met with greater deployment of existing balancing tools. The cost of maintaining system security is likely to mean that the UK maintains at least some baseload capacity, such as nuclear power, to limit system costs. High nuclear deployment could be constrained by system costs, although uncertainty over future demand profile, supply mix and the cost of balancing tools means that this is currently difficult to assess.

FINDING 12

In the current UK context, nuclear power helps diversify the UK's electricity supply mix, reducing risks arising from individual fuels and technologies. Although uncertain, evidence suggests that there are adequate uranium resources to fuel a global expansion of nuclear power, including new of nuclear power stations in the UK. Development of thorium fuel cycles, technologies to enable a closed fuel cycle and new extraction techniques could all improve fuel security and expand the potential of nuclear energy.

Affordability

Affordability is made up of many components, each examined in this report, including technology costs, finance costs, system costs, policy support, risk, bills impacts and value for money.

Characteristics and history of nuclear costs

Levelised costs are the best place to start looking at technology costs, and although measured in the same units, strike prices are not a good means of comparing technologies. Current nuclear designs being considered for the UK are characterised by having high upfront construction costs and a construction period of several years, followed by long and low cost expected operating life, and finally decommissioning and waste disposal. Consequently, the cost of equipment, materials and finance during construction as well as the power station load factor are the most critical factors that determine the overall levelised cost of nuclear power. The development of alternative reactor designs could however change the cost structure and economics of nuclear power, for example small modular reactors could substantially reduce finance requirements and construction risk.

In the UK, and under similar circumstances in Western Europe, North America and Japan, the cost of nuclear power has generally risen throughout its history. Despite this, the Government's central forecasts predict that the cost of nuclear power will fall. The introduction of the Generic Design Assessment process is intended to mitigate delays and cost escalation due to design changes during construction, which has been a major driver in the past.

Other risks of cost escalation and opportunities for cost reduction include supply chain congestion and skills shortages. A 2011 estimate of nuclear construction costs included a 25 per cent 'congestion premium'. Supply chain congestion could continue to put a premium on the price of equipment and materials for nuclear new build as many countries around the world pursue new nuclear power. The Government is working with industry and academia to identify and address skills shortages which could arise after a pause of two decades in nuclear power station construction in the UK and as much of the UK's existing nuclear workforce reaches retirement over the next decade. As well as reducing risks of delay and higher labour costs, improving skills could help secure more supply chain opportunities for UK companies and workers which could greatly increase the wider economic benefits of nuclear. These are potentially large, but difficult to assess and compare to other energy options.

Future costs

There are many factors which determine the trajectories of technology costs, some more controllable than others. This makes forecasting technology costs particularly difficult and recent improvements in forecasting will likely result in wider ranges of uncertainty, rather than more accurate point estimates. Comparing the main power generation technologies, it is not clear which will be cheapest in the future or what exact mix of technologies will achieve decarbonisation most cheaply, because of uncertainty in technology cost reductions, fossil fuel prices and carbon prices. The picture is complicated by technologies being at different stages of maturity and therefore having varying levels of cost reduction potential calling for varying levels and types of Government support.

Government strategy

Faced with this uncertainty, the Government has chosen to diversify its risk by supporting a broad mix of technologies by a variety of planned means including a capacity mechanism, different 'flavours' of contracts for difference, capital funding and infrastructure loan guarantees. Although policy support for low carbon technologies, including nuclear power, is expected to be the main driver of increasing electricity bills over the coming decade, reducing the amount of fossil fuels in the electricity mix will reduce the exposure of consumers to volatility from fossil fuel prices (the main driver of higher bills historically) and rising carbon prices.

We identify a number of policy challenges resulting from the current strategy, including: deciding if and how to begin narrowing the portfolio of technologies; how to reflect non-price based considerations in planned price-based technology neutral auctions for revenue support; and assessing the impact of possible tensions between options in the portfolio. In particular, introducing competition into the allocation of revenue support for low carbon generation technologies will be very challenging. In the first instance, introducing competition within a technology-specific allocation for nuclear is likely to be a challenging step, due to the limited number of projects, sites and project developers. Beyond this, it is not yet clear how the Government's goal of technology neutral auctions for revenue support contracts in the 2020s will be realised given the fundamental differences between low carbon generation technologies, explored throughout this *Future Electricity Series*, and the vastly different arrangements for renewables and nuclear currently.

FINDING 13

Reducing investment risk, learning by doing and supply chain expansion could all put downward pressure on the costs of new nuclear power, but could be outweighed by other factors driving costs upwards. Historically, under circumstances similar to the UK, costs have tended to rise despite high deployment, primarily due to increasing safety requirements and construction delays.

FINDING 14

The Government hopes to reverse the trend of escalating costs for new nuclear power by licensing reactor designs before construction, offering a guaranteed and index-linked price for electricity for 35 years and selling loan guarantee facilities.

FINDING 15

It is not yet clear which generation technologies will be cheapest in the 2020s, including gas power, because of substantial uncertainty over technology costs, fossil fuel prices and carbon prices. This is the main reason for supporting a broad mix of generation technologies today, including nuclear power.

FINDING 16

There are substantial economic opportunities for the UK if it can secure a high proportion of business in the supply chain for new nuclear, both at home and abroad. It is difficult to compare these opportunities with other energy options however, because there are few studies that make comparisons on an equal basis.

Hinkley Point C

The first project since privatisation of the power markets to reach a provisional agreement with Government on building a new nuclear power station is EDF's Hinkley Point C. The Government has done a lot to lower the cost of finance for low carbon generation by allocating risks away from the project and onto electricity consumers and taxpayers. On Hinkley Point C, key steps taken by the Government include offering a guaranteed and inflation-linked price of electricity for 35 years and offering a HM Treasury loan guarantee.

Hinkley Point C has been quoted as a £16 billion investment in the UK. We estimate that this includes £10.2 billion of construction costs, £2.2 billion of construction contingency, £1.6 billion of interest on debt during construction and £2.0 billion of non-construction costs such as site licensing and public consultation.

We have assessed that expected equity returns on Hinkley Point C are around 19-21 per cent, substantially higher than expected equity returns on Private Finance Initiative projects and regulated electricity network assets. In reviewing the investment contract for Hinkley Point C, the European Commission has questioned whether the extent of support from the Government and the expected returns of the project are justified. Given that cross-party support for nuclear power in the UK is conditional on a limited role for Government in supporting nuclear power, it is important that politicians work together to maintain consensus whilst clarifying and agreeing with the European Commission a regime for pursuing new nuclear power.

Overall, it is not yet possible to conclude on the value for money of the Hinkley Point C agreement. Both the negotiation process and the resulting investment contract are important for determining value for money. It is difficult to judge the effectiveness of the negotiation process in driving value for money because it was neither competitive nor transparent.

FINDING 17

We estimate that equity investors in Hinkley Point C could achieve returns of around 20 per cent before refinancing. This compares with typical equity returns on regulated network assets of 8 to 10 per cent and on Private Finance Initiative projects of 12 to 15 per cent.

FINDING 18

We estimate that the £16 billion expected investment in Hinkley Point C includes £10.2 billion of construction costs, £2.2 billion of construction contingency, £1.6 billion of interest during construction, £2 billion of non-construction costs. It is not yet clear whether consumers would benefit from construction coming in under budget.

FINDING 19

It is not yet possible to conclude on the value for money of the Hinkley Point C agreement. Both the negotiation process and the resulting investment contract are important for determining value for money. It is difficult to judge the effectiveness of the negotiation process in driving value for money because it was neither competitive nor transparent.

FINDING 20

The broad political consensus behind new nuclear power in the UK is predicated on agreement over the relative roles of the public and private sector. It is important that politicians work together to maintain consensus whilst agreeing with the European Commission a regime for pursuing new nuclear power.

Sustainability

Carbon

To achieve the UK's statutory 2050 carbon target, there is consensus that the amount of low carbon generation in the power sector will need to increase significantly, from 30 per cent today to between 72 and 90 per cent by 2030. Chapter 5 highlights that nuclear power is amongst the lowest carbon forms of electricity generation. This conclusion is consistent with existing evidence on life cycle carbon intensities, taking into account limitations and uncertainties.

There are also potential applications for nuclear energy to provide carbon reductions beyond the power sector, outlined in Chapter 2. Nuclear reactors could be used to provide low carbon heat for buildings in combination with district heat networks. Advanced reactor technologies are being developed that could generate high grade heat suitable for industrial processes, or hydrogen production, for use as a low carbon energy vector in a variety of sectors such as heat and transport beyond 2030.

Wider sustainability

Nuclear power, like any other industrial activity, has other environmental and social impacts, such as visual, noise and pollution effects. These are important to consider because reducing carbon emissions should not be achieved at the cost of other environmental impacts. Chapter 5 examines the wider sustainability impacts of nuclear power, finding that it is favourable to some generation technologies and comparable to others, although the long lived nature of some radioactive nuclear waste, and the dual use potential of nuclear technology for civil and military applications, creates unique social and economic sustainability challenges.

Nuclear power is similar to fossil fuels in that some environmental impacts are generated upstream during fuel extraction and processing. However, the environmental damage per unit of energy delivered to consumers is significantly lower for nuclear fuel than coal because uranium has a much higher energy. This greater energy density results in a smaller environmental footprint for the materials required to construct nuclear facilities, and a smaller footprint for power stations themselves, compared to many forms of renewable generation. Nuclear power stations occupy relatively small areas of land for a significantly longer period of time, however, due to their longer operational lives and the considerable duration of fuel management and decommissioning activities. There is also significant potential to re-use many of the materials used in construction.

Nuclear power is not unique among power generation technologies in producing hazardous substances, the most significant of which are radioactive materials, present across the nuclear energy lifecycle. The risks of radioactive emissions to the environment are highly regulated and controlled in nuclear power, however, to ensure that contamination risks are kept to a minimum. These risks should be understood in the context of the range of health risks that are generated by energy technologies, such as other pollution effects and occupational risks and accidents. Although not a definitive measure of sustainability or safety, evidence suggests that, on a per unit energy basis, the rate of deaths arising from the nuclear energy lifecycle, including radioactivity, compares favourably with renewables, with both technologies having a lower impact than coal and gas.

The presence of high concentrations of radioactivity at nuclear facilities creates unique risks to nuclear workers and the general public in the event of an accident, with relatively high contamination possible over a large area. Regulation of the nuclear industry, and the safety of reactors has increased in response to major accidents such as Chernobyl and Fukushima, and the UK has a good nuclear safety record.

The dual use potential of nuclear technology in civil and military applications remains a concern. Although the first nuclear power stations in the UK were designed to produce material for nuclear warheads, there has been a subsequent separation of nuclear weapons programmes and civil nuclear power, both in the UK and abroad. The reactor designs to be deployed in the UK and the proposed approach to spent fuel suggest a low proliferation risk. Finding and implementing a solution for the UK's stockpile of plutonium will reduce proliferation risks arising from nuclear activities in the long term. The options currently being explored by Government, and their significant impact on the UK's wider nuclear strategy, are explored at the end of Chapter 5.

Radioactive waste

As with some other types of power generation, nuclear power produces waste by-products, some of which are radioactive. Like other hazardous substances, these are managed to safeguard human health and minimise environmental damage. The vast majority of waste produced during the lifetime of a nuclear reactor has very low levels of radioactivity, and is currently stored in near-surface repositories. The majority of radioactivity is contained within a small volume of the overall waste, from spent fuel and some reactor components. This high and intermediate level waste can remain radioactive for up to hundreds of thousands of years, and also contains plutonium, which can be used to make nuclear weapons. In the long term, this waste must effectively be isolated from people and the environment.

The UK has a substantial legacy of high and intermediate level waste from 60 years of military and civilian nuclear activity, which is an important issue of public concern. However, it is important to distinguish between the legacy impacts of the UK's existing nuclear capacity and accumulated waste, and the impacts that would arise from a new build programme. The Government's preferred long term solution for high and intermediate level waste is to build a deep geological facility. High and intermediate level waste produced in new build reactors will also be stored in this facility, leading to a modest increase in its size. Finding a location for and implementing this solution will likely improve the long term safety, sustainability and public acceptability of nuclear power in the UK. The Government has adapted its process for finding a community to accommodate a facility in the light of past failures, most recently in January 2013. The process is currently stalled, however, and it is crucial that Government find a way to move this forward.

In the future, advanced reactors could enhance the sustainability of nuclear power through more efficient fuel use and reduced waste production. The commercialisation of fast reactors also could open up the potential to eliminate some of the longer lived elements of high level waste, making it easier to handle for final disposal. Many proposed advanced reactor designs are 'inherently safe', which could further improve the safety of nuclear reactors. Some future scenarios for the energy system, explored in Chapter 1, anticipate a large role for nuclear power. In such scenarios, advanced technologies could deliver significant benefits by increasing fuel resources and reducing volumes of end waste. Following the Beddington review and the promising initial response from the Government, it is important that the UK's research and development funding and activity is re-aligned and coordinated to reflect the strategic value of potential developments in nuclear to the UK.

FINDING 21

Nuclear power is amongst the lowest carbon generation technologies with a carbon intensity of 5-25 gCO_2/kWh, compared to the average from the power sector in 2013 of around 470 gCO_2/kWh. Around half of these emissions arise from the mining and milling of uranium ore.

FINDING 22

The costs of managing waste from new build reactors will be borne by the owners of these power stations. Some uncertainty remains as to whether financial contributions from operators to pay for the use of a future deep geological facility have been set by Government at an adequate level, as the costs of a facility will remain very uncertain at least until a site is selected.

FINDING 23

The UK has amassed a large stock of long-lived nuclear waste from 60 years of nuclear weapons development and power generation at 39 reactors. Although the Government has developed a long term strategy for managing this waste, efforts to identify a site for a Geological Disposal Facility have failed to date. Having stalled, the Government must revisit the process for resolving a crucially important challenge.

FINDING 24

New reactor and fuel cycle technologies could substantially increase fuel efficiency, reducing both mining requirements and the longevity of long-lived waste. New technologies could also reduce proliferation risks.

FINDING 25

The environmental impacts of nuclear power are comparable to some generation technologies and favourable to others, although the long lived nature of some radioactive nuclear waste and the dual use potential of nuclear technology for civil and military applications create unique but manageable challenges for social and economic sustainability.

1. STRATEGIC LANDSCAPE

This Chapter identifies and discusses key strategic opportunities and challenges for the UK related to civil nuclear power. They are of immediate relevance to politicians, policy makers, industry and academics and are correspondingly given prominence at the head of this report. Subsequent chapters examine the chronology of nuclear power in the UK and nuclear's contribution towards energy policy objectives now and in the future. This is essential context for considering the cross-cutting issues outlined here, and the UK's civil nuclear strategy, with a critical eye.

1.1 Current strategy

The origins of the UK's current civil nuclear power strategy are in the Government's 2007 Energy White Paper, which concluded that new nuclear power should be considered as one of three large-scale low carbon technology groups – nuclear power, renewables and fossil fuels with carbon capture and storage. The UK strategy is to facilitate deployment of current nuclear technologies up to 2030 whilst supporting reactor and fuel cycle innovations which could unlock new technologies to compete for deployment beyond 2030. This is predicated on studies showing that a cost effective pathway to meeting the UK's 2050 carbon target is likely to require deploying between 23 and 55 gigawatts of new nuclear power[1]. The Government's Carbon Plan includes 33 gigawatts of nuclear in its lowest cost 2050 scenario and a range of 16 to 75 gigawatts across other modelled 2050 scenarios[2].

All nuclear power stations built in the UK were constructed by the state before the privatisation of the power sector in the late 1980s and early 1990s. Since privatisation, no new nuclear power stations have been built and the UK faces the possible closure of most of its existing fleet by 2024. A major part of the Government's Electricity Market Reform package has been putting in place a policy framework to support the construction of new nuclear power stations by the private sector. Creating the conditions for private sector investment in new nuclear sector has re-introduced greater Government intervention in the sector, needed to turn nuclear power into a commercial proposition. Some aspects of nuclear power will always be strategic issues for the state which warrant some degree of state intervention or oversight, such as dealing with nuclear waste, decommissioning and safety.

It has proved a great challenge to formulate a new regime which strikes the right balance between public and private involvement and protecting market competition, consumers and taxpayers. Getting the right balance is also important for maintaining political consensus behind nuclear power (discussed below). The UK is now in the final stages of agreeing reforms with the European Commission and putting them into practise.

The UK will also continue to decommission old nuclear power stations and seek a long term solution for its nuclear waste. Its current strategy is to identify a community that is voluntarily willing to host a geological disposal facility which will then be built to hold nuclear waste for thousands of years. Part of the UK's legacy nuclear material is a stockpile of separated plutonium, which is currently in temporary secure storage. The Nuclear Decommissioning Authority is considering three credible options (discussed below) for re-using the stockpile with a view to developing a new long-term strategy after one to two years of technical studies.

---

[1] UK Energy Research Centre (2013) The UK energy system in 2050: Comparing Low-Carbon Resilient Scenarios

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

1.2 Political consensus

Nuclear power benefits from a broad consensus between the main political parties. Labour has supported nuclear power since 2006, as have the Conservatives, whose support has increased since an originally cool response to Labours change in position[3]. Liberal Democrats have historically been opposed to nuclear power, although this changed in 2013 when the party voted to support new nuclear, provided it received no public subsidy. This has translated into Government policy that no additional support is given for new nuclear power unless comparable support is provided to other types of low-carbon generation.

Political consensus is crucial in any regulated market that wishes to attract private investment, because it provides longer term confidence in the credibility of policy. It is particularly crucial in the energy sector, and especially for nuclear power, where investments are large and can take many years to complete (discussed in Chapter 4). The development and construction of a new nuclear power station, for example, can span several election cycles, exposing developers to a particularly high risk of policy change.

The cost of capital on money used to pay for building a nuclear power station has a significant impact on the overall cost of nuclear power (discussed in Chapter 4). The cost of capital reflects the amount of risk perceived in the project investment, with higher perceived risk meaning a high cost of capital which makes nuclear power more expensive. Perceived political risk can therefore have a significant impact on the affordability of nuclear power and the political consensus that the UK has established could contribute to making new nuclear power stations more affordable. Preserving and building upon this consensus could in turn help keep energy bills down.

Cross-party support in the UK contrasts with some other countries, notably Japan, Germany and Italy. Japan shut down its entire fleet of 58 reactors in response to events at Fukushima in 2011, although it now plans to restart some. In Germany, a plan to phase out nuclear power in the wake of the Fukushima disaster in Japan was passed with near unanimous Parliamentary approval in 2011. A total of 31 countries were operating fission reactors worldwide in 2013, and 14 countries are currently constructing new reactors. Since the turn of the century, construction activity has been focussed in China, Russia, India and South Korea[4]. Many countries are currently embarking on new nuclear power programmes with the forerunners, according to the World Nuclear Authority, being the United Arab Emirates, Turkey, Vietnam, Belarus and Poland[5].

FINDING 1

Nuclear power benefits enormously from the political consensus in the UK on its continuing importance. Political consensus is particularly critical because the development and construction of power stations often spans two to three political cycles, and because political risk can have a material impact on the cost of nuclear power.

1.3 EU State Aid

One of the most immediate challenges facing the UK's new build programme is obtaining approval from the European Commission on the package of support measures proposed by Government to support new nuclear, initially demonstrated in the investment contract for Hinkley Point C.

---

[3] BBC (2006) Nuclear 'last resort' for Tories. 06.07.06 (Accessed February 2014) http://news.bbc.co.uk/1/hi/uk_politics/5152410.stm

[4] The World Nuclear Industry Status Report 2013 (Accessed February 2014) http://www.worldnuclearreport.org/-2013-.html

[5] World Nuclear Authority (2014) Nuclear Power in the World Today

EU State Aid regulations aim to prevent governments unfairly favouring particular industries or companies, and avoid any adverse effects on trade between member states. Some forms of State Aid can be exempted from the rules if, for example, they are justified by reasons of general economic development or help the EU meet its energy and climate goals.

The European Commission began investigating whether the investment contract for Hinkley Point C meets State Aid criteria in December 2013. If it decides that the deal breeches these rules, it could prevent it from going ahead, or require changes. The UK Government has argued that the Hinkley Point C deal should be exempted from State Aid rules on three grounds[6,7].

1. It will help the UK and the EU meet greenhouse gas emissions reduction targets.

2. It will help provide energy security for the UK and the EU, by providing new capacity and diversifying supply away from volatile fossil fuels.

3. It will help achieve broader EU goals.

The European Commission published its initial findings in January 2014[8], and strongly questioned the UK Government's justifications in a number of areas, including:

- the assertion that the UK needs more nuclear power to reduce greenhouse gas emissions, suggesting that other technologies, such as renewables, could achieve this, and warning that alternatives could be unfairly crowded out.

- the claimed security of supply benefits, arguing that UK electricity supply concerns are greatest in the years up to 2020, before Hinkley Point C is expected to begin generation electricity in 2023. The Commission specifically asks whether UK has underestimated the benefits that greater interconnection with neighbouring countries could provide.

- whether the nuclear technology considered for Hinkley Point C is immature technology that warrants support, citing UK Government modelling which indicates that under rising carbon prices, unsupported private investment in nuclear power could be likely by the latter half of the 2020s. It also cites evidence that nuclear power stations are being built without direct State Aid in France and Finland, albeit by a state-backed company (EDF).

At the earliest, a decision on whether the project qualifies for exemption is expected by summer 2014. The European Commission is also consulting on whether to make changes to State Aid rules and a decision on these changes is expected in June 2014.

As discussed above, the UK currently has strong cross-party backing for the proposed support package covering nuclear as well as other low carbon generation technologies. Changing this support package would not be an impossible task if made necessary and politicians should work together to maintain consensus whilst agreeing with the European Commission a regime for pursuing new nuclear power. For example, if the Government were to construct a new nuclear power station on its own balance sheet, this would likely meet State Aid rules. Whilst pursing nuclear power in this way could also significantly reduce costs for consumers (perhaps by 40 per cent), additional considerations would include the impact

---

[6] European Commission (2013) State Aid SA. 34947 (2013/C) (ex 2013/N) – United Kingdom Investment Contract (early Contract for Difference) for the Hinkley Point C New Nuclear Power Station

[7] Carbon Brief (2013) In brief: Why the UK's new nuclear deal may fall foul of EU law (Accessed February 2014) http://www.carbonbrief.org/blog/2014/02/in-brief-why-the-uk%E2%80%99s-new-nuclear-deal-may-fall-foul-eu-law/

[8] Ibid 6

on political consensus, potential delay to the new build programme and exposure of tax payers to greater risks (by taking construction risk).

FINDING 2

The broad political consensus behind new nuclear power in the UK is predicated on agreement over the relative roles of the public and private sector. It is important that politicians work together to maintain consensus whilst agreeing with the European Commission a regime for pursuing new nuclear power.

1.4 Implications of delay

There would be potentially important implications for security of supply, affordability and decarbonisation objectives in the medium term should this happen. Three factors make the timing of new nuclear power particularly important. Firstly, much of the UK's incumbent and highly experienced nuclear workforce (operations, research and regulation) is ageing and likely to retire in the next decade (discussed further below). There is therefore a limited window of opportunity to capitalise upon their skills and experience and to pass these on to a new generation of nuclear workers.

Secondly, existing infrastructure (regulatory capability, spent fuel and waste operations, specialist transport and emergency response) may be more difficult and expensive to revive after a period of decline should existing nuclear power stations not be replaced with new ones shortly after the expected closure of all but one by 2023. There could therefore be benefits on incrementally extending existing infrastructure and capabilities by replacing existing nuclear power stations before or shortly after existing ones close.

Finally, delays could exacerbate energy security challenges in the 2020s. It is currently anticipated that a large volume of coal and nuclear capacity will close between now and 2023, before new nuclear power will be built (expected from 2023 at the earliest). However, both coal and nuclear power stations could receive life extensions provided that they meet regulatory requirements (air pollution regulations for coal and safety regulations for nuclear) and commercial decisions are taken to invest in life extensions. The timing of life extensions and of new nuclear power stations could therefore both be important for maintaining energy security, particularly in the early-to-mid 2020s (see Chapter 3). Any 'gaps' in security left by nuclear would potentially be filled by unabated fossil fuel power, which would increase the risk of the UK failing to meet the fourth carbon budget. Having to contract for more capacity through the capacity mechanism to cover the risk of shortfalls in the early 2020s could also increase costs.

1.5 Skills

Nuclear power stations are significant construction projects employing large numbers of people and requiring a diverse range of specialist skills. There are challenges in ensuring these needs are met, but also economic opportunities (discussed in the Affordability chapter). The Government estimates that 25,000 jobs will be created during the construction of the two reactors at Hinkley Point C, with peak on-site employment reaching 5,600 people[9]. This compares with the ten-year Crossrail project in London, thought to be Europe's largest construction project, which currently employs 10,000 people[10].

Having enough workers who are suitably skilled and experienced will be important for delivering new build projects on time and to budget. Around 60 per cent of a project

---

[9] DECC (2013) Initial agreement reached on new nuclear power station at Hinkley. 21.10.13 (Accessed November 2013) https://www.gov.uk/government/news/initial-agreement-reached-on-new-nuclear-power-station-at-hinkley

[10] Crossrail (2014) Crossrail in numbers. (Accessed February 2014)] http://www.crossrail.co.uk/benefits/crossrail-in-numbers

workforce will be construction workers[11], and although these can be drawn from the existing labour pool, additional training in safety and quality is required to work on nuclear sites. The last reactor to be built in the UK was completed in 1995, and as a result the number of workers with these skills has fallen and would need to be substantially increased to meet the potential demand of multiple nuclear construction projects[12]. Particular areas of concern are the availability of project managers, onsite supervisors and safety and security regulators[13]. New nuclear build will be taking place at a time when the Government is seeking to increase the UK's spending on infrastructure projects, with a pipeline of projects worth £375 billion estimated for construction over the next decade[14, 15].

Skills shortages could delay construction programmes, or lead to higher costs through upward pressure on wages. Strengthening the UK workforce could also boost the wider economic benefits captured by the UK through jobs and export opportunities (see Chapter 4). The UK has been investing in training whilst formulating the support regime for new nuclear, with several bodies including the National Skills Academy setting up training and certification schemes to ensure that the construction and engineering workforce have the necessary skills and competencies to secure more UK supply chain content. Although training will help to alleviate these risks, there is a limit to how quickly people can gain experience, which could prove to be a bottleneck for infrastructure construction. These risks could be particularly acute during the early part of the next decade, when multiple reactors could be undergoing simultaneous construction.

Nuclear power stations also require a skilled workforce to operate them, with up to a thousand employees required per plant across a range of activities including fuel processing, operation and maintenance and waste disposal. There is a particular need to train a new generation of workers for these roles, as many of the incumbent workforce in these areas are likely to be retiring within the next decade. This is particularly acute for higher skilled and more experienced parts of the workforce, where up to 70 per cent of employees (in 2009) are estimated to retire by 2025[16].

Research and development capability also plays an important role in supporting nuclear operational activities by providing skills and knowledge for innovation, technology development and safety regulation. The UK's nuclear fission research and development base will also need to be renewed and increased to meet the needs of operating a fleet of reactors, using technologies that are new to the UK[17].

FINDING 3

There is potential for the UK to be constructing multiple nuclear power stations alongside a substantial amount of other infrastructure. Part of the Government's portfolio management should include making sure that there is an adequately sized and skilled workforce to avoid increasing the cost or slowing the deployment of all new infrastructure, not just nuclear.

1.6 Public acceptability

Public acceptance is a crucial factor in energy policy. All energy infrastructure has a wide range of local impacts, which can for example be environmental (discussed in Chapter 5) or economic (discussed in Chapter 4). Decarbonisation is also likely to see new technologies, such as smart meters, impacting consumer behaviour. Local communities are consulted on planning for new nuclear power stations, but permission is granted at a national level

---

[11] CITB Construction Skills (2013) Written submission to ECC inquiry 'Building New Nuclear: The Challenges Ahead'
[12] Construction Skills (2011) Nuclear New Build Employment Scenarios
[13] NIA (2012) Capability Report: Capability of the UK nuclear new build supply chain
[14] HMT (2013) National Infrastructure Plan 2013
[15] Ibid
[16] Cogent (2009) Power People: The Civil Nuclear Workforce 2009 - 2025
[17] House of Lords (2011) Nuclear Research and Development Capabilities

through National Policy Statements. In addition to securing planning permission, national support is important given the scale of potential deployment, the cost of supporting new power stations which forms part of electricity bills, and the safety and proliferation risks associated with radioactive nuclear materials.

Public opinion of nuclear power and a Geological Disposal Facility (GDF) is more favourable in communities that have a history of a nuclear industry[18, 19], and for the new build programme, reactors are planned for sites which have already or currently host nuclear facilities. In contrast, recent surveys of public opinion show that nuclear power is amongst the least favoured forms of power generation, with roughly equal numbers of people in support, in opposition and undecided[20,21]. However, support increases from around 30 per cent to around 50 per cent when nuclear is framed as one of several options to tackle climate change and improve energy security, or is placed in the context of an overall mix that also includes renewable energy. The picture is therefore somewhat complex, but nuclear power currently benefits from having already approved sites with a history of holding nuclear facilities, which tend to have more favourable public acceptance, and which could hold up to around 23 gigawatts of new capacity.

At a local level, a narrow majority of people oppose the building of a nuclear power station in their area (within 5 miles of their home). Waste management and safety in the event of an accident are also key concerns[22], which may suggest that progress on a long term waste disposal facility and better management of waste at the Sellafield site could maintain and improve public acceptance of nuclear power.

1.7 Long term waste solution

The issue of high level nuclear waste is important for reasons of safety, sustainability and public acceptability (see Chapter 5). Implementing a long term solution for nuclear waste is likely to improve the safety, sustainability and public acceptability of nuclear power in the UK. High level nuclear waste can remain radioactive for thousands for years, and requires isolation from both people and the environment. Plutonium, which can be used to make nuclear weapons, is also present in spent nuclear fuel. These properties raise issues that are unique to nuclear power, such as proliferation risks and inter-generational equity.

When considering these issues, it is important to distinguish between the UK's nuclear waste legacy, and the waste arising from new build reactors. The majority of the UK's legacy high level waste is currently in interim storage at the Sellafield site in Cumbria. Waste arising from new reactors will be stored at purpose built facilities that operators will be required to construct on-site. The Government's preferred long term solution for this waste is to build a deep geological facility. Its estimated costs are uncertain, and will remain so until a site is identified. It is intended that the dedicated storage facility store both sets of waste (legacy and new). Although the Government will fund construction of the facility, the operators of new plant will be required to pay for the disposal of their waste within it. The total waste arising from 10 gigawatts of new reactors is expected to increase its size by less than ten per cent.

The greatest challenge in managing this nuclear waste is finding and agreeing a suitable site. A suitable location requires stable geology, and support from local communities. Following the failure of previous attempts to find a site, the Government began a new voluntary process

---

[18] Parliamentary Office of Science and Technology (2014) POSTnote 457: New Nuclear Power Technologies

[19] Pidgeon, N & Henwood, K (2013) Written Evidence Submitted to: Hoc Energy & Climate Change Select Committee (2013) Building New Nuclear – The Challenges Ahead

[20] Poortinga, W., Pidgeon, N.F., Capstick, S. and Aoyagi, M. (2014) Public Attitudes to Nuclear Power and Climate Change in Britain Two Years after the Fukushima Accident - Synthesis Report (UKERC: London).

[21] DECC (2014) Public Attitudes Tracker – Wave 8

[22] Parkhill, K.A., Demski, C., Butler, C., Spence, A. and Pidgeon, N. (2013) Transforming the UK Energy System: Public Values, Attitudes and Acceptability – Synthesis Report (UKERC: London).

in 2006. However, despite strong backing at the national and community level, the Cumbria County Council rejected a proposal in January 2013 to allow a more detailed site assessment to take place for a site in West Cumbria. Having stalled, the Government is now revisiting the process for identifying a potential site.

Once a site for a geological disposal facility is identified and agreed, the Government should consider relocating waste held temporarily at other sites, including power stations. By consolidating waste storage facilities and concentrating waste storage in one location, there is scope to save money and boost the public acceptability of nuclear power.

Advanced nuclear technologies could provide alternative means of dealing with some of this waste, in particular the level of hazard and timescale over which it remains. It is possible to reprocess spent fuel and turn it into fuel for further energy production (in current nuclear reactors). Alternatively, spent fuel could be used as fuel in fast reactors, reducing its radioactivity and proliferation risks.

FINDING 4

The UK has amassed a large stock of long-lived nuclear waste from 60 years of nuclear weapons development and power generation at 39 reactors. Although the Government has developed a long term strategy for managing this waste, efforts to identify a site for a Geological Disposal Facility have failed to date. Having stalled, the Government must urgently revisit the process for resolving a crucially important challenge.

1.8 Plutonium

The UK is currently storing the world's largest civilian stockpile of separated plutonium at Sellafield in Cumbria, and Dounreay in Scotland. Separated plutonium can be used to produce nuclear weapons and therefore poses a proliferation and security risk. Plutonium can also be used as a fuel in current and advanced reactors, and whatever strategy is adopted will have a significant impact on other strategic nuclear issues.

Plutonium is highly radioactive, with the half-life of some isotopes lasting thousands of years. Because it poses a threat to humans and the environment, plutonium will require isolation in the long term. The Government's strategy is to reduce safety and proliferation risks by putting the plutonium 'permanently beyond reach'[23] – referred to as disposition – firstly making it more proliferation resistant and secondly disposing of it in an underground repository being planned for high activity nuclear waste.

Before it can be stored permanently, separated plutonium requires processing to reduce the risks from decay and to make it harder to re-separate for use in weapons. Although current facilities could store the material until 2120 at the latest, this would create additional ongoing costs through continued active management and because radioactive decay will make the material more complex and costly to handle over time. The Government has therefore identified re-use as fuel as its preferred option to prepare plutonium for final disposal. Three credible options or re-use have been identified, all of which are deemed available or capable of being developed within the foreseeable future (around 25 years). The three credible options – MOX, CANDU and PRISM – are outlined in Chapter 2.

Whichever option is selected will interact with other key strategic nuclear issues as well as determining future safety and proliferation risks. Plutonium is a fuel resource, and each option has different potential for providing additional low carbon generation. Plutonium can be used to kick start thorium based fuel cycles, and some advanced reactors that could allow

---

[23] DECC (2011) Management of the UK's Plutonium Stocks: A consultation response on the long-term management of UK-owned separated civil plutonium

a move to a closed, and more sustainable, fuel cycle in future. The development of fast to dispose of the plutonium could provide an opportunity to establish the UK as a world leader in this technology, to capitalise on existing expertise and to rejuvenate research and develop activity. Whichever option is selected may also have important implications on the scale and timings of the geological disposal facility that will store the leftover waste.

These factors make the important and pressing decision process on plutonium management a challenging one. Coordination of the decision process is also challenging because the relevant factors cut across the institutional structure which the Government has set for developing and delivering nuclear policy and energy policy more broadly. Lessons can be learned from the first carbon capture and storage demonstration programme where criteria for judging success and a budget were not established at the outset, resulting in the programme being set back by several years[24].

FINDING 5

Assessing options and finding a solution for managing the UK's plutonium stockpile needs to be pursued with more urgency and better coordination given its implications for several national strategic priorities (nuclear non-proliferation, technology development, waste and power generation). Setting clear criteria against which to assess potential solutions and identifying budgetary requirements for supporting the development and deployment of solutions would help expediate the process.

1.9 Research and development

Industry, Government and regulators rely on research at public and private institutions for expertise and training across the civil nuclear industry. As well as supporting existing civil nuclear activities, expertise will be required to tackle some of the issues outlined in this Chapter, such as managing spent nuclear fuel into the long term, managing and disposing of plutonium and building a deep geological facility. It is therefore important that the UK's research and development strategy and spending matches long term ambitions for nuclear energy.

Despite the return of new nuclear power to Government plans for power sector investment since 2007, a 2013 review by the Government's then Chief Scientific Advisor found that the institutional landscape and funding still reflected the policy environment of the 1990s and early 2000s[25]. In particular, activity was focussed on the nuclear power of the past (decommissioning) the present (safety and performance) and the very long term future (fusion), but not on developing new nuclear fission technologies or fuel cycles for the medium to long term. Consequently, the UK's plans for involvement in nuclear research and development are at a relatively early stage, having been revisited since the Beddington review of the civil nuclear research and development landscape, published in March 2013.

Advanced fission reactors and fuel cycles, discussed in Chapter 2, could offer many benefits to the UK and others, particularly if high nuclear deployment emerges as favourable for cost effective decarbonisation or if uranium prices rise substantially. Very high temperature reactors could open up more options for decarbonising industrial processes, including hydrogen production which in turn could be valuable for decarbonising transport and heat. Fast reactors could vastly improve fuel efficiency and lessen the costs and risks of managing nuclear waste by allowing a more closed nuclear fuel cycle. Small Modular Reactors could reduce financing, siting and grid integration challenges, which could be particularly advantageous if high deployment of nuclear is favoured in the UK. Advanced and alternative fuel cycles (such as thorium) are often but not always interlinked with advanced reactor

---

[24] National Audit Office (2012) Carbon capture and storage: lessons from the competition for the first UK demonstration

[25] HMG (2013) A review of the civil nuclear R&D landscape in the UK

development. For example, thorium could be used in both Generation III+ (current) and Generation IV (future) reactors. There are many strands of advanced and alternative fuel cycle research and development, but across this area potential future benefits of work includes reduced proliferation and safety risks, lower costs of waste management and options for re-using spent fuel, including the UK's stockpile of separated plutonium.

Although the UK has experience across a range of fission technologies thanks to a long history of nuclear research and development, many people in the nuclear research community are expected to retire over the next 10 to 15 years. It is likely to be harder to re-establish this expertise once lost than to ensure that it is passed directly to a new generation. Attracting a new generation of engineers and scientists to civil nuclear research and development is therefore a priority and one which could be helped by a greater focus on developing new technologies for the long term and on international collaboration.

The size and diversity of the civil nuclear research and development landscape means that international collaboration is especially valuable. Having become less involved in international forums for civil nuclear research and development, the UK is now re-joining this 'top table' in international collaboration, such as the Generation IV International Forum. This is one of a number of positive developments resulting from the Government's initial response to the Beddington review. The Government has also established the Nuclear Innovation Research Advisory Board and Nuclear Innovation Research Office to help define a national programme of nuclear energy research and development[26]. Public funding for nuclear fission in 2011-12 was £13 million, which is broadly comparable to other low carbon technologies[27]. A package of £28 million for research and innovation across the fission fuel cycle was announced by the Government at the end of 2013, although only some of this was aimed at advanced reactor research[28].

The UK's technology neutral stance is currently useful whilst the range of reactor technologies is evaluated and whilst the UK has no indigenous reactor design of its own under consideration for new nuclear build. However, if the UK commits to a large roll out of nuclear power in future there may be cost savings in refining the scope of the technologies used and adapting one or several solutions to local conditions. The selection of a single technology relatively early on was one of the reasons behind France's relatively successful reactor build programme. There are risks to balance, however, between allowing time for options to develop and narrowing technology spending early on. In the meantime, re-engaging in international collaboration on fission research could help the UK act as an intelligent customer for reactor designs and provide opportunities to understand technology operation, regulation as well as potentially leverage future investment[29]. There are also questions regarding how the UK would go about commercialising advanced nuclear technologies. The current model of financing new nuclear power through private finance is not conducive to encouraging investment in newer, higher risk technologies. Currently, new reactors will only be built by the private sector, financed by private investors, who will prefer tried and trusted technology over new undemonstrated technologies.

FINDING 6

Good progress has been made in reorganising the UK's nuclear research and development activity and spending to reflect long term ambitions for nuclear energy. More could be done, however, to engage in advanced fission reactor and advanced and alternative fuel cycle research, capitalising on UK expertise and reflecting the strategic value of these technologies.

---

[26] HMG (2013) Nuclear Energy Research and Development Roadmap: Future Pathways
[27] National Audit Office (2013) Public funding for innovation in low carbon technologies in the UK
[28] DECC (2014) Innovation funding for low-carbon technologies: opportunities for bidders
[29] Energy Research Partnership (2012) UK Nuclear Fission Technology Roadmap – Preliminary Report

1.10 Competitive auctions

The way in which an agreement was reached between the Government and EDF for Hinkley Point C was not a competitive process and both the method and final agreement differ significantly from what is expected for renewables. Competition is desirable both for affordability, by exerting downward pressure on bids for projects, and to a lesser extent public support, in that it can provide a more transparent guide as to how revenue support is allocated.

Government plans a transition for Contracts for Difference, moving from the current phase of administratively set guaranteed prices, to technology-specific then technology-neutral auctions, finally arriving at a "fully competitive and open" phase. Introducing competition even within a technology-specific allocation for nuclear is likely to be a challenging step, due to the limited number of projects, sites and project developers. There are key differences between the nature of different low carbon technologies, such as construction time and operational lifetime that are likely to present significant challenges to moving to technology-neutral auctions in the long term (see Chapter 4).

FINDING 7

Introducing competition into the process of awarding revenue support for new nuclear power will be a substantial challenge for policy makers over the coming two decades. In particular, it is not yet clear how the Government's goal of technology neutral auctions for revenue support contracts in the 2020s will be realised given the fundamental differences between low carbon generation technologies and the vastly different arrangements for renewables and nuclear currently.

1.11 Compatibility with other low carbon options

Some commentators, particularly supporters of renewables technologies, have argued that pursuing nuclear power as part of the UK's low carbon strategy will have an adverse overall impact on achieving policy objectives. This section considers the three such arguments relating to competition for a limited pot of funding, the higher opportunity cost of nuclear power and tension between supporting both centralised and decentralised energy technologies. For all three, the general conclusion is that there is insufficient evidence to properly assess the impacts.

A fixed budget to support low carbon generation technologies will be shared between renewables and nuclear (and eventually fossil fuels with carbon capture and storage). Empirical evidence shows a strong link between technology deployment and technology cost reduction[30] for some technologies, such as solar photovoltaics and onshore wind (but not for nuclear power to date). Therefore it is reasonable to assume that spreading a limited budget for deployment support across several technologies will result in slower cost reductions for specific technologies than picking a smaller selection of technologies to back. However, this expectation needs to be balanced against the difficulties of forecasting technologies costs, particularly when there is not enough robust evidence to support the use of experience learning curves (see Chapter 4). For example, it is not yet possible to tell which low carbon generation options will be cheapest in the medium to long term and the downward pressure on costs from experience-based learning can be outweighed by upward pressures from exogenous drivers (see Chapter 4). On balance, support for a mix of technologies until a clear winner or an optimal mix becomes clearer appears justified as it minimises the risk of policy failure[31].

---

[30] UK Energy Research Centre (2013) Presenting the Future: An assessment of future costs estimation methodologies in the electricity generation sector

[31] UK Energy Research Centre (2013) The UK energy system in 2050: Comparing Low-Carbon, Resilient Scenarios

Under current plans of revenue support for low carbon technologies, there is a higher opportunity cost associated with supporting nuclear power, which has an expected lifetime of 60 years, compared to renewables, which have an expected lifetime of 22-25 years (see Chapter 4). Although it is clear that investing in nuclear power means forgoing some future technology investment opportunities, it is not yet clear whether or how much this will cost consumers, because of the great uncertainty over future technology costs. Again, evidence suggests that picking winners early increases the risk that the UK locks itself into more expensive decarbonisation pathways.

Some have further argued that supporting nuclear power, currently a centralised energy technology, undermines support for decentralised low carbon technologies, including many renewables. Evidence shows that it is technically possible for centralised and decentralised technologies to co-exist and there are several examples around the world where substantial volumes of nuclear and renewables have coexisted, such as Sweden and Germany[32]. There is however a shortage of empirical research into whether there are instances of countries successfully supporting the *concurrent* deployment of large volumes of nuclear and renewables, as is planned for the UK[33].

---

[32] Tyndall Centre (2013) A Review of Research Relevant to New Build Nuclear Power Plants in the UK

[33] Watson et al (2012) Will a commitment to nuclear power have negative impacts on other low carbon options?

2. TECHNOLOGY & CHRONOLOGY

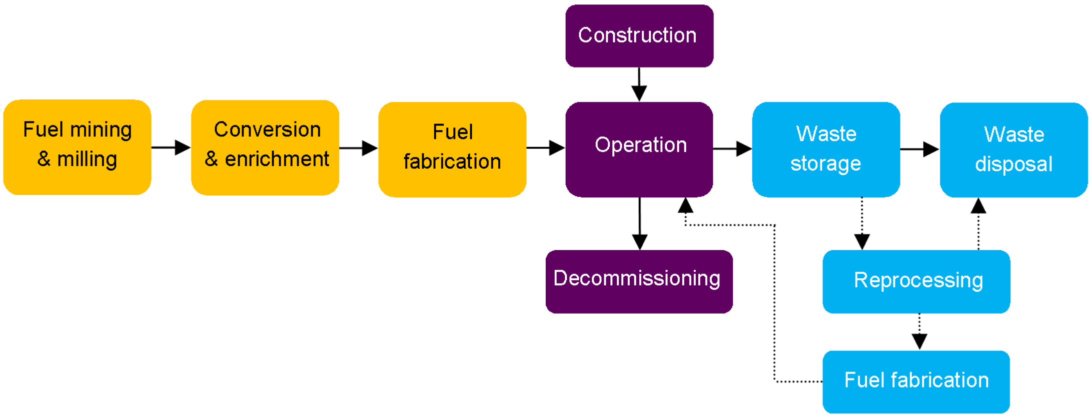
This chapter begins by giving an introduction to nuclear fuel lifecycles and reactor technologies, which is useful to understand not only the contribution that nuclear power makes to energy policy objectives today, but also the potential value that a number of fuel cycle and reactor technology developments could offer. This is followed by a history of civil nuclear power in the UK, an overview of recent developments and the UK's current position, and finally an exploration of nuclear's potential in the future. Understanding the chronology is important for considering the key strategic opportunities and challenges for nuclear power, introduced in Chapter 1.

2.1 The nuclear fission lifecycle

Nuclear power stations harness the energy contained within the nuclei of atoms, which can be done in two ways. Nuclear fission, which has been used to produce power for 60 years, splits the nucleus of an atom into smaller parts, releasing energy. Nuclear fusion, which is at a very early stage of development, fuses different sized nuclei to release energy. Both rely on an important property, namely that the nuclear energy available per atom is approximately one million times bigger than the chemical energy per atom of typical fuels.

The production of nuclear power involves three distinct stages: fuel mining and processing, power generation, and decommissioning and back-end fuel cycle. Figure 1 illustrates the key stages for a light water reactor. Around 88 per cent of install nuclear capacity is light water reactors, with reactors in countries such as the UK, the US, France, Japan, Russia, China and Sweden. Only one of the UK's current 16 reactors is a light water reactor with the remainder being gas-cooled reactors. However, all the reactor designs currently being considered for the UK new build programme are light water reactors (discussed later in this Chapter). Discussion of alternative fuel cycles and reactors designs follows.

Figure 1: Nuclear lifecycle (light water reactor)



Nuclear fuel

The first stage of the nuclear lifecycle involves the sourcing and processing of fuel. Today's nuclear reactors use uranium, a naturally occurring element found across the world (see Chapter 3). Once extracted, uranium ore is processed (milled), to separate uranium from the ore, producing uranium oxide. Leftover waste material (tailings) contains low concentrations of long-lived radioactive materials as well as toxic materials such as heavy metals[34]. Tailings are placed in engineered facilities to isolate them from the environment. Depending on the concentration of uranium in the ore, around 20,000 to 400,000 tonnes of extracted uranium ore is needed to fuel a one gigawatt light water reactor for a year[35].

Before uranium oxide can be used as a fuel in today's reactors it is enriched to increase the percentage of fuel that is able to undergo thermal fission (releasing energy). Around 27 tonnes of fresh enriched fuel is required to operate a one gigawatt light water reactor for a year[36]. Enriched uranium is transformed into ceramic pellets, encased in metal fuel rods and inserted inside a reactor. The current and future availability of nuclear fuel, and alternatives to uranium, are discussed in Chapter 3, on security.

Power generation

Today's nuclear reactors use heat generated by controlled fission reactions in fuel rods to drive a gas or steam turbine which generating electricity. This process is similar to that in fossil fuel and biomass power stations where heat from burning fuel is used to turn water into steam, which drives a turbine. Nuclear power stations can be made up of single or multiple reactor units. The other key components of a nuclear reactor are the moderator and the coolant. The moderator controls the rate at which fission reactions take place. A variety of chemical and mechanical means can be used to moderate the fission reaction. First generation reactors used graphite, whereas most designs today use 'light water', or normal water. The coolant, liquid or gas, captures heat from fuel rods and transfers it elsewhere to drive a turbine for power generation and regulate the temperature of the reactor core.

Decommissioning and back-end life cycle

Nuclear power stations are designed to operate for 30 to 60 years, after which they are decommissioned. In the UK, the ultimate aim of decommissioning is to return nuclear sites to 'greenfield' status. This involves the removal of nuclear materials, and the decontamination and dismantling of buildings to progressively reduce onsite hazards.

The final stage of the nuclear lifecycle involves dealing with spent fuel and other radioactive waste material ranging from nuclear site worker gloves and reactor components to storage liquids and metal fuel cladding. Spent fuel and other waste materials fall under three categories: high, intermediate and low level waste. High level waste (mostly unprocessed and reprocessed spent fuel) accounts for around 3 per cent of the volume and 95 per cent of the radioactivity of all waste, whilst lasting for up to hundreds of thousands of years. Intermediate level waste accounts for around 7 per cent of the volume and 4 per cent of the radioactivity of all waste. Low level waste accounts for 90 per cent of the volume and 1 per cent of the radioactivity of all waste. Low level waste materials can be recycled, reused or disposed, whereas the best long term solution for intermediate and high level waste is generally considered to be contained underground burial for thousands of years in a geological disposal facility (see Chapter 5).

The UK has chosen to reprocess much of its spent fuel, separating it into three mostly high-level waste components: actinides, uranium and plutonium. There are various potential options for re-using the separated uranium and plutonium as fuel, either with current reactor designs or future advanced reactor designs (discussed further below). Otherwise, reprocessed spent fuel materials would ultimately be put into a geological disposal facility.

Past and current generations of nuclear reactors operate a 'once through' fuel cycle, where fuel is used once in a reactor and is then managed as waste. Spent fuel can however be re-

---

[34] World Nuclear Association (2013) Website: The Nuclear Fuel Cycle (Accessed November 2013)

[35] Ibid

[36] Ibid

used as nuclear fuel, which is referred to as a more 'closed' fuel cycle. Current reprocessing produces a fuel that is more expensive than mined uranium, and therefore most countries have continued to use a once-through fuel cycle. In the future, advanced reactor designs could be run on existing spent fuel several times over, significantly reducing the need for fuel mining and reducing final waste volumes. This could be particularly advantageous in the UK, given the large volumes of unprocessed and reprocessed spent fuel it holds (see Chapter 5). The opportunity and challenges of developing advanced reactors and moving to a more closed fuel cycle are discussed later in this Chapter.

2.2 Present reactor technologies

There are a number of fission reactor technologies and design evolutions of these as well as new fission technologies have been proposed for the future. The key differences between fission technologies concerns their type of fuel and how they are moderated and cooled. This section outlines the evolution of current reactor technologies, and potential avenues in future.

Gas cooled reactors

The UK developed its own technology, Magnox, in a programme which led to the commissioning, in 1956, of the world's first full scale nuclear reactor at Calder Hall, by Sellafield in Cumbria. The Magnox reactor has a carbon dioxide gas coolant and graphite moderator. This combination of coolant and moderator was later adopted in Advanced Gas-cooled Reactors (AGR) developed by the UK in the latter half of the twentieth century and making up all but one of the UK's existing 16 reactors. They make up less than three per cent of installed world nuclear capacity.

Light Water Reactors

Many combinations of fuels and coolants were tested for nuclear reactors in the 1950s. Whereas the UK focussed on gas-cooled technologies, the USA and USSR developed Light-Water Reactors (LWR), which use water as both a coolant and moderator. These reactors are the now the most widespread commercial design in the world, accounting for around 88 per cent of installed capacity.

There are two dominant types of light water reactor. The first is the Pressurised Water Reactor (PWR), which has been used for around 65 per cent of worldwide reactors, and is that which is proposed by the EDF and Nugen consortiums for the UK. The second type is the Boiling Water Reactor (BWR) which has a simpler design[37] but slightly longer refuelling outages. Around 20 per cent of the world's reactors are Boiling Water Reactors, and the Horizon consortium proposes to construct this type of reactor at its UK sites – Wylfa and Oldbury. Reactors proposed for the UK are 1,100-1,600 megawatts capacity, as part of twin reactor designs.

Pressurised Heavy Water Reactors

Pressurised Heavy Water Reactors (PHWR) have been developed in Canada since the 1950s (as CANDU reactors), and more recently in India also. They make up around seven per cent of installed world nuclear capacity and reactors are generally 700 or 1,200 megawatts. Reactors use heavy water for coolant and moderator, although newer designs such as the Advanced Candu Reactor use light water coolant. Pressurised Heavy Water Reactors extract more useful energy per kilogram of mined uranium than other designs and do not need to be shut down for refuelling. Reactors have normally used unenriched (natural) uranium as fuel, but can also use reprocessed spent fuel (optionally mixed with depleted uranium), or thorium (discussed below). CANDU originally entered their Advanced Candu Reactor design into the UK's Generic Design Assessment process in 2007, but have since withdrawn it. The

---

[37] NNL (2013) Boiling Water Reactor Technology – International Status and UK Experience

Enhanced Candu 6 (EC6) design is being assessed as one of three 'credible solutions' for re-use of the UK's plutonium stockpile (see below and Chapter 1).

Current generation

The vast majority of reactors currently being constructed around the world are 'Generation III+' reactor designs and are the result of incremental improvements to light water design concepts first demonstrated in the 1960s and 1970s. The main driver for design changes has been to enhance safety, following accidents such as at Three Mile Island and Chernobyl. Design changes have also been made in an attempt to improve profitability, for example by designing longer life and bigger reactors to capture economy-of-scale benefits. However, as discussed in Chapter 4, bigger reactors has also resulted in increasingly complex designs and cost escalation. Around 80 per cent of on-going construction is of Pressurised Water Reactors and the remainder is a mix of Advanced Boiling Water Reactors, Pressurised Heavy Water Reactors and a small number of others[38].

2.3 Future reactor technologies and fuel cycles

Future fission reactors

A variety new advanced nuclear technologies, referred to as 'Generation IV', are in development, which depart from the dominant light water and heavy water designs. In addition, several countries are developing a variety of Small Modular Reactors based both on Generation III designs and variants of Generation IV designs (See Figure 2). Advanced technologies propose using different fuels, coolants and moderators to improve performance through greater fuel efficiency (fast reactors), higher temperature operation (thermal reactors) and more flexible siting and system integration (small modular reactors). In addition, development of advanced technologies could continue to improve safety and reduce proliferation risks of nuclear energy.

Fast reactors

Fast reactor technologies have been researched and developed for many years, resulting in a number of pilot and larger scale power stations around the world in countries such as France, Russia, China, Japan, India and the UK. Fast reactors provide a method to re-use various components of spent fuel including depleted uranium, separated plutonium and actinides, depending on the system. This could reduce some of the longer lived elements of spent fuel, reducing legacy waste and the specification of a future geological disposal facility.

For the UK, which has the world's largest stockpile of separated plutonium, systems which could make use of this could be particularly advantageous. One such Sodium-cooled Fast Reactor design, the PRISM reactor by GE Hitachi, is currently being considered by the Nuclear Decommissioning Authority as one of three 'credible options' for re-using the UK's stockpile of separated plutonium (see Chapters 1 and 5).

As well as potentially reducing the relative cost of managing nuclear waste (by increasing the energy to waste ratio), the greater fuel efficiency of fast reactors could also be advantageous if uranium prices rise significantly in future – a possibility under very high global nuclear deployment scenarios. Fast reactors could vastly extend our ability to extract useful energy from already mined fuel resources whilst producing smaller volumes of long lived waste.

---

[38] World Nuclear Association website: Plans for New Reactors Worldwide (accessed February 2014)

Figure 2: Overview of main advanced technology developments - Generation IV and Small Modular Reactors

System	Thermal / Fast	Coolant	Temperature (°C)	Fuel Cycle	Size (megawatts)
Very High Temperature Reactor (VHTR)	Thermal	Helium	900-1000	Open	250-300
Super Critical Water-cooled Reactor (SCWR)	Thermal (/Fast)	Water	510-625	Open / Closed	300-700 1,000-1,500
Sodium-cooled Fast Reactor (SFR)	Fast	Sodium	550	Closed	30-150 300-1,500 1,000-2,000
Gas-cooled Fast Reactor (GFR)	Fast	Helium	850	Closed	1,200
Lead-cooled Fast Reactor (LFR)	Fast	Lead	480-800	Closed	20-180 300-1,200 600-1,000
Molten Salt Reactor (MSR)	Fast (/Thermal)	Fluoride salts	700-800	Closed	1,000
Small Modular Reactors (SMRs)	Various	Various	Various	Various	Up to 500

Source: DECC (2013) Nuclear Energy Research and Development Roadmap: Future Pathways

Notes: 1) Existing Light Water Reactors operate at around 300-400°C and are 1,000-typically 1,600 megawatts.
2) More efficient power production can be achieved at around 500°C, high grade heat for industry from around 700°C and direct hydrogen production at around 950°C.

High temperature reactors

High temperature reactors are generally based upon developments of Generation III reactors but operate at much higher temperatures. This means that they could produce steam and high grade heat for co-located industrial processes, such as chemicals, metals, synthetic fuels, seawater desalination and hydrogen production. These synergies could reduce the costs of decarbonisation, either through decarbonising industrial heat or in the production of hydrogen which could be low carbon energy vector in a number of sectors including heat and transport. Synergies could also allow for more versatile reactor operation and economics, with nuclear providing flexible, or load following, output. (see Chapter 3).

Small modular reactors

Small modular reactors are in development in a number of countries including Argentina, China, Japan, Korea, Russia, South Africa and the United States[39]. The large size of many existing light water reactor designs has increased financing, construction complexity, siting and system integration challenges. Power stations could be sited more flexibly and integrated into the grid more easily because of the small capacity of reactors, which could be installed as single or multiple units (and changed over the power station lifetime). Whilst potentially losing out on economy of scale benefits, modular design could open up better possibility for cost reduction as has been seen in other energy technologies with modular designs, such as onshore wind turbines (see Chapter 4). However, the small size of modular reactors could also pose new challenges, such as making the economics stack up against the currently high fixed costs of regulation[40].

---

[39] DECC (2013) Nuclear Energy Research and Development Roadmap: Future Pathways

[40] NNL (2012) Small Modular Reactors Their potential role in the UK

Advanced fuel cycles and processing

Alongside and often interlinked with research and development of new reactor technologies is work on advanced fuel cycles and processing. This is particularly important for developing a more closed fuel cycle in parallel with the fast reactor designs discussed above. In a closed fuel cycle, fissile material is recovered and recycled from spent fuel and fed back into 'new' fuel. Some fuel cycles also incorporate long lived actinides into fuel, reducing the disposal challenge. Outcomes being pursued in advanced fuel cycle and processing work include reducing the volumes and radio-toxicity of waste, vastly improving fuel efficiency and reducing proliferation risks. Much of this work is being pursued through international forums and not only considers uranium and uranium-plutonium based fuel cycles and processing, but also thorium as an alternative nuclear fuel cycle.

Thorium fuel cycles

Thorium is more abundant than uranium and its chemical properties mean that waste from the thorium fuel cycle contains far less high level waste and poses a greatly reduced proliferation risk. Thorium is not itself fissile and so cannot be used directly in a thermal neutron reactor, which makes its fuel cycle potential more complex[41]. The thorium must be irradiated in a reactor to transmute to an isotope of uranium which is itself a fissile fuel. The fissile material can either be chemically separated to make nuclear fuel, or used 'in situ'. This second options is thought to be particularly suited to Molten Salt Reactors (see above).

Thorium could also be used in a fuel cycle with plutonium to reduce volumes of separated plutonium which is otherwise a high level nuclear waste and a proliferation risk. Pressurised Heavy Water Reactors, such as those developed by CANDU (ACR-1000 and EC6) are thought to be particularly well suited to thorium-plutonium fuel cycles. One of these reactor designs (EC6) is one of the three 'credible options' being considered for management of the UK's plutonium stockpile, although for use in a uranium-plutonium fuel cycle.

Although there was some early research and development, thorium research has suffered historical from a focus on uranium and uranium-plutonium fuel cycles. More recently, there has been a revival in thorium research, although this remains at an early stage. Several countries, such as India and Norway, have research and development programmes exploring using thorium both in Generation III and Generation IV reactors. Use of thorium in current reactors designs is a closer prospect (perhaps 10-15 years) with use of thorium fuel cycles in advanced reactor design being several decades away[42]. The economics of thorium fuel cycles are as yet unclear, but could be made more attractive in the future if uranium prices increase with scarcity[43]. Thorium is discussed in the context of fuel security and potentially high future uranium prices at the end of Chapter 3.

Nuclear fusion

Unlike fission technologies, nuclear fusion has yet to be demonstrated on a commercial scale. It has huge potential as a clean form of electricity generation due to an abundant fuel source (deuterium combined with tritium) and the lack of long-lived radioactive waste. It is also thought to be 'inherently safe' as any accident would be negligible outside the plant. However, research has been conducted into harnessing nuclear fusion for power generation for over 50 years and has yet to demonstrate a controlled reaction in which the useful energy released exceeds that being input. On-going research is now lead through several international collaboration projects, such as the International Thermonuclear Experimental Reactor (ITER) in France. It is thought that fusion is several decades from commercial demonstration at present.

---

[41] Birmingham Policy Commission (2012) The Future of Nuclear Energy in the UK
[42] National Nuclear Laboratory (2010) The Thorium Fuel Cycle
[43] DECC (2013) Nuclear Energy Research and Development Roadmap: Future Pathways

2.4 UK nuclear history

Box 1: UK-focused nuclear history

1950s – Government announces plans to build 5-6 gigawatts of Magnox reactors by 1965. First reactors were designed primarily for plutonium production, but later for power generation only. Reprocessing of spent fuel was chosen, partly because it was expected that separated, plutonium would provide fuel for a next generation of fast reactors. Little thought was given to either power station decommissioning or to the practicalities or costs of long-term waste management. Gas-cooled reactors were chosen and would turn out to be inherently more complex and expensive to decommission than other available technologies.

1960s – Commercial scale nuclear power production progressed and the now dominant Light Water Reactor developed from submarine propulsion developed by the USA and USSR. The UK Government launched a second nuclear build programme in 1964, to replace Magnox reactors and opted for Advanced Gas-cooled Reactors rather than Light Water Reactors. The programme suffered from construction delays and cost escalation, complicated by pursuing multiple design variants with little standardisation across the 15 reactors built between 1966 and 1989

1970s – Rapid expansion of nuclear power in USA and USSR. In 1974, responding to the oil crisis, France and Japan embarked on ambitious nuclear programmes. In the latter half of the decade, concerned by dependence on coal and the risks industrial action, the UK decided to build further Advanced Gas-cooled Reactors and its only Pressurised Water Reactor (Sizewell B). In 1979 there was a major nuclear accident at the Three Mile Island plant in Pennsylvania which slowed deployment, particular in the USA.

1980s – Following a long public inquiry, construction of Sizewell B began in 1987. The Nuclear Industry Radioactive Waste Management Executive (NIREX) was established in 1982, charged with finding a solution for the UK's long lived nuclear waste. In 1986 there was a major accident at Chernobyl in the Ukrainian Soviet Socialist Republic. In 1988 the UK announced power sector privatisation, but managing nuclear waste was excluded. The UK Government announced a moratorium on new nuclear power stations until 1994.

1990s – Worldwide deployment slowed, especially in the USA and Western Europe as a result of the difficulties of funding nuclear power stations in increasingly liberalised energy markets. In 1995, the UK Government concluded that there would be no public sector support for new nuclear, and no new private sector investment was planned. Existing operational nuclear reactors were privatised in British Energy in 1996. In 1997, a NIREX proposal for permanent waste storage near Sellafield was rejected by planning authorities, prompting Government to consult on a new approach in 2001 and establish the independent Committee on Radioactive Waste Management (CoRWM).

2000s – Driven by interest in emerging economies, rising fossil fuel prices and concern over climate change, interest in nuclear power recovered during the early 2000s. Nuclear continued to be out of favour in the UK, however, with a 2003 White Paper on Energy judging it to be an unattractive option due to poor economics and waste issues. In 2004, a struggling British Energy was re-nationalised and further waste liabilities transferred to Government before re-sale to EDF in 2008. The Nuclear Decommissioning Authority was established in 2005 to deal with the UK's nuclear legacy. In 2006, the CoRWM recommended that long lived waste should be stored in a deep geological repository and a site identified through partnership and voluntarism. A 2007 White Paper put nuclear back on the table as one of three broad options for electricity decarbonisation, alongside renewables and fossil fuels with carbon capture and storage.

2.5 Present: Four key strands of nuclear

There are four key strands of nuclear being pursued in the UK today.

1. **New build programme** – to replace soon retiring nuclear power stations with up to 16 gigawatts of new Generation III+ reactors before 2030.

2. **Waste and decommissioning** – largely concerned with decommissioning old sites and managing legacy waste, including finding a long term solution for intermediate and high level waste.

3. **Plutonium decision** – a process for deciding how to manage the large stockpile of separated plutonium which the UK holds from spent fuel reprocessing.

4. **Research and development** – to look at nuclear technologies with potential for deployment beyond 2030 (see above).

This section gives an overview of these four areas of work and points to where they are discussed elsewhere.

1) New build programme

The origins of the current nuclear programme can be traced back to 2006 when the then Department for Trade and Industry published its *Energy Review* proposing that nuclear should be considered as one of three broad low carbon power generation options alongside renewables and fossil fuels with carbon capture and storage. This was confirmed in a 2007 Energy White Paper which made clear that it made clear that it would be for the private sector to initiate, fund, construct and operate new plants and to cover the full cost of decommissioning and waste, to ensure the mistakes of the past were not repeated[44].

An ambition for the new build programme from the start was to replace today's existing nuclear power stations which provide around 20 per cent of the UK's annual electricity supply[45]. There are 16 operational nuclear reactors in the UK, with an installed capacity of around 10 gigawatts. These include: one Magnox reactor, owned by the Nuclear Decommissioning Authority and run by Magnox Limited: seven Advanced Gas-cooled Reactors owned by EDF; and a Pressurised Water Reactor at Sizewell B, also owned by EDF. The Magnox reactor is scheduled to close in 2015, and three Advanced Gas-cooled Reactors in 2019 followed by the rest in 2023. Sizewell B is currently scheduled to operate until 2035. The operators of these power stations may decide to extend the lives of these plants, subject to regulatory approval (discussed in Chapter 3).

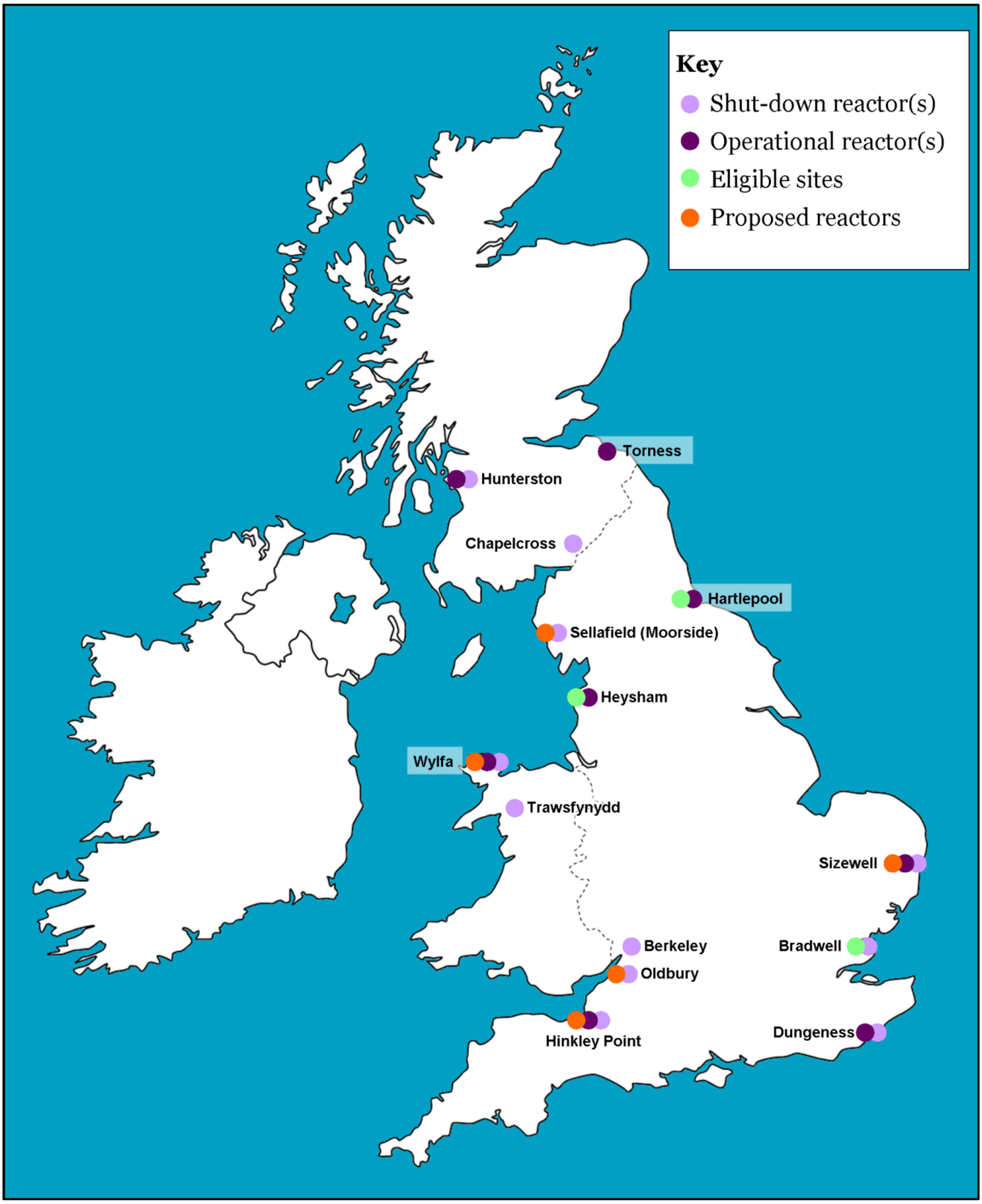
A series of measures to facilitate new reactors was proposed, including a National Policy Statement to allow nuclear power projects to follow a streamlined planning approach for 'nationally significant' infrastructure, a strategic site assessment to identify suitable sites for new reactors, and a pre-licensing Generic Design Assessment process to obtain regulatory approval for new reactor designs.

In 2008, EDF acquired sites for new nuclear in the re-sale of British Energy and land next to existing nuclear sites was also marked for sale to host new reactors. In 2009, Horizon and NuGen consortiums were formed and successfully bid for new sites, illustrated in Figure 3.

---

[44] Business Enterprise & Regulatory Reform (2008) A White Paper on Nuclear Energy
[45] DECC (2013) Digest of UK Energy Statistics

Figure 3: Map of existing and closed civil nuclear reactors



	EDF and Areva	Horizon	NuGen
Owners	EDF, Areva	Hitachi	Toshiba, GDF Suez
Technology	European Pressurised Water Reactor (Areva)	Advanced Boiling Water Reactor (Hitachi-GE)	AP1000 Pressurised Water Reactor (Westinghouse)
Plans	Hinkley Point (3.2 GW) Sizewell (3.2 GW)	Wylfa (2.7 GW) Oldbury (2.7 GW)	Moorside (3.4 GW)

The 2010 general election saw a split between the three main parties on nuclear power, with Labour and the Conservatives supportive, and the Liberal Democrats against. The formation of the Conservative – Liberal Democrat coalition saw a compromise over new nuclear, with Liberal Democrat MPs allowed to abstain in any House of Commons votes on nuclear power but not in the event of a confidence vote. In 2013, the Liberal Democrat's voted to support nuclear power, shortly before a deal between the Government and EDF was announced, giving the technology cross-party support on the basis of no public subsidy for new nuclear (political consensus is discussed further in Chapter 1).

In July 2011, the Government published a further Energy White Paper introducing early Electricity Market Reform proposals. This proposed changes to the electricity market to allow investment in high capital cost, low carbon generation through a new form of revenue support for all low carbon technologies (including new nuclear) which would replace the existing scheme for large scale renewables, the Renewables Obligation. The aim was to create a competitive framework between low carbon technologies allowing, where possible, market forces to decide levels of deployment.

Setting up the new build programme has made significant progress over the last few years. The Energy Act 2013, containing the various elements of Electricity Market Reform, was introduced as a Bill to Parliament in November 2012. It was at this time that the Government opened negotiations with EDF regarding the level of revenue support and other measures it would provide for the construction of the first two new reactors at Hinkley Point C, and a deal was announced in October 2013. This has been notified to the European Commission, which is currently investigating whether it meets its State Aid criteria. EDF plans to commence construction in 2014, pending State Aid approval, with the two reactors expected to come online in 2023 and 2024. The other nuclear consortiums, having both undergone changes of ownership, expect to deliver their first projects, at Wylfa and Sellafield, by 2025[46, 47]. Current developer plans could deliver 15 gigawatts of new capacity by 2030.

2) Waste and decommissioning

The UK also has a substantial nuclear legacy, with 25 closed Magnox reactors across 11 sites that have either commenced or are awaiting decommissioning. As well as sites for decommissioning, the legacy includes nuclear waste (see earlier in this Chapter). In particular, finding a long term solution for managing high and intermediate level waste from 60 years of military and civilian nuclear activity is an important issue of public concern.

The Government's preferred long term solution is to build a deep geological facility. High and intermediate level waste produced in new build reactors will also be stored in this facility, leading to a modest increase in its size. Finding a location for and implementing this solution will likely improve the long term safety, sustainability and public acceptability of nuclear power in the UK. The Government has adapted its process for finding a community to accommodate a facility in the light of past failures, most recently in January 2013 when despite strong support at a national and community level, Cumbria County Council rejected plans. Following this, the process is currently stalled and it is crucial that Government find a way to move this forward. The strategic importance of this finding a solution for long term waste is discussed further in Chapter 1 and nuclear waste is discussed in the context of sustainability in Chapter 5. An overview of the types of nuclear waste and where they fit into the nuclear lifecycle is given at the start of this Chapter.

3) Plutonium decision

---

[46] Telegraph (2014) 'UK nuclear project NuGen to be up and running in 2024'. Telegraph Newspaper, 14.01.14 (Accessed online February 2014) http://bit.ly/1i1qtWE

[47] Hitachi (2013) 'Co-operation agreement signed on Infrastructure Guarantee Scheme for Wylfa Newydd nuclear power station' 04.12.13 (Accessed February 2014) http://www.hitachi.com/New/cnews/131204.html

The UK is currently storing the world's largest civilian stockpile of separated plutonium at Sellafield, Cumbria, and Dounreay in Scotland. Separated plutonium is highly radioactive, and can be processed for use in nuclear weapons, and must therefore be handled safely and securely. It can also be used as nuclear fuel, in both existing and advanced reactors.
The plutonium, in its current form, is particularly hazardous and is a proliferation risk, and for these reasons the Government's strategy is to re-use the stockpile in reactors, to transform it into a state that is more suitable for emplacement underground in the planned Deep Geological Facility[48]. Current facilities are able to store the material until 2121 at the latest[49], although this is deemed impractical as over time the material will become more hazardous and difficult to handle due to radioactive decay. Direct immobilisation (for example by encapsulation in another material such as cement) is currently thought to less technically and economically viable than reactor re-use.

In January 2014, the Nuclear Decommissioning Authority announced that it had identified three 'credible solutions' for re-use and would spend up to two years undertaking technical studies of these solutions. The current strategy aims to begin the implementation of a chosen solution within around 25 years[50]. The details, advantages and disadvantages of the solutions are far from fully clear yet, but Figure 4 gives an overview of the three options.

The decision has implications for a number of the UK's strategic priorities including nuclear waste, non-proliferation, research and development and power generation, and therefore requires substantial coordination across Government. As Figure 4 explains, two of the three options involve the construction of dedicated reactors, each offering a number of ways to immobilise the plutonium as rapidly as possible, or to extract the energy contained within the plutonium. These options, and their implications for power generation and final waste disposal, should also form part of the Governments' assessment. The key strategic opportunities and challenges of this decision are discussed in Chapter 1.

4) Research and development

Despite the return of nuclear power to Government plans for power sector investment since 2007, a 2013 review by the Government's then Chief Scientific Advisor found that the institutional landscape and funding still reflected the policy environment of the 1990s and early 2000s[51]. In particular, activity was focussed on the nuclear power of the past (decommissioning) the present (safety and performance) and the very long term future (fusion), but not on developing new nuclear fission technologies or fuel cycles for the medium to long term. Consequently, the UK's plans for involvement in nuclear research and development are at a relatively early stage, having been revisited since the Beddington review of the civil nuclear research and development landscape, published in March 2013.

The Government's initial response to the Beddington review has been promising. Several major international initiatives, such as the Generation IV International Forum, are coordinating national research and development activities into new reactors and fuel cycles and the UK is now re-joining this 'top table' in international collaboration on nuclear research and development. The Government has also established the Nuclear Innovation Research Advisory Board and Nuclear Innovation Research Office to help define a national programme of nuclear energy research and development. The strategic importance of the UK's nuclear research and development work is discussed further in Chapter 1 whilst an overview reactor technologies and fuel cycles is given earlier in this Chapter.

---

[48] DECC (2011) Management of the UKs Plutonium Stocks: A Consultation On The Long-Term Management Of UK Owned Separated Civil Plutonium
[49] NDA (2011) Plutonium: Current Position Paper, February 2011
[50] Ibid
[51] HMG (2013) A review of the civil nuclear R&D landscape in the UK

Figure 4: Comparison of the three 'credible options' for plutonium re-use

Option 1: Mixed Oxide (MOX)

Construct a MOX plant at Sellafield to convert the plutonium into Mixed-Oxide fuel (MOX) for use in light water reactors in the UK or potentially abroad.

- Relatively low technology risk.
- Previous experience of reprocessing in the UK.

- Uncertain market for MOX fuel – new build operators currently have little appetite or economic incentive to use it.
- May only be able to deal with 80 – 90 per cent of the stockpile cost-effectively.
- Direct MOX disposal will increase space requirement in Geological Disposal Facility.

Option 2: Candu-MOX

Plutonium converted into CANMOX fuel using dedicated fuel fabrication facilities, for use in Candu EC6 (heavy-water) 600 megawatt reactors. Resultant spent fuel is similar to MOX spent fuel and is ready for final disposal. Two reactors could operate on plutonium fuel for 60 years, or four reactors could use plutonium for 30 years, after which they could be reconditioned to operate for another 30 years on thorium, natural uranium or recovered uranium.

- Able to utilise a wider range of the plutonium inventory.
- Simpler fuel manufacturing process compared to MOX, with likely lower capital and operating costs.
- Reactor is an evolutionary (Generation III+) update to existing technology.
- Commercial viability – interest from developers and third parties to finance a project.

- Some technology risk - fuel fabrication systems have not been delivered at full industrial scale for plutonium fuels.
- Limited regulatory experience of Heavy Water moderated reactors in the UK.

Option 3: GE Hitachi PRISM

Plutonium converted into a metal fuel for use in two 300 megawatt PRISM reactors (Sodium Cooled Fast Breeder Reactors). Plutonium not consumed but highly irradiated in 5 – 20 years, resulting in harder to handle and therefore more proliferation resistant spent fuel, ready for storage. Alternatively, this spent fuel could be re-used in the reactors for 60 years of power generation.

- Able to utilise a wide range of the plutonium inventory.
- Potentially rapid plutonium neutralisation (5 years) through irradiation.
- Re-use of resultant spent fuel would provide 60 years of power generation and reduce radioactivity of final spent fuel.
- Opportunity to commercialise fast reactor technology and establish UK as a technology leader.

- Final disposal of highly irradiated spent fuel more challenging (if this option is chosen).
- Higher technology risk, due to reliance on relatively unproven materials and fuel fabrication systems.
- Uncertainty of financing such a project without further state support.

Sources: NDA (2014) Progress on approaches to the management of separated plutonium
The Engineer (2013) Prism project: A proposal for the UK's problem plutonium
Candu website: www.candu.com (Accessed February 2013)
Institute of Mechanical Engineers (2013) UK Plutonium: The way forward

2.6 Role of nuclear in future scenarios

The remainder of Chapter 2 explores the range of roles suggested for nuclear energy across a variety of electricity and energy system pathways, initially in the medium term to 2030, and later in the long term to 2050. Energy system models are typically used to look at different pathways for achieving the 2050 carbon target whilst maintaining minimum levels of energy security and optimising costs. Pathways are normally tested across a range of input assumptions to test their sensitivity and robustness to existing uncertainty in inputs, such as future technology costs, fuels prices and carbon prices.

In order to meet the UK's 2050 carbon target, the long term objective for the power sector, as recommended by the Committee on Climate Change is to reach zero or negative emissions by mid-century[52]. Whilst navigating the power system (and wider energy system) through this transition, Government will continue to face the challenge of balancing security and affordability policy objectives. Moving to low carbon generation will ensure long term affordability in a carbon constrained world, with the costs of today's dominant source of electricity generation, fossil fuel power, increasing in cost as carbon prices rise over the next decades (see Chapter 4). Constructing a mix of generating technologies could also help diversify security of supply risks (see Chapter 3).

In the medium term, around 50 per cent of existing power station capacity is set to retire by 2030. To meet carbon budgets, replacement power stations will need to be predominantly low carbon generation with some new unabated gas power operating increasingly as back up and peaking plant, rather than baseload. Reducing electricity demand could also offset the need to build many new power stations. The supply of electricity may need to expand significantly towards 2030, depending particularly on the extent of electrification in heat and transport.

2.7 Nuclear to 2030

There is a relatively known pathway of power generation deployment to the end of this decade, with Government setting the ambition to generate at least 30 per cent of electricity from renewable sources by 2020, up from 11.3 per cent in 2012[53, 54]. New renewable generation will help offset the loss of up to 10 gigawatts of retiring plant capacity this decade (see Chapter 3). New nuclear will not play a role, given the eight to ten year lead time of new reactors. Up to two fossil fuel power stations with carbon capture and storage could be operating by 2020, depending on progress of the Government demonstration competition. The retirement of old power stations will continue in the 2020s, with up to 27 gigawatts of capacity potentially retiring by 2023, although there could be life extensions for up to 3.5 gigawatts of existing nuclear power stations out to around 2030, in addition to coal power life extensions (see Chapter 3). Electricity demand is expected to grow slowly, especially if Government energy efficiency programmes are successful.

There are two key variables that will decide what supply mix develops during the 2020s, and what level of nuclear deployment takes place. The first is the effective budget for supporting deployment of low carbon technologies (the Levy Control Framework, discussed later). This is currently agreed to 2020/21 when annual spending, on a range of policies including support for low carbon generation, can reach £7.6 billion (2012 prices). This is expected to be enough to increase the share of renewable electricity to over 30 per cent[55]. There is no indication yet as to what money will be available to support deployment of low carbon technologies beyond 2020, other than for Hinkley Point C. It has been calculated that to

---

[52] CCC (2012) The Fourth Carbon Budget
[53] DECC (2013) Digest of United Kingdom Energy Statistics
[54] Under the EU Renewables Energy Directive the UK must source 15 per cent of energy from renewable sources by 2020
[55] Carbon Connect (2013) Power from Renewables

achieve recommended emissions reductions by 2030, annual spending would need to rise to £11.5 billion per annum in 2025 before falling to £10 billion in 2030[56].

The second factor that will determine the mix of generation technologies in 2030 is the cost and deliverability of options (see Chapter 4). Although the exact process and timing is unclear, Government's intention is to move towards a regime under which low carbon technologies compete for revenue support, directly with one another on cost. The Government's ambition is to move to this regime at some point during the 2020s[57]. The challenge of deciding if and how and when to make this transition is discussed in Chapter 1.

The volume and mix of low carbon generation deployed will determine the extent to which fossil fuel power stations are used and consequently at what rate the power sector is decarbonised[58]. To be on track to meet the 2050 carbon reduction target cost effectively, the Committee on Climate Change recommends that the carbon intensity of the power sector be reduced to around 50 grams of carbon dioxide per kilowatt-hour (gCO2/kWh) by 2030[59]. The Government has yet to provide clarity on its ambition for the power sector to 2030. It has set economy wide carbon budgets up to 2027 and has indicated the existing and planned policies are likely to result in a carbon intensity for the power sector of around 100 gCO2/kWh, although it has modelled scenarios between 50 and 200 gCO2/kWh in 2030[60].

Availability of sites on which to build new nuclear power stations is not expected to be a constraint up to 2030. Eight sites in England and Wales are eligible for new reactors under the 2011 National Policy Statement on Nuclear. Although there are several existing nuclear power sites in Scotland, these were not included in site selections for the new build programme. The granting of planning consent for large power stations is devolved to the Scottish Government, which voted against new nuclear power in 2008[61]. It is estimated that eligible sites could accommodate a maximum of 23 gigawatts of new nuclear capacity[62]. If all current plans go ahead, eleven new reactors will be built across five of the sites, giving a total of 15.2 gigawatts (see Figure 3).

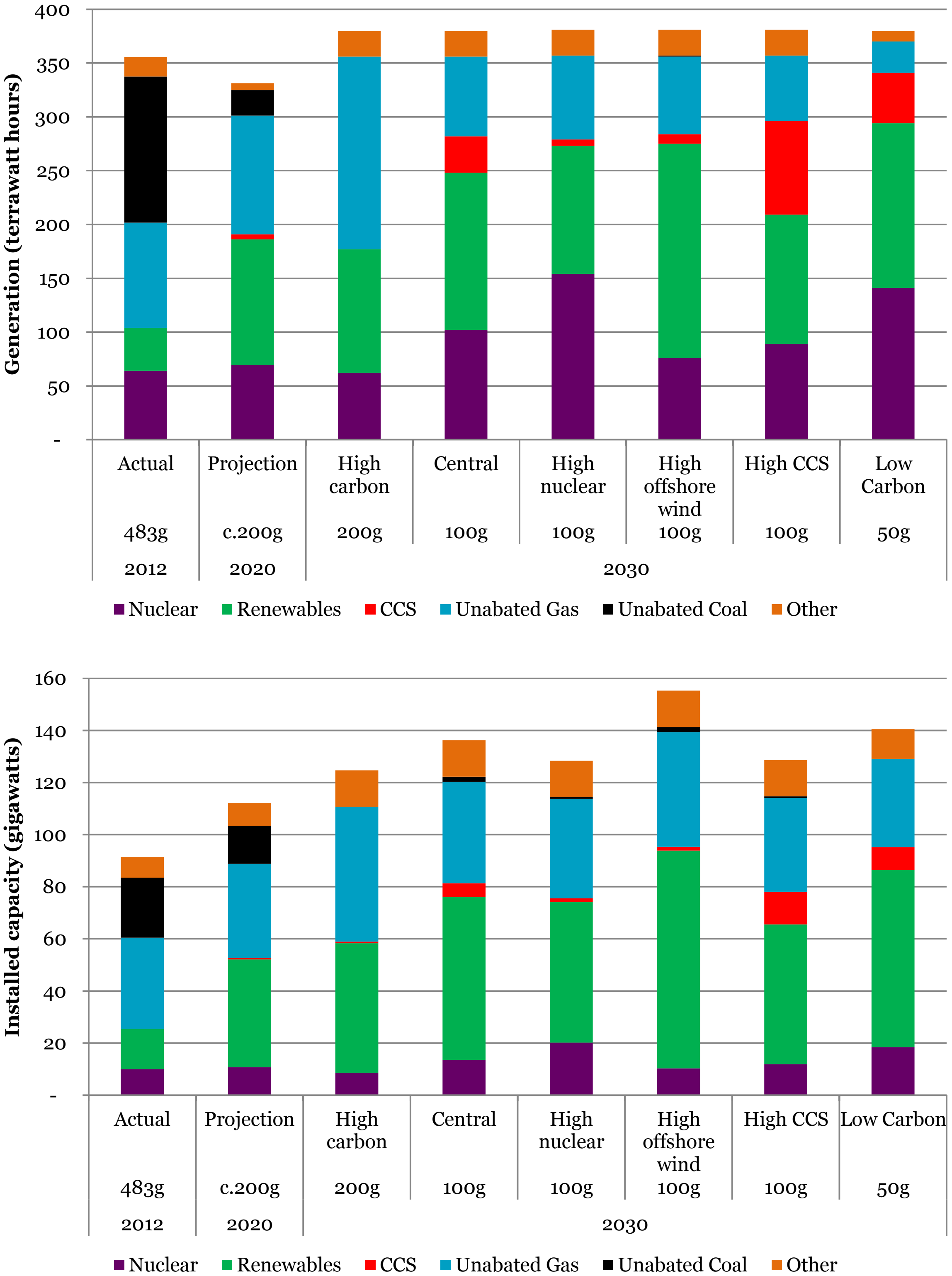
Scenarios

Government has modelled scenarios reaching 100 gCO2/kWh power sector carbon intensity by 2030 with between 10 and 20 gigawatts of nuclear capacity, with a central case of 14 gigawatts (new and old) (see Figure 5)[63]. This central scenario however assumes that the levelised costs of nuclear fall to around £85 per megawatt hour in the mid-2020s, and therefore assumes that new nuclear build will reverse the long term trend of cost escalation (see Chapter 4). Alternative 2030 scenarios deploying higher amounts of offshore wind (up to 41 gigawatts) and fossil fuels with carbon capture and storage (13 gigawatts) are accompanied by 10 to 12 gigawatts of nuclear. Even in a scenario of 200gCO2/kWh in 2030, a scenario incompatible with carbon budgets, there is nine gigawatts of nuclear in 2030 (new and old). Achieving a power sector carbon intensity of around 50 gCO2/kWh by 2030, as recommended by the Committee on Climate Change, would require an increased share of low carbon generation. This would result in the displacement of more unabated gas generation, which is likely to be the largest remaining source of carbon on the system (although there is a carbon risk from coal power life extensions[64]). The Government's central scenario for achieving this includes 19 gigawatts of nuclear, alongside increased offshore wind (26 gigawatts) and fossil fuels with carbon capture and storage (9 gigawatts).

---

[56] CCC (2013) Next Steps on EMR Reform
[57] DECC (2013) EMR Delivery Plan
[58] Carbon Connect (2013) Power from Fossil Fuels
[59] Ibid 56
[60] Ibid 57
[61] The Scotsman (2008) MSPs vote no to new nuclear stations (Accessed February 2014)
[62] National Nuclear Laboratory (2011) UK Nuclear Horizons: An independent assessment
[63] Ibid 57
[64] Ibid 58

Figure 5 - Comparing generation and capacity mixes (2012, 2020 and 2030)



Sources: DECC (2013) Energy Trends; Energy and Emissions Projections; EMR Delivery Plan
Notes: 1) 'g' refers to grams of carbon dioxide per kilowatt-hour – the carbon intensity of the power sector
2) 2012 is the latest complete calendar year for which data is available
3) CCS is coal and gas powered with carbon capture and storage
4) Other includes storage and interconnection
5) Capacity is installed capacity, not de-rated

No nuclear?

Government scenarios have been criticised by some for not exploring a no-nuclear future in the UK[65]. This section considers how medium term ambitions might be achieved in the event that the new build programme achieves limited or no deployment. It is technically feasible to achieve medium term targets without new nuclear power stations, but the costs of doing so are very unclear. 'No nuclear' pathways using the Government's 2050 pathways calculator can be cheaper or more expensive than the cost-optimised scenario demonstrated which includes around 31 gigawatts of nuclear in 2050. The UK Energy Research Council found that across nine cost-optimised model runs, nuclear has the highest power sector contribution in six of them[66]. All model runs include significant contributions from all of nuclear, renewables and fossil fuels with carbon capture and storage, although the mix depends particularly on cost assumptions. All the runs used 2010 published engineering cost estimates of nuclear power[67] which have been updated to around 14 per cent higher in the Government's 2013 electricity generation cost estimates[68].

Power sector carbon reductions to 2030 could be achieved without nuclear by expanding the deployment of renewables and fossil fuels with carbon capture and storage. Renewables with the potential to be deployed at scale by 2030 are likely to be onshore and offshore wind and solar photovoltaic. Biomass could have considerable potential, but there is uncertainty regarding the size of the sustainable fuel resources in future[69]. Other renewable technologies (tidal, marine) are at an early stage of technological development and are not likely to be deployable at scale in time. With the majority of additional generation available from varying renewables, a significant expansion in the tools to manage their varying output would be required, the costs of which are highly uncertain (see Chapter 3). This strategy would also likely need significant deployment of fossil fuels with carbon capture and storage to provide low carbon baseload generation. The costs and deliverability of this technology are also uncertain, with recent estimates that a maximum of 13 gigawatts could be deployed by 2030[70, 71]. The Government argues that according to current estimates, the cost of achieving medium term objectives without nuclear power would likely be higher[72]. There is a high degree of uncertainty regarding this claim, because it is far from clear which power generation technologies will be cheapest in 2020-30 (see Chapter 4).

2.8 Nuclear to 2050

The electricity supply mix in the long term (from 2030 to 2050) is necessarily less certain, but is likely to be guided by two principle factors. Firstly, power sector emissions will need to be reduced to near zero or negative as carbon budgets tighten, and secondly, demand for electricity could increase dramatically.

Higher electricity demand could be driven by economic and population growth, demand from more electronic appliances such as air conditioning and potentially substantial electrification of heat or transport or both[73]. Energy system modelling consistently shows that at least some electrification of heat and transport is likely to be required to achieve the 2050 targets cost effectively[74,75,76]. Domestic gas boilers and internal combustion engines will need to be replaced, and there are a number of electric (electric vehicles, heat pumps) and non-electric (hydrogen fuel cell vehicles, biofuels and biomass) options that could be substituted for them.

---

[65] Friends of the Earth (2012) A plan for Clean British Energy: Powering the UK with renewables – and without nuclear
[66] UKERC (2013) The UK energy system in 2050: Comparing Low-Carbon, Resilient Scenarios
[67] Mott MacDonald (2010) UK Electricity Generation Costs Update
[68] DECC (2013) Electricity Generation Costs July 2013
[69] Carbon Connect (2013) Power from Renewables
[70] DECC (2013) Updated Energy & Emissions Projections
[71] CCC (2013) Next Steps on EMR Reform
[72] DECC (2013) EMR Delivery Plan
[73] CCC (2012) The 2050 Target
[74] UKERC (2013) The UK energy system in 2050: Comparing Low-Carbon, Resilient Scenarios
[75] ETI (2011) Modelling the UK energy system: practical insights for technology development and policy making
[76] AEA (2011) Pathways to 2050 – Key Results

If substantial electrification of heat and transport takes place, annual electricity demand could increase by between 30 and 60 per cent by 2050 (on 2007 levels)[77]. Some of this upwards pressure on electricity demand could be offset if energy efficiency polices are successful.

Nuclear power stations could be used as a source of low carbon heat, as well as power, in the future. Like all thermal generators, nuclear power stations produce heat, around two-thirds of which is not utilised due to the thermal efficiency of the power generation process[78]. Some of this heat can be captured and transported via heat networks for use in buildings and industry (located within 50 kilometres), as has been demonstrated in Switzerland and Russia. Recent modelling for the Government suggests that waste heat from nuclear power stations could supply around 30 terrawatt-hours per year to district heat networks in 2050, equivalent to around seven per cent of the estimated total heat demand from domestic and non-domestic buildings[79].

It is technically possible to adapt the steam turbines used in today's nuclear power stations to co-produce heat and power, increasing the overall energy efficiency of a plant although at the penalty of reduced electrical output and greater operating constraints[80]. In the future, advanced reactor designs could produce higher temperature heat, opening up further options for producing low carbon heat for industry, including hydrogen production, as well as more efficient power production[81]. Very High Temperature Reactors (see earlier in this Chapter) could open up these opportunities. Pilot plants have been constructed in China and Japan, although technical challenges remain on the path to commercialisation[82]. Alternative low carbon options for industrial process heat include fuel substitution with (low carbon) gas, hydrogen and electricity or fitting carbon capture and storage. Alternatives for hydrogen production include electrolysis (using excess low carbon electricity) or coal, gas and biomass gasification in conjunction with carbon capture and storage.

The technologies needed to meet the range of possible future challenges exist, but it is not yet clear what mix of them will prove economically and practically feasible. With many scenarios indicating a potentially large increase in future electricity demand, developing a range of low carbon generation technologies, including nuclear power, until an optimal mix becomes more apparent is sensible[83].

How much nuclear?

New generating capacity will be required beyond 2030 to replace retiring plant, including old unabated gas plant and wind capacity built in the 2010s and 2020s. Given tightening carbon budgets during this period, new generation will need to come from low carbon sources, with little scope to add unabated gas if it is to be used for baseload power. Nuclear built in the new build programme currently being planned will operate beyond 2050 (according to vendor lifetime estimates), with additional nuclear capacity one of several options to expand low carbon supply. Scenarios using the energy system model that informed the Government's Carbon Plan in 2011 and the Fourth Carbon Budget indicate that a range of 23 to 55 gigawatts of nuclear capacity could be required by 2050, under different cost and policy assumptions. Annual electricity supply varies between 423 and 842 terawatt hours across these scenarios[84], in comparison to total supply of 375 terawatt hours in 2012[85].

---

[77] DECC (2011) The Carbon Plan

[78] World Nuclear Association (2013) Nuclear Power Reactors (Accessed November 2013) http://www.world-nuclear.org/info/Nuclear-Fuel-Cycle/Power-Reactors/Nuclear-Power-Reactors/

[79] Redpoint Energy (2013) Modelling to support The Future of Heating: Meeting the Challenge

[80] Jones, C. (2013) Utilising Nuclear Energy for Low Carbon Heating Services in the UK. University of Manchester

[81] Birmingham Policy Commission (2012) The Future of Nuclear Energy in the UK

[82] The Breakthrough Institute (2013) How to Make Nuclear Cheap

[83] UKERC (2013) The UK energy system in 2050: Comparing Low-Carbon, Resilient Scenarios

[84] Ibid

[85] DECC (2013) Digest of UK Energy Statistics

The balance of deployment between nuclear, renewables and fossil fuels with carbon capture and storage will be guided primarily by their relative costs and feasible deployment. High deployment of nuclear power (say significantly beyond 20 gigawatts) raises a number of issues including the siting of new reactors, the availability of uranium fuel and the impact that additional waste would have on long term waste management.

A key issue for deployment of high levels of nuclear would be the location of new reactors. Three of the sites eligible for new reactors under the National Planning Statement for nuclear have no current development plans[86] (see Figure 3) and could accommodate up to nine gigawatts of reactors. Sites with existing nuclear power activities (operational or closed reactors) are the most likely to be considered for expansion beyond these locations. A Government commissioned review in 2007 proposed a hierarchy for identifying new sites, with existing nuclear power sites considered the most favourable due to the presence of existing infrastructure and network connections, and local communities with the relevant skills[87]. There are a further three existing nuclear power sites in Scotland and two in England and Wales[88] that were not put forward during the current new build programme and could have future development potential. Additional locations could include existing civil nuclear licensed sites (such as fuel processing centres) followed by existing coal or gas plant sites. The social and governance implications of siting new nuclear in locations with no history of such operations have however received little research or policy attention.

Deployment of around 40 gigawatts is generally assumed to be the very upper bound of feasible deployment using existing nuclear power sites[89, 90]. Small Modular Reactors with smaller land, water and grid access requirements could allow more flexible siting of reactors in the future (see earlier in this Chapter). These reactors could also more easily be placed close to industrial clusters or centres of heat demand for combined heat and power production.

High nuclear deployment beyond the current new build programme will require careful consideration of long term waste management and fuel availability. A large ‘once through’ Generation III+ reactor fleet operating by 2050 would increase the UK’s nuclear fuel requirements and generate significant quantities of waste. For example, the uranium fuel requirements of a 41 gigawatt fleet in the UK would represent approximately 7 per cent of global uranium ore production in 2010[91]. With the global fleet of nuclear reactors expected to grow over the next decades, closed fuel cycles or alternative fuel cycles such as thorium could become practically more necessary and economically more attractive. Spent fuel reprocessing, or the development of advanced reactors able to extract significantly more energy from fresh fuel and spent fuel, would help alleviate both fuel and waste challenges arising from a high nuclear deployment (see earlier in this Chapter, and Chapter 5).

---

[86] Bradwell, Heysham and Hartlepool

[87] Jackson Consulting (2007) Siting New Nuclear Power Stations: Availability and Options for Government

[88] Hunterstone, Torness, Chapelcross in Scotland, Trawsfynydd in Wales and Berkeley in England.

[89] NNL (2011) UK Nuclear Horizons

[90] ETI (2011) Modelling the UK energy system: practical insights for technology development and policy making

[91] Ibid 89

3. SECURITY

We take for granted that power is always available and ready when we need it, and a widespread interruption to supply can cause significant social and economic disruption. Security is provided by ensuring that risks to operational and fuel security are properly managed. Historically, electricity has not been easily storable at scale and storage has been 'up-steam' in the form of fuel (such as coal, gas, biomass and uranium) or pumped hydro. Electricity is generated from these up-stream stores as well as other un-storable sources such as wind and solar energy, to keep supply from power stations balanced with demand from consumers as it varies across seconds, hours, days, weeks seasons and years.

This chapter examines what benefits and risks nuclear power provides to system and fuel security. Important changes in the nature of both electricity supply and demand are expected to take place over the coming decades, and the interaction between nuclear power and these trends is also explored.

How do we ensure system security?

Electricity supply is the result of the operation of the whole electricity system - markets, fuel supply chains, power stations and networks. There are a variety of risks to the continued and stable operation of the system, ranging from the physical (power station and network failure caused, for example, by weather events), price (volatility in the price of key inputs such as fuel) and geopolitical (external risks to fuel supply chains). Maintaining energy security involves reducing and managing these risks .

Understanding individual risks related to a technology or fuel is useful, but ultimately, it is the ability of the system to handle these risks that will determine how secure it is. The critical question, when assessing options for power generation, is whether, and to what extent, a technology can form part of a secure and reliable system. How the characteristics of nuclear power interact with power system operation is assessed over three key operational timeframes. Fuel security and interactions with other changes required in the energy system are also examined.

3.1 The characteristics of nuclear power

Nuclear is a type of thermal power generation, in which water is heated into steam, spinning a turbine which in turn drives an electrical generator. Conventional thermal generation (coal, gas, biomass) uses fuel combustion as a source of heat, whereas nuclear reactors use a controlled nuclear-fission chain reaction.

The output of nuclear power stations is determined by reactor physics, the characteristics of large steam turbines, and economics. It can take several days to bring a reactor on or offline, but once generating, it is able to operate continuously, but for occasional unplanned outages and planned outages such as for maintenance. Nuclear power stations are currently designed to run continuously throughout the year, with planned pauses for maintenance and refuelling only. Re-fuelling takes place only every two years, due to the highly concentrated nature of nuclear fuel. Some reactors are able to refuel during operation, extending their potential to run without interruption. Pauses for refuelling, maintenance and regulatory checks can be scheduled for periods of low demand, such as the summer, and there is a considerable amount of flexibility over when exactly power stations close for re-fuelling as nuclear fuel loses intensity gradually rather than being completely consumed like fossil fuels or biomass. Nuclear power stations can achieve availability factors (percentage of hours in a year they are available to generate) similar to or above other thermal generators.

The technical and economic characteristics of nuclear power stations are suited to continuous operation. Whilst it is technically possible to vary output over the course of several hours by modifying reactor output, this comes at the penalty of greater wear and tear, and cost. Nuclear power stations have very high capital costs, and operators are therefore incentivised to operate as much as possible in order to pay back the significant volumes of capital borrowed upfront. Historically there have been cheaper ways of providing system flexibility than varying the output of nuclear power, and this is likely to continue to be the case in the future.

FINDING 8

Nuclear power stations currently have an inflexible electrical output for economic, rather than technical reasons. Although they could be operated more flexibly in future, it is likely that other technologies could provide system flexibility at lower cost.

3.2 System security

The electricity system is operated by ensuring that output from power stations (supply) matches demand at all times. Demand follows predictable daily, weekly and seasonal patterns, and power stations are contracted through the electricity market to provide supply to match. A variety of factors can cause an imbalance between supply and demand, ranging from market errors to power station outages, and are managed to ensure a secure and stable supply to consumers. These risks are managed across three principle timeframes:

- **Short term: one hour before delivery**; risks from anticipated and unexpected changes in supply and demand during the final hour before delivery are managed by keeping a proportion of capacity in reserve, which is able to adjust supply and demand rapidly (seconds to minutes) on request.
- **Medium term: load following**; electricity demand fluctuates significantly over the course of a day, and power stations are scheduled to come online to follow these changes, or to adjust their output accordingly.
- **Long term: capacity adequacy;** demand also varies over the seasons. Peak demand in winter can be up to 45 per cent higher than in summer. A sufficient margin of generating capacity must be maintained over and above peak demand, to provide contingency should some power stations be unavailable (through maintenance or unexpected outages) when needed, or due to spikes in demand.

We now look at the effect of integrating nuclear power on each timeframe of system operation and consider impacts on overall system security. Most of the technical challenges facing electricity system operation can be met using available technologies, and for many challenges the principle policy implication is the economic cost of providing adequate system security, rather than the technical feasibility of doing so. For this reason, this chapter also includes a discussion of the costs of providing system security, which links to Chapter 4.

3.3 Short term balancing

Levels of electricity supply and demand fluctuate continuously, and large imbalances can occur through errors in predicting demand and unexpected power station outages (through technical fault). These imbalances are managed by the system operator, National Grid, which takes responsibility for ensuring supply and demand are balanced once trading in the electricity market has ceased, in the final hour before electricity is delivered to consumers.

Unexpected changes during this final hour are managed with a variety of tools. Rapid adjustments to adjust supply up or down are provided by automatic controls on operating power stations that can respond in seconds, demand reduction from industrial and commercial users, and by fast responding 'peaking plant' such as open cycle gas turbines or back-up diesel generators that can be ready within 20 minutes. The characteristics of individual power stations affect the level of system risk, and ultimately, the services that will be contracted by the system operator to manage them. The quantity of reserves contracted is determined by three principle risks: the size of the largest single generator that could fail, the expected availability (probability) of all conventional plant on the system and a given amount of demand prediction errors.

The availability (probability of operation) of nuclear power stations is similar to that of other conventional generators like coal and gas. Their output is relatively stable, with scheduled pauses required for maintenance and re-fuelling only. New nuclear power stations are designed for a higher level of availability than in the past. Although only a handful of current generation reactor designs are in operation worldwide, evidence shows that historically, the availability of plants in operation worldwide has increased over time[92].

The larger size of planned new build reactors compared with the UK's existing fleet will, however, increase short term risks should a reactor fail unexpectedly. Today, the largest single unit on the network is the Sizewell B reactor, at 1.1 gigawatts. Hinkley Point C, once operational, will feature two reactors of 1.6 gigawatts, a 45 per cent increase in size. The risks of a larger potential loss can be managed by increasing the size of the reserves contracted. It has been estimated that the connection of several reactors of this size could increase these short term operational costs from around £160 to a £319 million pounds per year[93]. This compares to an overall budget for actions by the system operator of £603 million in 2012/13[94], which constituted less than one per cent of the unit price of electricity. New build nuclear will therefore be similar to other technologies, such as varying wind[95], that can increase some short term operational risks.

System services

In comparison to other forms of generation, nuclear power stations currently make a limited contribution to the tools used to manage system risks in this timeframe. Their contribution is limited by economic, rather than technical properties. It is technically possible to use nuclear power stations to make small changes (up to 5 per cent) in output or frequency at short notice from the system operator[96, 97]. However, these responses are general slower, smaller and more expensive in comparison to other tools such as thermal plant or demand side response. Because of the high capital and low operating costs of nuclear power and the wear and tear that providing these services would entail, other tools have generally been cheaper alternatives, and will probably continue to be.

One advantage that nuclear power stations bring to the system, in common with other types of thermal generation, is inertia. This is a useful property of synchronous (rotating magnet) generators, whose rotating components store kinetic energy, which is released after a power source is disconnected. In the event that a large generator fails, the combined inertia properties of these generators act like a buffer to slow the rate at which system frequency drops, giving the system operator longer to activate alternative measures thus enhancing the system's resilience. Non-synchronous generators such as wind turbines and solar photovoltaic do not provide inertia, and although alternative methods to provide this exist, thermal plant currently do so at lower cost. The amount of inertia required on a system is a function of the supply mix and the technical properties of the grid itself.

---

[92] IAEA (2012) Operating Experience with Nuclear Power Stations in Member States in 2011
[93] National Grid (2010) Charging for Large Loss Frequency Response
[94] National Grid (2013) Procurement Guidelines Report
[95] Carbon Connect (2013) Power from Renewables
[96] OECD & NEA (2012) Nuclear Energy and Renewables
[97] EDF (2013) 'Frequency Response from UK NPPs': presentation by P. Hanney to IAEA 09.2013: http://www.iaea.org/NuclearPower/Meetings/2013/2013-09-04-09-06-TM-NPE.html

The risks arising from nuclear power's relatively inflexibility over this timescale are determined by the overall mix of technologies on the system. Today, short term balancing services are contracted from less than five per cent of total generation capacity. In the future, increasing amounts of varying generation, such as wind and solar photovoltaic, will also require more reserves to be contracted, to manage their short term varying output. It has been estimated that by 2020, seven gigawatts of flexible generation (or 14 per cent of total non-wind and nuclear capacity[98]) would be required to manage risks on a system with 30 per cent wind capacity and larger nuclear reactors[99]. Provided there is enough alternative capacity with the right properties, large nuclear reactors can be accommodated on a system without being required to be flexible. In the future, smaller nuclear reactor sizes, and modular nuclear power station design (where power stations are made up of a number of reactors smaller than around 300 megawatts) would reduce the operational challenges of accommodating very large nuclear reactors and other generating units.

3.4 Medium term: load following

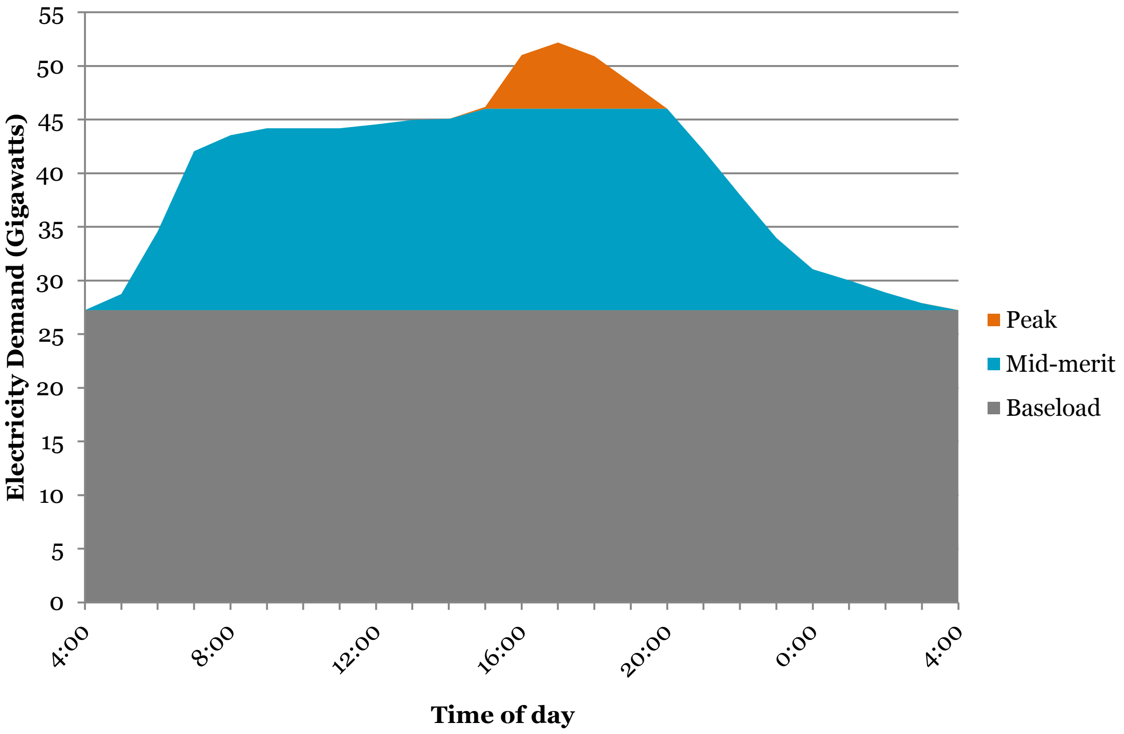
Supply in this timeframe is allocated by the market, with power stations responding to wholesale electricity prices and scheduled to come on or offline, or to make adjustments in their output. Risks in this time frame are managed by ensuring that there is sufficient capacity that can be brought on or offline to match the needs of the system, with sufficient spare capacity to provide contingency should some power stations be unavailable.

Over the course of the year, electricity demand very rarely falls below 19.5 gigawatts[100] which is referred to as 'baseload' demand. Approximately 69 per cent of total annual electricity consumption falls within this baseload demand[101]. A significant portion of remaining electricity demand undergoes large swings over the course of a day, increasing rapidly in the morning, peaking in the early evening before falling away to an overnight low[102]. Approximately 29 per cent of annual demand fluctuates in this manner ('mid-merit'), and is met with supply from load following tools such as unabated coal and gas power stations[103]. A final two per cent of demand can be categorised as 'peak' and occurs only infrequently and often in winter evenings. It is met by many of the same tools that provide load following supply, which as well as conventional fossil fuel plant includes pumped hydro, interconnection and peaking plant[104] (see Figure 6). Measures to ensure that this peak demand is met, as it varies between seasons, are examined in the following section.

---

[98] Total transmission connected system capacity estimated to be 100 gigawatts
[99] National Grid (2011) Operating the Electricity Transmission Networks in 2020 - Update
[100] National Grid (2011) Seven Year Statement
[101] CCC (2012) Meeting the 2050 Target
[102] National Grid (2011) NGETS Seven Year Statement
[103] Ibid 101
[104] Ibid 101

Figure 6: Example profile of daily demand and baseload, mid-merit and peak demand



Source: Committee on Climate Change calculations based on real electricity demand data (Elexon Portal)
Notes: 1) Baseload is defined as the minimum level of demand that is present throughout at least 90 per cent of the hours of the year. In 2011 it was around 20 gigawatts
2) Mid-merit is defined as that part of demand greater than baseload and occurring in at least 20 per cent of the hours in the year. In 2010 it was between around 25 to 40 gigawatts
3) Peak is defined as those high levels (beyond baseload and mid-merit) that occur in no more than 20 per cent of the hours in the year. In 2011 it was between around 40 and 55 gigawatts

As discussed above, nuclear is not suited to 'load-following' operation, but is well suited to meeting baseload demand. Reactors take around two days to come on or offline, and so are not suited to the start/stop operation of thermal power stations that are currently used to respond to overnight lows and afternoon peaks in demand. Nuclear reactors in France are used for load following [105], to help meet the daily demand curve there, but is a feature of high electricity demand for heating and a high penetration of nuclear power in the electricity mix. Flexible operation of nuclear power stations comes at high financial cost, however, both in increased reactor wear and tear and lost revenues[106]. With new nuclear power station economics for existing designs predicated on high load factors (see Chapter 4), and with a guaranteed off-take price through Contracts for Difference, they will likely run regardless of fluctuations in wholesale electricity prices, with more price-sensitive tools likely to respond to price fluctuations (fossil fuels, demand side response and biomass).

3.5 Long term: capacity adequacy

To ensure reliable supply in the long term, a buffer of system (generating) capacity must be maintained over and above expected peak demand. This provides contingency should plants be taken out of service, break down or when demand is higher than anticipated. Capacity adequacy is measured by 'loss of load expectation', which is the number of hours per year that, over the long-term, it is statistically expected that supply will not meet demand. From

---

[105] Eurelectric (2011) Flexible Generation: Backing up Renewables
[106] World Nuclear Association (2013) Advanced Nuclear Reactors' (Accessed Dec 2013) : http://www.world-nuclear.org/info/Nuclear-Fuel-Cycle/Power-Reactors/Advanced-Nuclear-Power-Reactors/

this measure of capacity adequacy, the need for additional capacity can be calculated. Additional capacity can take the form of permanent demand reduction, demand side response or new generating capacity. The delivery of capacity has, since privatisation, been left to the investment decisions of the market, although the Government now plans to introduce a capacity market to supplement wholesale price signals (discussed below). Without a capacity market, expected falls in capacity adequacy should lead to higher prices, creating a signal for investment in new capacity. Given the strategic importance of security of supply and the lead times for increasing capacity, capacity adequacy is monitored by the System Operator (National Grid), the Regulator (Ofgem) and Government.

Contribution to capacity adequacy

The average probability of power stations being able to meet demand and the variability around this average are important in determining capacity adequacy, as measured by loss of load expectation. An important feature of a system with lots of nuclear power is its relatively high average availability and low variability around this average. Both these features strengthen capacity adequacy (as measured by loss of load expectation) and are features that nuclear power shares with fossil fuel and biomass power. By limiting capacity adequacy risks, nuclear can also limit costs for consumers. This benefit could be reduced by an unplanned, extended shutdown of a nuclear reactor, as occurred at Sizewell B in 2010, when the rectification of a water leak required that the plant be taken offline for six months[107]. Such events are infrequent and could in theory affect any plant, although the shutdown of a nuclear reactor will have a proportionately larger impact on system security owing to its larger size.

A system with high penetration of varying generation, such as wind, and limited balancing tools would have lower average availability and more variability around this average, which would result in lower capacity adequacy. Varying generation can however, still form a substantial part of a secure system with high capacity adequacy, provided that there are enough grid balancing tools such as storage, demand side response, interconnection, or backup generation. The costs of a system with very high penetration of varying generation and these grid balancing tools are very uncertain, but there is likely to be some point at which the economic returns of greater penetration diminish more steeply. Although the exact point at which this could happen is currently very uncertain, it is generally accepted that the UK is a long way from this point and is certainly unlikely to approach it in the short or medium term. For example, the cost of providing backup capacity for wind generation at a 20 per cent penetration is estimated to add only between £3 and £5 per megawatt to the final unit price of electricity[108].

FINDING 9

In the context of the current UK electricity system, nuclear power has a lower impact on system-wide costs than varying renewables. It has a slightly higher impact than conventional thermal generation due to the large size of planned new power stations.

Delivering capacity adequacy

The recent passage of the Energy Act (2013) through Parliament, containing the Electricity Market Reform package, has led to a hiatus among some investors who are awaiting the outcome of political negotiations and the confirmation of policy changes. In response to concerns that the reformed market may not provide adequate signals to bring forward investment to maintain capacity adequacy, the Government will introduce a capacity mechanism.

---

[107] World Nuclear News (2010) ‘EDF Energy puts Sizewell B back to work’ (Accessed Feb 2014)

[108] UKERC (2006) The Costs and Impacts of Intermittency: An assessment of the evidence on the costs and impacts of intermittent generation on the British electricity network

Under the proposed design of the capacity mechanism, National Grid will produce an annual estimate of future capacity adequacy. Following this advice, the Government will set a reliability standard and Ministers will decide how much capacity to auction to ensure this standard is met. Capacity auctions will take place four years ahead of when capacity is needed with additional year-ahead auctions to capture subsequent adjustments. Both supply and demand measures will be able to bid in capacity auctions, although demand side measures will have separate auctions to begin with, starting in 2015, a year later than the supply side. Successful bidders will receive capacity agreements and consequently capacity payments in advance of delivering capacity four (or one) years later. Failure to deliver additional capacity at the time of a 'stress event' in line with capacity agreements will result in penalties based on the value to consumers of preventing blackouts. The capacity market will operate alongside the existing electricity market and balancing services market.

Capacity adequacy forecasts and the setting of capacity auction volumes will have to reflect uncertainty over the timing of power station closures and new power stations commissioning. During this period 2019-24, there is potential for around 20 per cent (22 gigawatts) of installed capacity to close including around eight gigawatts of gas, nine gigawatts of coal and six gigawatts of nuclear[109]. Most of these closures could take place in two batches, around 2019/20 and around 2023/24. Around five gigawatts of old gas power stations and two gigawatts of nuclear[110] could close in 2019/20, whilst around seven gigawatts of coal and a further four gigawatts of nuclear[111] could close in 2023/24. This is likely to mean that large volumes of capacity will be auctioned through the capacity markets, however there is substantial uncertainty over the timings of closures and this uncertainty may not be resolved until much nearer the time.

Existing nuclear power stations could receive life extensions, delaying the need for several gigawatts of new capacity for around eight years. The owner of these power stations, EDF, has said that it expects several life extensions, shown in Figure 7. Life extensions for nuclear are agreed between plant operators and regulators, and are often not confirmed until near the date of potential closure. Operators, in this case EDF, will consider the costs of maintaining plant and their safety against the commercial opportunities of further generation. Indications so far, including their intention to enter existing nuclear power stations into the capacity mechanism[112], indicate that the commercial willingness is there.

Existing coal power stations face tightening air pollution regulations under the EU Industrial Emission Directive which could limit their operating hours and ultimately force their closure in 2023. Favourable coal economics could see many coal power stations using up their limited allowance of hours well before 2023 and closing early, as has happened recently under the Large Combustion Plant Directive. Equally, low coal prices, lower than expected carbon prices (see discussion of Carbon Price Floor in Chapter 4), and capacity payments could all contribute towards persuading owners of coal power stations to investment in technology to reduce pollutants, meeting the tougher regulations under the Industrial Emissions Directive and allowing them to continue operating beyond 2023[113]. Life extensions are also possible for gas power stations built in the early 1990s and will similarly depend on the business case, with key variables being the relative price of gas, carbon prices and potential capacity payments.

The expected commissioning of the first reactor at Hinkley Point C in 2023 and the second reactor in 2024, as well as other potential new nuclear reactors, could meet some of the potential shortfall in capacity around this time. However, the risk of delay in the construction

---

[109] DECC (2013) Energy and emissions projections
[110] Hartlepool & Heysham 1
[111] Heysham 2, Hinkley Point B, Hunterstone B & Torness
[112] Subject to final details
[113] The risk to carbon budgets from the uncertain future of coal power stations is discussed in Carbon Connect (2013) Power from Fossil Fuels

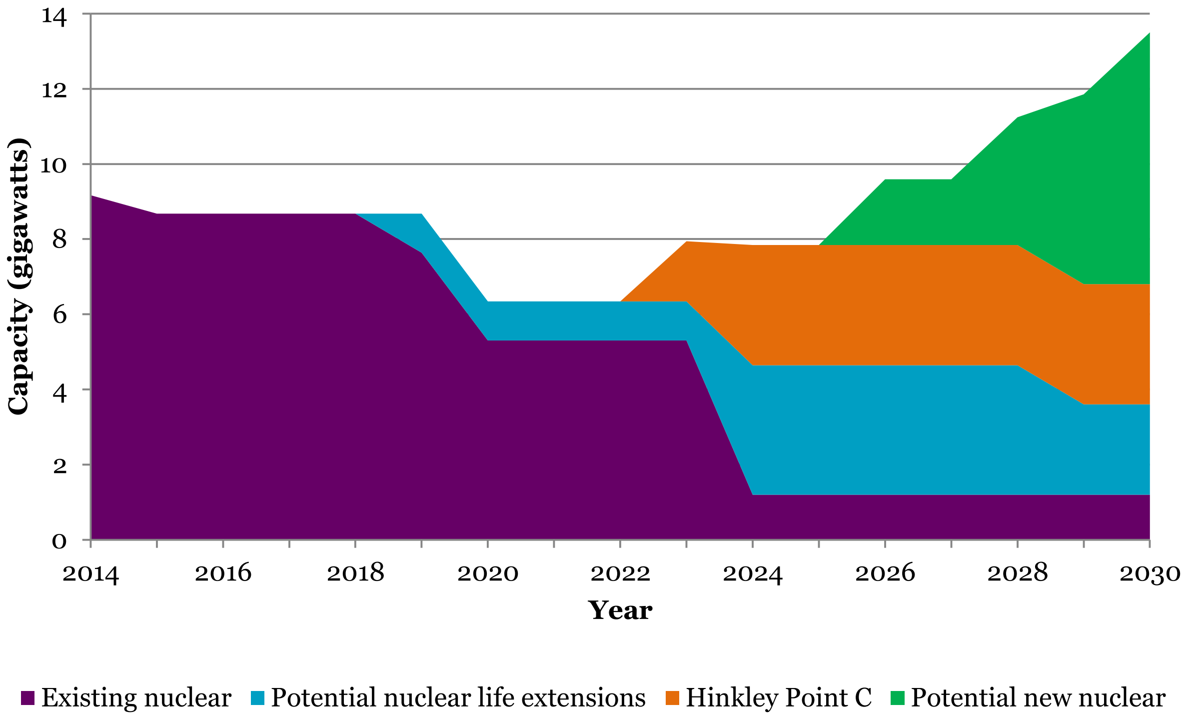
of new nuclear could add to the challenge of maintaining capacity adequacy. Other reactors under construction by Areva (which will construct reactors at Hinkley Point C) are significantly behind schedule, although more recent projects in China are currently on schedule.

Many of the uncertainties outlined above have the potential to be unresolved until much nearer the time. This could mean that large volumes of additional capacity are needed at relatively short notice. This not only poses a challenge for the capacity markets, which are planned to operate four years in advance of delivery (with supplementary auctioning one year ahead), but could also increase the costs of maintaining capacity adequacy if it leads to congestion premiums in deployment. The capacity mechanism, which has been proposed to overcome these challenges, will still be a relatively new and complex policy tool at this point, and past experience, for example the Renewables Obligation, shows that it can take time for markets to become comfortable in taking signals from such market-based instruments.

FINDING 10

Around 2019/20 and 2023/24 a substantial volume of coal, gas and nuclear power stations could close, but this is currently uncertain. These uncertainties and possible delays to the commissioning of new nuclear reactors will need to be considered in implementing the capacity mechanism, which will still be a relatively new policy tool during this period.

Figure 7: Retirements, potential life extensions and new build of nuclear power



Sources: DECC; Lake Acquisitions Limited[114]
Notes: 1) Existing power stations reflect recent public information from EDF's website
2) Potential life extensions reflect recent public information from EDF's website.
3) Potential new nuclear reflects DECC's central projection, adjusted for Hinkley Point C.

---

[114] Lake Acquisitions Limited (2014) Updated lifetime guidance of Dungeness B – 13 February 2014

3.6 Compatibility and cost of future system

Changing system dynamics

The electricity system, and the increasingly connected energy system it is part of, will undergo significant changes over coming decades, as unabated fossil fuel plant is replaced by low carbon alternatives (including variable generation), more small generators are connected to local electricity networks, and potentially substantial volumes of the transport and heat sectors are electrified. As well as substantially increasing demand, which could partially be offset by energy efficiency, many of these new assets could drive greater variation in both supply and demand.

These trends are likely to be accompanied by a substantial increase in measures which flatten, or enable the flattening of, supply and demand. Such measures include smart meters and grids, demand side response, interconnection and storage. There are many more possibilities for supply/demand flattening that could develop, but discussion of these is beyond the scope of this report. The key point is that the expected increase in assets driving greater variation in supply and demand is likely to be accompanied by an increase in supply/demand flattening tools.

The uncertainty around each of these trends and their interactions means that overall, it is very unclear what the dynamics of the power system and the system security challenges will be in coming decades, particularly beyond 2030. It does however appear that the challenges will not be novel in nature but perhaps novel in scale. It also appears that the tools to meet greater system security challenges generally already exist and the that the primary challenge will be reducing the cost of deploying these tools at scale and putting in place a policy, regulatory and market framework that will drive deployment of the best tools for the job, whatever that 'job' turns out to be.

These potential developments are important for considering whether future conditions are likely to be favourable for nuclear or not, and what might determine this. Given the importance of load factor for the economics of nuclear power, its deployment could be limited by reaching a point where the system is unable to find a use for all the electricity that an additional nuclear power station would produce (at a load factor of potentially around 90 per cent).

Favourable conditions

A system with high baseload demand, such as one with substantial supply/demand flattening measures, could therefore enable a high deployment of nuclear power. Whilst baseload generation is not a prerequisite for system security, nuclear power could emerge to be the most cost effective means of meeting baseload demand (see Chapter 4). Certainly between now and 2030, other sources of low carbon baseload faces challenges to deploying at a scale comparable to existing baseload demand of around 20 gigawatts. Fossil fuels with carbon capture and storage are progressing slowly and on top of uncertainty of its commercial viability, there are concerns that the current level of support will be insufficient to see deployment reaching 10 gigawatts by 2030[115]. There are also uncertainties over the long-term future of biomass power[116].

Less favourable conditions

On the other hand, a system with low baseload demand, such as one with high variation in supply/demand and few flattening measures, could severely restrict deployment of nuclear power. The potentially high deployment of both varying renewables and nuclear power over the coming two decades could raise the immediacy of these considerations.

---

[115] Carbon Connect (2013) Power from Fossil Fuels

[116] Ibid

At high deployments with limited tools for grid balancing, these technologies could interact to increase system costs. Under certain conditions their combined output could exceed levels of demand. Because both technologies have very low variable operating costs and could have relatively high variable income through contracts for difference, this could result in negative wholesale prices and increased curtailment costs. Germany has already begun to experience this following a rapid expansion in wind and solar capacity in combination with existing nuclear power stations[117].

Demand side response, storage and interconnection, could offer economic alternatives to curtailment. Scenarios modelled by the consultancy Poyry indicate that less than 1 per cent of generation would need to be curtailed on a system with 72 gigawatts of renewable generation and 19 gigawatts of nuclear and investment in 4 gigawatts of bulk storage, 16 gigawatts of interconnectors and 15 per cent of demand made responsive[118,119]. Historically, the installed capacity of low marginal cost power stations (such as nuclear, wind and solar) has been lower than minimum demand and for these reasons, the costs of load following, such as forcing power stations to lower output in times of anticipated over-supply (curtailment), have been modest.

Whilst it is possible to build a secure system that meets emissions ambitions for 2030 without nuclear, this would likely be achieved through significant expansion of mainly wind and solar photovoltaic[120]. To maintain system security, a large amount of backup capacity (able to sustain output for up to several weeks), alongside a large expansion of measures to deal with hourly and daily variability (demand side response, interconnection and storage). The costs of doing so are currently uncertain, and therefore under levels of nuclear deployment predicted in 2030 (10 to 20 gigawatts) the benefits, in terms of security and cost, outweigh the disadvantages that larger reactor sizes will bring to short term balancing risks and maintaining capacity adequacy.

FINDING 11

The deployment of nuclear power is likely to be influenced more by the economics of system balancing than technical system balancing challenges, which can be met with greater deployment of existing balancing tools. The cost of maintaining system security is likely to mean that the UK maintains at least some baseload capacity, such as nuclear power, to limit system costs. High nuclear deployment could be constrained by system costs, although uncertainty over future demand profiles, supply mix and the cost of balancing tools means that this is currently difficult to assess.

Increasing importance of system considerations

The substantial changes expected to the electricity system, and other parts of the energy system, will mean that system considerations such as compatibility and cost become more important. This has already lead to a change in the way that capacity adequacy is measured (from capacity margin to loss of load expectation), but integrating these consideration into policy and decision making will continue to be a challenge as system considerations become more influential in conditioning power station deployment and other features of how the energy system develops.

Network investment costs

As well as indirectly influencing system operation costs, new power stations can directly influence investments needed in the physical network. The sites selected to host new nuclear

---

[117] Reuters (2014) Europe's storms send power prices plummeting to negative. http://reut.rs/1eWZOGa
[118] Total supply is estimated at 409 terrawatt hours
[119] Poyry (2011) Analysing Technical Constraints on Renewable Generation to 2050
[120] Carbon Connect (2013) Power from Renewables

are adjacent to existing nuclear power stations, and therefore benefit from existing grid connections. Although most sites will require an expansion in capacity, these will mostly be reinforcement rather than extension costs[121]. The exception to this is the site at Sellafield, in Cumbria, where new nuclear and offshore wind farms will require an expansion of the capacity of the West Cumbrian transmission system before new capacity can be added[122]. The costs for connecting some renewables (such as offshore wind and marine technologies) will be higher, as location choices are driven primarily by resource availability rather than existing network capacity.

3.7 Fuel security

The reliance of some power generation technologies on fuel to operate adds an additional dimension to the consideration of energy security. Stable supply is essential to maintain both physical security and to avoid price volatility.

Nuclear power is more resilient against fuel price rises than fossil fuel power generation. The price of fuel accounts for a relatively small proportion of nuclear generating costs (typically five per cent) whilst fuel cost can be over 50 per cent of the generating costs of coal and gas plants. Therefore, a large increase in the price of uranium will have a smaller effect on nuclear generation costs than an equivalent increase for fossil fuels.

The ability to store fuel provides a valuable hedge against both interruptions and price volatility. The high energy density of nuclear fuel significantly reduces the scale of transportation and refuelling activities, and reactors can operate for up to two years between re-fuelling[123]. Nuclear power stations can also continue to operate in the event that refuelling is delayed – output simply decreases slowly as energy intensity of the reactor fuel declines.

Fuel availability

The UK has no indigenous sources of traditional nuclear fuel, but imports are available from a diverse set of countries including Canada and Australia. Provided that the UK has access to a large number of potential suppliers, this need not increase risks to supply, and indeed may reduce risks by encouraging supply diversity. The UK has fuel processing facilities, and therefore reactor fuel can be obtained from either direct fuel purchases from abroad or purchases of ready assembled fuel rods, available from both the US and Europe.

The availability and price of uranium fuel will be determined in the long run by the availability and cost of reserves relative to demand for fuel. The Euratom Supply Agency has expressed confidence that there are sufficient identified uranium resources to meet the current energy demand for about 100 years. Much will depend on future demand from nuclear reactors. The OECD's Nuclear Energy Agency (NEA) has stated that current uranium resources are more than adequate to meet fuel demand, even under very high global nuclear deployment scenarios to 2035, although this would require expansion of current mining capacity. There is a high degree of uncertainty regarding longer term global nuclear deployment, with recent estimates suggesting increases relative to current capacity (370 gigawatts) of between 66 and 326 per cent are possible by 2050[124]. Some countries, such as China, are planning for potentially substantial reactor build programmes given expected increases in energy demand. High deployment may put earlier pressure on uranium reserves.

Thorium and plutonium based fuels could provide alternatives in the event of uranium scarcity. Thorium is thought to be three to four times more abundant than uranium, although

---

[121] DECC (2011) National Policy Statement for Nuclear Power Generation vol I (EN-6)

[122] National Grid (2014) North West Coast Connections (Accessed February 2014)

[123] World Nuclear Association: "Nuclear Power Reactors": http://world-nuclear.org/info/Nuclear-Fuel-Cycle/Power-Reactors/Nuclear-Power-Reactors/#.Ulf_slCoXqU (Accessed October 2013)

[124] IAEA (2010) International Status and Prospects for Nuclear Power

the proportion of this that is exploitable is less well known[125]. Thorium could be used in some existing reactor designs, such as heavy water reactors, or in several advanced reactor concepts (see Chapter 2).

The UK's legacy nuclear waste contains a significant volume of separated uranium and plutonium, which could be used as a fuel in future (see Nuclear Strategy and Sustainability chapters also). As such, these materials contribute to the long term security of supply of nuclear power in the UK, although technical and economic challenges would need to be overcome to derive significant quantities of power from these. For example, Generation IV reactors operating a breeding cycle could be deployed which could in principle vastly reduce dependency on uranium ore. Proliferation risks associated with spent fuel reprocessing and additional high level waste arisings would also need to be considered as part of a decision to re-use spent nuclear fuel.

FINDING 12

In the current UK context, nuclear power helps diversify the UK's electricity supply mix, reducing risks arising from individual fuels and technologies. Although uncertain, evidence suggests that there are adequate uranium resources to fuel a global expansion of nuclear power, including new of nuclear power stations in the UK. Development of thorium fuel cycles, technologies to enable a closed fuel cycle and new extraction techniques could all improve fuel security and expand the potential of nuclear energy.

---

[125] Birmingham Policy Commission (2012) The Future of Nuclear Energy In The UK

4. AFFORDABILITY

Ensuring that energy remains affordable is both an economic and social priority. Increasing energy bills have become a key political concern, bringing greater scrutiny to the current and future drivers of energy costs. Affordability has many components and is about more than just the costs of building and running power stations or today's energy prices. System costs, carbon prices, fuel prices, risk, uncertainty, learning effects and macroeconomic impacts are also crucial components and evaluating affordability requires careful consideration of these components both in the near and long term.

This chapter examines each of these components, assesses the possible impacts of financial support for nuclear and outlines what nuclear power contributes to meeting affordability policy objectives.

4.1 Levelised costs

Methodology and limitations

A common method of beginning to understand the affordability of different power generation technologies is to estimate and compare the levelised cost of each. The levelised cost of electricity is calculated by dividing the 'lifetime cost' of a power station by the amount of electricity it generates over its life, giving a measure of money spent per unit of electricity produced (typically measured in pounds per megawatt hour, £/MWh)[126]. The 'lifetime cost' is the total of discounted costs for developing, constructing, running and decommissioning a power station. This provides a metric that is relatively easy to calculate and clear in its outputs.

Whilst a useful tool in these respects, levelised cost estimates have several limitations which mean that they do not reflect all the information used by investors nor policy makers in making decisions. Levelised costs are highly dependent on input assumptions which in the case of nuclear power can be particularly uncertain due to a relative lack of reliable cost data. In addition, finance costs are only approximated in levelised cost analysis through the choice of discount rate. The choice of discount rate can also skew the relative attractiveness of different technologies, with high discount rates disadvantaging technologies with substantial upfront costs such as nuclear power (vice versa for low discount rates). Equally, adopting a single discount rate across technologies fails to reflect the differing levels of risk that investors face in the real world, often linked to technological maturity. Finally, network impacts and system costs, discussed in Chapter 3, are omitted from levelised cost calculations, but are a relevant consideration particularly for policy makers.

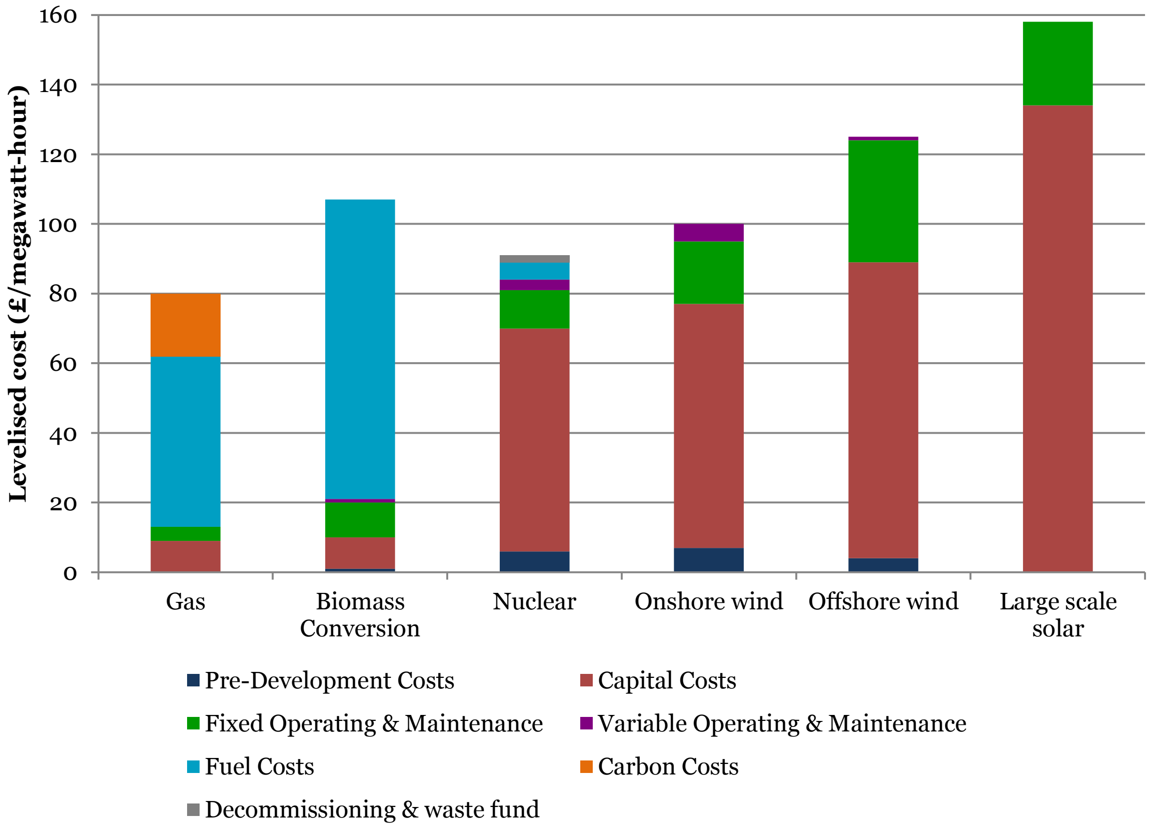
As long as limitations are understood, levelised costs remain the most useful starting point in comparing the affordability of different technologies. In particular, they are a better starting point than strike prices – a matter discussed towards the end of this chapter.

Figure 8, illustrates the Government's latest levelised cost estimates for a variety of power generation technologies, with their cost structure broken down. This analysis shows the estimated costs of projects beginning development in 2013. Lead times from beginning development to commissioning (generating electricity) vary, ranging from around five years for a gas plant, six years for onshore wind and eleven years for a first-of-a-kind nuclear reactor. Later in this Chapter, levelised cost information is compared for projects *commissioning* at the same time rather than *beginning development* at the same time.

---

[126] Both are discounted to give present values for costs and electricity generated

Figure 8: Levelised cost estimates for projects beginning development in 2013



Source: DECC (2013) Electricity Generation Costs December 2013

Notes: 1) Offshore wind is round two and onshore wind is UK and >5 megawatts
2) Nuclear is first of a kind
3) Gas is combined cycle gas turbine
4) Coal is not shown because no new coal can be built in the UK without full chain carbon capture and storage on at least 300 megawatts
5) 2012 real prices assuming a 10 per cent discount rate

Pre-construction

Before construction begins, project development is undertaken which in the UK currently takes around five to six years. Project development activities can include reactor design licensing, site preparation and public consultation. Pre-construction costs for nuclear are a small part of overall levelised cost, although normally the majority of these costs are incurred by developers before a final investment decision for the prospective power station is made.

Construction

Construction costs are the largest component of the levelised cost for nuclear, typically accounting for 60 to 75 per cent[127]. Construction costs include materials, equipment and labour. Civil engineering works such as foundations, buildings and other containment structures are the largest item, accounting for approximately 40 per cent of construction costs, followed by the reactor island (reactor, cooling system and steam turbine) accounting for 30 per cent of construction costs[128].

---

[127] UKERC (2012) Technology and Policy Assessment Cost Methodologies Project: Nuclear Case Study

[128] Mott McDonald (2011) Costs of low-carbon generation technologies. Report for the Committee on Climate Change

Interest on debt used to finance construction is a significant project cost associated with the construction period. Finance costs are not however included as a separate item in levelised cost analyses but are instead factored into each cost element through discounting (see limitations of levelised cost analysis). Construction costs excluding the cost of finance during the construction period are often referred to as 'overnight' construction costs, as it is as if construction happens overnight with no interest accruing on money borrowed.

The amount of interest accruing during the construction period depends on several factors including the interest rate, proportion of construction costs financing through debt (rather than equity) and length of the construction period. As an example, we estimate that if Hinkley Point C has 'overnight' construction costs of £12.4 billion and construction is financed over eight years using 65 per cent debt at a four per cent annual interest rate, then the cost of interest during construction would be around £1.6 billion (see Figure 10).
The planned Hinkley Point C project has been criticised for its high expected construction cost compared to other technologies[129]. However, Figure 8 demonstrates that construction costs are only one part of the picture. Looking at overall levelised cost gives a more complete picture. Figure 8 illustrates that whilst the difference between the *capital* costs of unabated gas and nuclear power stations is very significant, the difference in *levelised* cost is much less extreme because of the higher fuel and carbon costs of gas generation.

Operating and maintenance

The next largest component of levelised cost for nuclear is fixed and variable operation and maintenance costs, including labour and plant servicing. These represent around 15 per cent of the overall levelised cost in the analysis shown in Figure 8.

Fuel

Fuel costs are around only five per cent of levelised cost, which includes the costs of raw materials (usually uranium ore) and processing and fabricating fuel rods. The relatively minor share of levelised cost attributable to fuel means that fuel price increases or decreases will not have a great impact on total costs[130]. This is one reason why, once operational, nuclear power exposes consumers to a lower risk of price instability than fossil fuel generation.

Decommissioning and waste

Waste management and decommissioning costs are also included in the analysis. New nuclear power stations built in the UK will be required to set aside funds to fully decommission reactors, and to pay for on-site facilities to store spent fuel and intermediate and high level waste until a permanent storage solution is ready (see Chapter 5). Total decommissioning and waste management costs for a 1.3 gigawatt pressurised water reactor are estimated to be between £0.8 – £1.8 billion pounds[131](2010 prices). This includes an estimate of the contribution that operators will be required to make to the costs of using a purpose-built facility for long term storage. The cost of this facility will remain uncertain until a site is located, and therefore any pricing agreed in advance with operators is necessarily uncertain. Although total decommissioning and waste management costs are relatively large, the majority of costs will be incurred after a power plant is closed, and therefore have a small impact on electricity generation costs, due to the effect of discounting over more than 60 years.

---

[129] Liberum Capital (2013) 'Flabbergasted – The Hinkley Point Contract' 30.10.13

[130] Tyndall Centre (2012) A Review of Research Relevant to New Build Nuclear Power Plants in the UK

[131] DECC (2010) Consultation on a Methodology to Determine a Fixed Unit Price for Waste Disposal and Updated Cost Estimates for Nuclear Decommissioning, Waste Management and Waste Disposal

Electricity output

In calculating levelised cost, the total of the above cost elements is divided by the electricity output expected from a power station. This depends primarily on how many years the power station is expected to be operational (life time) and the proportion of this time it is expected to be generating electricity (load factor).

The lifetime of new nuclear power stations is claimed by vendors to be around 60 years compared to lifetimes of 30 to 40 years for previous generations of reactors. Whilst load factors have a significant impact on overall levelised cost, the incremental difference of longer power station lifetimes is small. A power station operating for 60 as opposed to 40 years is likely to reduce levelised costs by only around one per cent, due to the effects of discounting[132].

Assumed load factors have a significant impact on levelised cost, as power stations operating at high loads will spread their costs over more units of output. For example, we estimate that reducing the assumed load factor from 90 to 80 per cent increases the levelised cost of electricity for nuclear power by around 12 per cent. The analysis in Figure 8 assumes a load factor of 91 per cent for nuclear plant, in line with the developer's claims. This is higher than average historic rates achieved by nuclear plant worldwide, although average load factors of operational nuclear plants have improved over time[133].

Cost of finance (discount rate)

Both the costs and the electrical output outlined above are discounted before dividing the former by the latter to arrive at the overall levelised cost of electricity. This discounting approximately reflects the returns that financers command. Projects are typically financed through a mixture of equity and debt, where debt financers command a comparatively lower rate of return. Consequently, a higher proportion of debt finance generally makes projects cheaper overall. The weighted average of returns commanded by debt and equity finance for a project is referred to as the weighted average cost of capital (WACC) and is often adopted as a discount rate to approximately factor in the cost of financing.

Recent estimates of new nuclear power stations in the UK have used discount rates of 10 or 11 per cent[134]. This is consistent with the expected returns of the planned Hinkley Point C project, which EDF has indicated are around 10 per cent. The discount rate has a significant impact on levelised cost with a reduction from 11 to 10 per cent reducing the cost of electricity by around six to seven per cent[135].

4.2 Sensitivity of nuclear costs

To summarise points made about sensitivity above, the overall levelised cost of nuclear power is most sensitive to assumptions about construction cost, load factor and discount rate. This section examines why these elements are so important, what can influence them and what history and the design of the UK new build programme tell us about the potential costs of new nuclear.

Construction costs

Costs incurred during construction account for the majority of the cost of nuclear power and are susceptible to the price of inputs such as equipment and labour as well as construction delays. It has been estimated that for every year of construction delay, levelised costs increase

---

[132] Tyndall Centre (2012) A Review of Research Relevant to New Build Nuclear Power Plants in the UK
[133] Ibid
[134] Ibid
[135] Ibid

by between eight and ten per cent[136]. Similarly, supply chain congestion has been estimated to increase the construction cost of new nuclear by 25 per cent[137].

Four potential drivers of construction cost escalation have in particular been identified: design changes; supply chain congestion; skills shortages; and, developers taking time to adapt foreign experience to UK conditions.

Design changes during construction, leading to delays, are thought to one of the main reasons for nuclear costs escalating fairly consistently in the past. An unstable regulatory environment during the 1960s and 1970s, when a large number of nuclear power stations were built in developed countries, led to delays and cost overruns[138,139]. Costs generally continued to escalate during 1980s as the increasing complexity of reactor designs meant that the expected benefits of economies of scale and learning evaded developers. Lower costs and cost estimates were seen in the 1990s and early 2000s, but are thought to have been a result of relatively few reactors being built in Western Europe, North America and Japan, and the majority of build happening in Eastern Europe, South America and Asia where regulatory and economic conditions differed considerably in ways unlikely to be replicated in the UK. More recently, design changes have contributed to delays and cost escalation of the first two European Pressurised Water (EPR) reactors in construction in Finland and France, where construction began before regulatory assessments had been fully completed[140].

The UK has taken an important step to reducing the risk of construction delays and cost escalations driven by design changes during construction. New voluntary arrangements have been introduced for project developers to secure *pre-construction* design approval for their reactor technologies from the Office of Nuclear Regulation and Environment Agency, through a Generic Design Assessment procedure. Areva and EDF secured design approval in December 2012 for the European Pressurised Water reactor planned at Hinkley Point C, with a possible follow-on project at Sizewell. In January 2013, the Generic Design Assessment process was started for the Advanced Boiling Water Reactor developed by Hitachi-GE Nuclear Energy. Westinghouse Electric Company’s AP1000 design and CANDU’s ACR1000 design were also entered into the original Generic Design Assessment process when it launched in 2007, although the latter was subsequently withdrawn.

Supply chain congestion from high demand for equipment and materials needed to construct a nuclear power station can lead to delays and higher prices. In 2011, Mott Macdonald estimated that supply chain congestion was adding 25 per cent to the construction cost of new nuclear power[141]. This problem is not unique to nuclear power, and has for example been experienced in offshore wind also. With the potential for multiple reactors to be under construction in the UK simultaneously, whilst nuclear build programmes are also underway in Eastern Europe, the Middle East and Asia, there is a real risk of supply chain congestion driving up the cost of nuclear power over at least the next two decades.

This could be alleviated through investment to increase supply chain capacity. However, because of the large project size and long construction period for nuclear, demand tends to be ‘lumpy’ and difficult to forecast over the long periods needed to make investments of this sort. Whilst substantial cost reductions could seemingly be achieved by eliminating supply chain congestion, it is difficult for policy makers in any one country to provide sufficient confidence needed to stimulate investments in increasing supply chain capacity whilst facing so much uncertainty over future technology costs.

---

[136] Harris, G., et al., Cost estimates for nuclear power in the UK. Energy Policy (2013), http://dx.doi.org/10.1016/j. enpol. 2013.07.116

[137] Mott MacDonald (2011) Costs of low-carbon generation technologies

[138] Mackerron, G (1992) Nuclear costs: why do they keep rising? Energy Policy 20 (7): 641 - 652

[139] Cohen, B (1990) The nuclear energy option. New York, Plenum

[140] HoC (2013) Energy & Climate Change Select Committee, 8th Report: UK Energy Supply: Security or Independence? (ev81)

[141] Mott MacDonald (2011) Costs of low-carbon generation technologies

Shortages in the skills needed to construct nuclear power stations are a further source of potential construction delays and higher labour costs. The UK has a strong and skilled nuclear workforce of around 40,000 already[142]. However, with the potential for multiple new nuclear power stations to be under construction in the UK simultaneously, and a large proportion of the incumbent workforce expected to retire in the next decade[143], this is a risk that some have identified as a concern.

In response, Government, industry and academia have been working together through the Nuclear Energy Skills Alliance. The Government has funded the development of a Nuclear Workforce Model to assimilate information about future skills supply and demand and identify what skills shortages could arise and when. Particular key skills areas where there is a risk of skills shortages include project managers, steel fixers, high integrity welders, construction supervisors and researchers. Work is already underway through a number of organisations to address some risk areas, for example, the Engineering Construction Industry Training Board is investing around £6 million a year into site supervisor training and new qualifications in high integrity welding.

In contrast to the UK's last multiple-reactor build programme in the 1960s, proposed technologies for the current new build programme are evolutionary designs that build on several decades of international design development and operational experience. However, this experience has been outside of the UK, and so the first reactors of the UK new build programme, if built, will be reactor designs never before built in the UK. Differences in regulatory regime and labour conditions in particular could pose challenges for developers bringing their technology to the UK for the first time[144]. Nevertheless, Areva, which is currently constructing four European Pressurised Water Reactors (EPRs) which it plans to bring to the UK for power stations at Hinkley Point and Sizewell, claims that lessons learnt from the first two projects (in Finland and France) have helped the more successful delivery of two subsequent plants in China. A different regulatory (safety) environment and larger workforce (10,000 as opposed to 3,000 in France) are however cited as major factors contributing to success in China[145].

Load factor

Nuclear power stations are able to achieve some of highest load factors of any generation technology, having improved considerably over time. The World Nuclear Association estimates that in 2012 the average load factor for nuclear power stations across the world (but excluding Japan) was 80 per cent. Over a quarter of nuclear power stations are estimated to have load factors in excess of 90 per cent and over two thirds in excess of 75 per cent[146]. In the UK, the average load factor for nuclear power stations in 2012 was 71 per cent, having peaked in 1998 at 80 per cent[147]. EDF claims that its new European Pressurised Water reactor, planned for Hinkley Point C, will achieve load factors of around 90 per cent.

The substantial impact that load factor has on the economics of nuclear power is the principle reason why nuclear power stations are not operated flexibly to contribute system balancing services. The limitation is therefore economic and not technical. For this reason, the Government has included in its agreed commercial terms with EDF that 'Hinkley Point C would be protected from being curtailed without appropriate compensation'.

---

[142] BIS (2013) Nuclear Industrial Strategy: The UK's Nuclear Future

[143] Ibid

[144] HoC (2013) Energy & Climate Change Select Committee: Building New Nuclear: the challenges ahead (HC 117)

[145] HoC (2013) Energy & Climate Change Select Committee, 8th Report: UK Energy Supply: Security or Independence? (ev81)

[146] World Nuclear Association website (accessed February 2014)

[147] DECC (2013) Digest of UK Energy Statistics

Cost of finance (discount rate)

Nuclear power stations require large sums of money to be borrowed and spent over a long construction period (around five to ten years) before revenues are generated over a long operating period with relatively low operating costs (around 40 to 60 years). This means that considerable interest accrues on money borrowed during construction and that the choice of discount rate has a significant bearing on nuclear economics.

New reactors in the UK will be the first to be built since privatisation of the energy sector in the late 1980s. Whilst the Government's proposed regime for new nuclear, and for Hinkley Point C in particular, reduces many risks, building new nuclear in a privatised market is still more risky than building new nuclear with direct state investment, as has been the case in the UK in the past. This higher risk combined with the very large amounts of finance needed to build reactors like the European Pressurised Water reactor means that securing enough finance at a rate that gives nuclear power a chance of being economically competitive with other low carbon technologies is challenging.

The Government has put considerable effort into supporting EDF in securing finance for Hinkley Point C and lowering the cost of finance by de-risking elements of the project. The introduction of index-linked Feed in Tariff Contracts for Difference removes a substantial amount of risk from all low carbon power station investments. Offering a 35 year contract for Hinkley Point is hoped to enable the project to attract between 50 and 65 per cent debt financing[148], which will lower the weighted average cost of capital and improve the economics of the project. Finally, Ministerial discussions with Chinese State-backed investors and a UK Government loan guarantee supported EDF in securing debt financing at a rate that is likely to be particularly low.

The European Commission has questioned whether the expected project returns of 10 per cent are too high for Hinkley Point C, given the substantial amount of risk removed from the project by the 35-year index-linked contract for difference in conjunction with a loan guarantee[149]. As well as careful risk allocation, competition is often an important element of a strategy to drive value for money in projects with elements of private and public sector involvement. In negotiating the investment contract for Hinkley Point C, the Government used its own and commissioned analysis to challenge EDF's negotiating position in an open book exercise, rather than competition.

To put the expected returns of the project in context, we have compared the anticipated returns to equity holders in the Hinkley Point C project to equity returns typical for other projects with a mix of private and public sector involvement (see Figure 9). We estimate that equity returns in Hinkley Point C could be between around 19 and 21 per cent[150] (post-tax nominal), before any post-construction refinancing which we would expect to be covered by a gain sharing agreement, in common with most private finance initiative contracts. In comparison, typical expected equity returns on private finance initiative projects at the point of contract agreement are between around 12 and 15 per cent[151]. Equity returns on regulated network assets on the other hand are around 8 to 10 per cent, factoring in inflation of between two and three per cent.

There are broadly two possible reasons which could explain why the expected rates of return for Hinkley Point C are higher. Firstly, the risks faced by EDF could genuinely be greater, therefore commanding a higher rate of return. Alternatively, or in addition, the negotiating process may not have been effective in driving down the expected rate of return relative to

---

[148] http://ec.europa.eu/competition/state_aid/cases/251157/251157_1507977_35_2.pdf

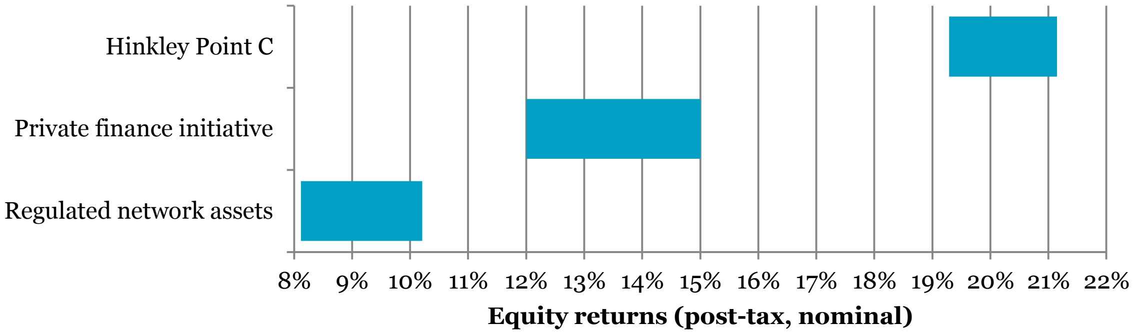
[149] Ibid

[150] Assuming 65:35 debt to equity ratio, a post-tax cost of debt of between 4 and 5 per cent and a post-tax nominal weighted average cost of capital of 10 per cent.

[151] National Audit Office (2012) Equity investment in privately financed projects

risk. A lack of competition in the negotiating process could have been influential here. The European Commission has questioned the likelihood of the first of these explanations, in light of what is already known about the allocation of risk.

Figure 9: Comparison of expected equity returns on Hinkley Point C



Source: Carbon Connect analysis based on figures from EDF, National Audit Office and Ofgem
Notes: 1) Assumes 65:35 debt to equity ratio, a post-tax cost of debt of between 4 and 5 per cent and a post-tax nominal weighted average cost of capital of 10 per cent.

FINDING 17

We estimate that equity investors in Hinkley Point C could achieve returns of around 20 per cent before refinancing. This compares with typical equity returns on regulated network assets of 8 to 10 per cent and on Private Finance Initiative projects of 12 to 15 per cent.

4.3 Pre-development and construction cost estimates for Hinkley Point C

Cost estimates for the Hinkley Point C project have risen over the course of the last five years. The costs quoted by the EDF-led consortium rose by around 70 per cent between 2010 and 2013. In 2010 a cost of ‘more than £9 billion’ was quoted by the consortium for building two 1.6 gigawatt reactors in the UK[152]. This figure rose to £14 billion in 2012[153], and £16 billion in 2013[154]. According to EDF, £2 billion of the 2013 estimate covers all non-construction costs that will have been sunk by the time construction is complete, such as site acquisition, preparatory work for regulatory authorisations and the training of future employees for the plant[155].

Figure 10 shows our assessment of what may have driven increases in the cost estimates provided by EDF. We assume that EDF’s 2010 estimate included around £1 billion of non-construction costs, such as site licensing, public consultation or estimated interest during construction. Firstly, between 2010 and 2013, estimates of construction cost for new nuclear rose by 28 per cent[156], reflecting increases in equipment and material prices, seen across many low carbon technologies[157] (adds £2.2 billion). Secondly, we have factored in contingency based upon a conservative assumption that construction costs escalate at a rate

---

[152] Hollinger,P (2010) ‘EDF Reveals Strategy for UK Nuclear Expansion’ [Online]. Financial Times. Available: *http://www.ft.com/cms/s/0/5376fc24-0a06-11e0-9bb4-00144feabdc0.html#axzz1ANdUnOjq* (Accessed January 2014)

[153] Harris, G., et al., Cost estimates for nuclear power in the UK. Energy Policy (2013), http://dx.doi.org/10.1016/j. enpol. 2013.07.116

[154] EDF (2013) Agreement reached on commercial terms for the planned Hinkley Point C nuclear power station. Online: *http://edfenergy.presscentre.com/News-Releases/Agreement-reached-on-commercial-terms-for-the-planned-Hinkley-Point-C-nuclear-power-station-82.aspx* [Accessed: 17.01.14]

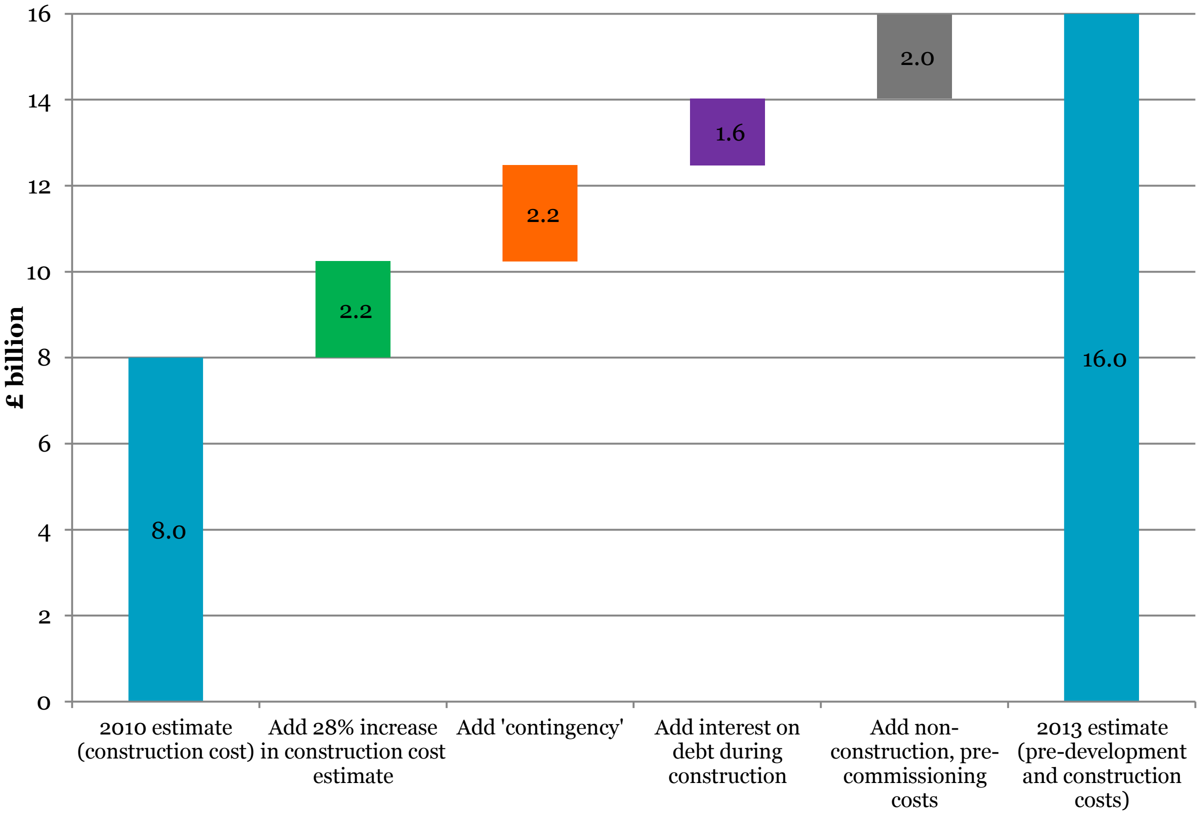
[155] Probert, T (2013) Was Hinkley a good deal? Utility Week, 17.01.13. (Accessed January 2014) http://www.utilityweek.co.uk/news/was-hinkley-a-good-deal/967182#.Ut6iZhDFLcs

[156] Parson’s Brinkerhoff (2010) Power the Nation Update [figures underlying this analysis]; and DECC (2013) Electricity Generation Costs [data provided by Parson’s Brinkerhoff]

[157] UKERC (2013) Presenting the Future: An Assessment of Future Costs Estimation Methodologies in the Electricity Generation Sector

of 2.5 per cent per annum over an eight-year construction period (adds £ 2.2 billion). Others have used cost escalation rates ranging from zero to 5.4 per cent, with estimates at the upper end of the range being most closely reflective of past experience[158, 159]. Thirdly, we have added interest accruing on debt during the construction period (eight years), assuming the project is 65 per cent debt financed and money is borrowed at four per cent after tax (adds £1.6 billion). Finally, we have included £2 billion which is EDF's own estimate of the non-construction costs that would be incurred up to when the power station is built.

Figure 10: Possible evolution of construction cost estimate for Hinkley Point C



Source: Carbon Connect analysis based on various sources (see main text)
Notes: 1) We assume EDF's 2010 estimate includes construction costs and £1 billion of non-construction costs
2) Parson Brinkerhoff's central estimate for the construction cost of nuclear rose by 28 per cent 2010-13.
3) A contingency has been added to reflect escalation of construction costs at 2.5 per cent per annum during an eight year construction period. This is a conservative assumption in light of historic evidence.
4) Interest on debt during construction has been calculated on the basis of 65 per cent debt financing at four per cent interest (after tax).
5) Non-construction, pre-commissioning costs are assumed to be as estimated by EDF.

Gain sharing agreements in Private Finance Initiative contracts normally cover gains on debt refinancing, and it is not yet clear whether consumers would share in any gains from construction coming in under budget. Details of these arrangements have not yet been made publicly available and it is not clear to what extent they might be in the future. Gain share agreements for debt refinancing (not construction underspend) have been included in investment contracts between Government and the private sector for some time, having been introduced through Private Finance Initiative contracts, and have had at least some success in limiting the returns on contracts by the private sector[160].

---

[158] Harris, G., et al., Cost estimates for nuclear power in the UK. Energy Policy (2013), http://dx.doi.org/10.1016/j. enpol. 2013.07.116
[159] Tyndall Centre (2012) A Review of Research Relevant to New Build Nuclear Power Plants in the UK
[160] National Audit Office (2012) Equity investment in privately financed projects

FINDING 18

We estimate that the £16 billion expected investment in Hinkley Point C includes £10.2 billion of construction costs, £2.2 billion of construction contingency, £1.6 billion of interest during construction, £2 billion of non-construction costs. It is not yet clear whether consumers would benefit from construction coming in under budget.

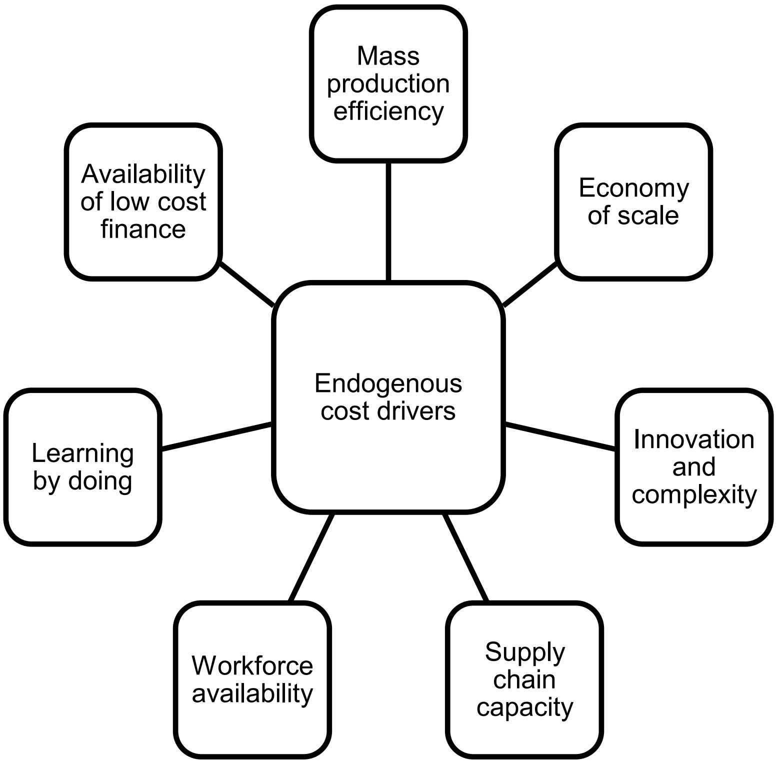
FINDING 19

It is not yet possible to conclude on the value for money of the Hinkley Point C agreement. Both the negotiation process and the resulting investment contract are important for determining value for money. It is difficult to judge the effectiveness of the negotiation process in driving value for money because it was neither competitive nor transparent.

4.4 Future cost of nuclear power

Despite a long history of generally escalating nuclear costs in Western Europe, Japan and North America[161], recent analysis commissioned by the Government forecasts that the costs of nuclear power could fall for power stations beginning to generate electricity over the course of the 2020s (see Figure 11). This work forecasts that levelised costs for power stations commissioning in 2020 will be between £83 and £108 per megawatt hour, falling to between £78 and £106 in 2025 and between £70 and £94 in 2030 (central estimates are £93, £90 and £80 for 2020, 2025 and 2030 respectively)[162]. This section considers what factors could determine future changes in the cost of nuclear power for the UK, first looking at cost-drivers which are at least partially controllable (endogenous), then looking at cost-drivers which are less controllable (exogenous). Finally, the section will look at what past experience and historic evidence tells us about the difficulty of forecasting the costs of nuclear power.

Factors affecting future costs of nuclear power in the UK



---

[161] UKERC (2013) Presenting the Future: An Assessment of Future Costs Estimation Methodologies in the Electricity Generation Sector

[162] DECC (2013) Electricity Generation Costs – Update December 2013

Some of the most influential endogenous cost drivers such as supply chain capacity and workforce availability are discussed in the section on sensitivity of nuclear costs above. Discussion of further cost drivers is continued here.

There are two broad areas where there is potential for learning by doing. The first is the scope for projects following in the footsteps Hinkley Point C to pass through policy and regulatory hoops more smoothly. In completing the Generic Design Assessment of Areva and EDF's European Pressurised Water reactor, the Office for Nuclear Regulation and the Environment Agency may be able to implement efficiencies learned on the assessment of subsequent reactor designs, such as the Advanced Boiling Water Reactor, AP1000 and ACR1000. The Government may also be able to implement learning from the investment contract negotiation process for Hinkley Point C which could enable them to drive better value for money and complete the process more quickly or with fewer resources.

The short-term risk of higher nuclear costs driven by developers adapting foreign development and construction experience to the UK regime is discussed in the section on the sensitivity of nuclear costs above. However, beyond this adjustment phase there is scope for learning by doing for developers and contractors, particularly during the long and complex construction period. The potential for follow-on projects, which has been explicitly considered by developers and Government, could increase the chances of such learning which is often challenging because of the scope for organisational forgetting across long project timescales.

Historical evidence suggests that nuclear power has not been able to tap into mass production efficiencies, due to some vendors focussing on attaining economy-of-scale benefits through bigger reactor sizes[163]. Other low carbon technologies have benefited greatly from having modular designs which *do* lend themselves to mass production. For example, mass production efficiencies have led to cost reductions for solar photovoltaic or wind turbines[164]. The drive towards bigger reactors, in tandem with regulatory and commercially driven innovation, has added complexity which may also have offset economy-of-scale benefits. Authors of a recent UK Energy Research Centre report summed this up as 'unlearning-by-doing at too large and complicated a scale'. Evidence is not yet available to justify whether the benefits of larger reactor designs outweigh the lost benefits of mass production efficiencies. However, the development of small modular reactor designs (SMRs) could shed more light on this question and is an area which the UK could contribute more to with its experience of modular nuclear reactors for submarines and advanced manufacturing.

As discussed above, the cost of finance is a significant element of the overall cost of nuclear power. Costs of finance could fall over time if financers perceive lower risks in lending, which could be expected if the first new build reactors are delivered successfully. However, the use of a UK Government loan guarantee and the involvement of two state-backed countries in the financing of Hinkley Point C will have lowered the cost of finance for this project considerably and it is not clear if future projects will benefit in the same way. As noted above however, there is still debate over whether the expected rates of return are reasonable. It is therefore unclear as to whether cost of finance will have a positive, a negative or little effect on future costs of nuclear power in the UK.

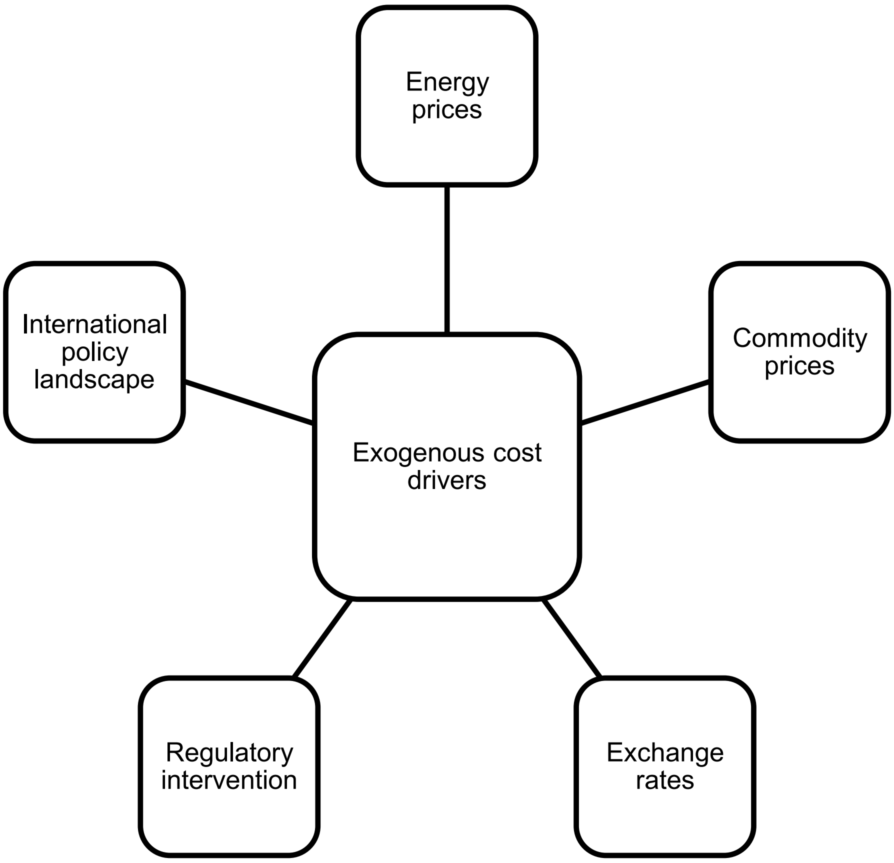
A further potential driver of cost reductions is competition between developers wanting to build new nuclear in the UK. With only a handful of projects in negotiation with the Government for revenue support, and with different timetables for delivery, it is not yet clear that consortia will face adequate competitive pressure to accept lower strike prices. The

---

[163] UKERC (2013) Presenting the Future: An Assessment of Future Costs Estimation Methodologies in the Electricity Generation Sector

[164] Ibid

Government has started from a non-competitive process for negotiating Hinkley Point C and faces a number of challenges in introducing competition, which are discussed in Chapter 1.



As well as cost-drivers with some with a degree of controllability (endogenous), there are factors which are less controllable and that are often particularly difficult to forecast (exogenous). Exogenous factors include movements in energy prices, commodity prices and exchange rates, regulatory intervention and changes to policy in other countries. These factors are general beyond the control of industry or UK policymakers.

Exchange rates are important because supply chains for nuclear are often international, especially for the UK which currently does not have a 'home-grown' reactor design. Energy and commodity prices are influential because of the resource-intensity of constructing nuclear power stations which involve high quantities of steel and concrete for example. Rising raw material prices have been shown to have overwhelmed learning effects in low carbon generation technologies from the early 2000s, with escalations in these inputs offsetting downward cost trends previously seen and anticipated[165].

Regulatory intervention is another exogenous threat which forecasts tend not to reflect, despite past experience showing that events such as those at Fukushima Daiichi often cause reactor designs to be re-visited, leading to delays and cost escalations.

With international supply chains and a global reactor vendor market, the policy decision taken in other countries can affect the market dynamics and prices for nuclear. For example, the major nuclear policy changes in Japan and Germany that followed events at Fukushima in 2011 led to changes in the players pursuing nuclear power in the UK. Germany's decision to move rapidly away from nuclear power was a contributing factor to RWE and EOn exiting

---

[165] See Carbon Connect (2013) Power from Renewables

from the UK nuclear market in March 2012. Whilst policy decisions in Germany contributed to RWE and EOn selling stakes in the Horizon nuclear venture, policy decision in Japan contributed to Hitachi replacing their stake in the consortium in October of the same year.

Difficulty of forecasting technology costs

There are broadly two methods for forecasting technology costs, either using bottom-up engineering studies or by extrapolating from past experience using 'experience curves' (or 'learning curves') which link rate of deployment to rate of cost reduction. Analysis underpinning the Government commissioned forecasts notes that there is a lack of robust data on learning rates for new nuclear projects, particularly in circumstances relevant to the UK[166], limiting the possibility of using experience curves. Recent research by the UK Energy Research Centre reiterates this conclusion but also points out that any learning rate draw from past experience would probably be negative. For these reasons, the majority of cost forecast for nuclear are therefore based upon bottom-up engineering studies.

Past experience shows that forecast cost reductions have rarely been realised in practice, even under seemingly favourable circumstances, reflecting the frequent 'optimism bias' which has been particularly prevalent in nuclear. In France for example, despite a large scale roll out of nuclear power between the 1970s and 1990s, empirical evidence shows that capital costs rose at a rate of 3.6 per cent per year on average[167]. Contemporary forecasts of falling nuclear costs should therefore be understood in the context of a history of escalating costs and the new steps taken to address past pitfalls, such as the Generic Design Assessment process.

Recent research concluded that that factoring exogenous cost drivers into forecasts is particularly challenging and something which has not been done well. Although improvements have been noted, the main effect of these is expected to be wider ranges of uncertainty rather than more accurate point estimates[168], which will not necessarily make the job of policy makers any easier.

FINDING 13

Reducing investment risk, learning by doing and supply chain expansion could all put downward pressure on the costs of new nuclear power, but could be outweighed by other factors driving costs upwards. Historically, under circumstances similar to the UK, costs have tended to rise despite high deployment, primarily due to increasing safety requirements and construction delays.

FINDING 14

The Government hopes to reverse the trend of escalating costs for new nuclear power by licensing reactor designs before construction, offering a guaranteed and index-linked price for electricity for 35 years and selling loan guarantee facilities.

4.5 Comparing future technology costs

The above overview demonstrates not only how difficult it is to forecast technology costs, but how difficult it is to reconcile contemporary forecasts for nuclear power which generally point to cost reduction with past experience which generally points to cost escalation. However, the long lead times and life times of power generation infrastructure mean that policymakers need to design policy that will support and guide investments today. This is a particularly acute issue for the UK now with around 15 per cent of existing capacity closing by 2020, 35

---

[166] Parsons Brinckerhoff (2013) Electricity Generation Cost Model - 2013 Update Of Non- renewable Technologies

[167] Harris, G., et al., Cost estimates for nuclear power in the UK. Energy Policy (2013), http://dx.doi.org/10.1016/j. enpol. 2013.07.116

[168] UKERC (2013) Presenting the Future: An Assessment of Future Costs Estimation Methodologies in the Electricity Generation Sector

per cent by 2025 and 50 per cent by 2030[169]. Policy makers therefore face a challenge in designing policy based upon highly imperfect and uncertain information about how the costs of technology options might change over the next one or two decades.

This section gives an overview of the context in which nuclear power is currently being supported – as one option in a portfolio of low carbon technologies at various stages of cost maturity.

Figure 11 illustrates the uncertainty in the trajectory of Government's levelised cost estimates for key technologies to 2030. As well as the cost elements discussed above, uncertainty over fossil fuel prices means that the range of future levelised cost estimates for all power sector technologies is considerable[170]. Based on this analysis, no single low carbon technology emerges as clearly cheapest and the levelised costs of low carbon technologies increasingly overlaps with unabated gas power, the next least carbon intensive option.

Although unabated gas power[171] is a mature technology, there is considerable uncertainty as to the future levelised cost of this form of generation, stemming largely from gas price uncertainty[172]. There is substantial uncertainty in gas price forecasts with the Government's high and low gas price projections differing by a factor of more than two in the medium term[173]. The Government's central projection however is that both gas and carbon prices will continue to increase over at least the next two decades, adding to the levelised cost of unabated gas power.

Onshore wind and nuclear power (Generation III) are considered more mature technologies with less scope for cost reduction than less mature low carbon technologies, such as large scale solar photovoltaic and offshore wind. Recent experience has demonstrated the unpredictability of *when* costs fall for less mature technologies. The cost of solar photovoltaics fell dramatically in recent years, driven by growing global deployment, however in contrast, the costs of offshore rose over the last decade, driven by factors such as increasing material and currency costs and the technical challenges of building projects further offshore and in deeper water (partly driven by concerns over visual impacts). Nevertheless, long term cost reduction brought about by learning through deployment is a generally well evidence phenomenon[174], albeit not in nuclear power in OECD countries to date.

Fossil fuel power stations with carbon capture and storage (CCS) are at an even early stage of development. Although each part of the chain (capture, transport and storage) has been demonstrated or is currently in use, the stages have not yet been combined with power generation at a commercial scale. Capital cost estimates are therefore highly uncertain, and the range of levelised cost also reflects fossil fuel price uncertainty. Similarly immature are wave and tidal range technologies, which have levelised costs forecast at around £150 to £250 per megawatt hour in 2030.

---

[169] Installed capacity

[170] Note that the Government's levelised cost forecasts do not reflect fossil fuel price uncertainty. The inclusion of fossil fuel price uncertainty in Figure 11 is based on Carbon Connect analysis using the Government's fossil fuel price projections.

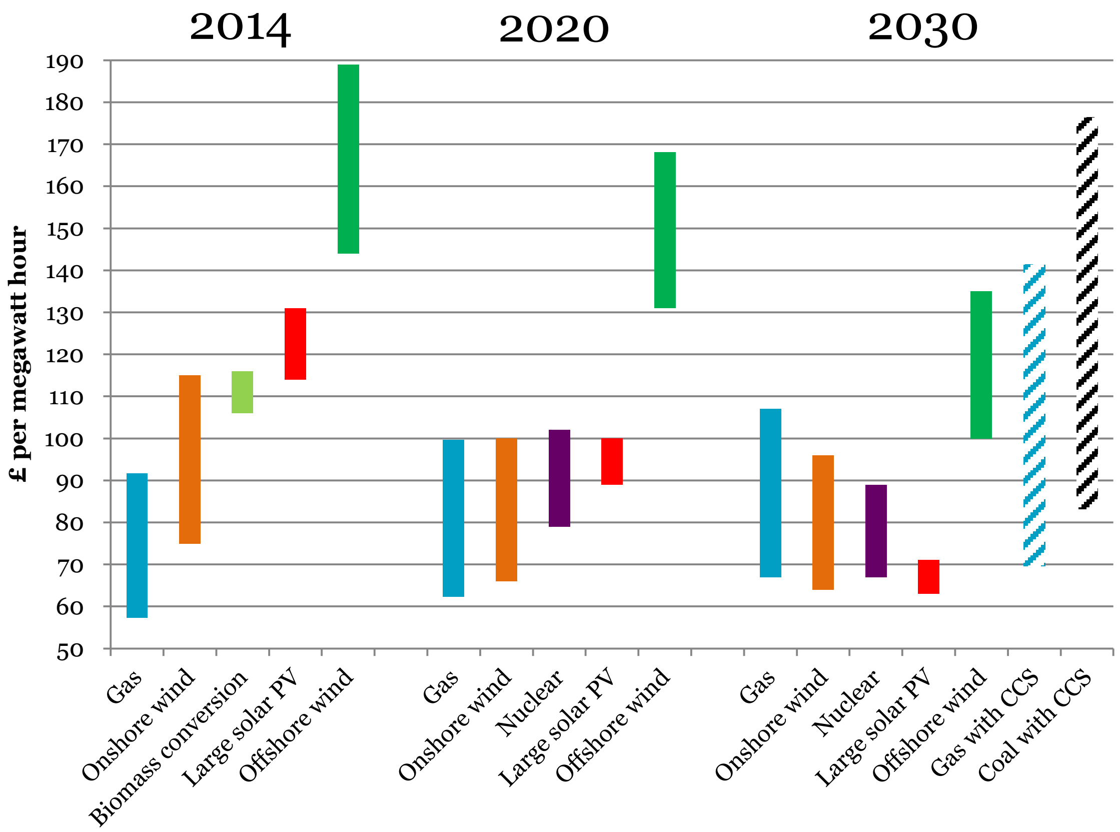
[171] Combined cycle gas turbine (CCGT)

[172] See Carbon Connect (2013) Power from Fossil Fuels

[173] Carbon Connect (2013) Power from Fossil Fuels

[174] UKERC (2013) Presenting the Future: An Assessment of Future Costs Estimation Methodologies in the Electricity Generation Sector

Figure 11: Levelised cost estimates for projects commissioning in 2014, 2020 and 2030, with technology specific hurdle rates



Source: DECC (2013) Electricity Generation Costs December 2013

Notes: 1) DECC's analysis does not reflect fossil fuel price uncertainty so the ranges for gas and CCS are based on Carbon Connect analysis using DECC's central levelised cost estimates and DECC's fossil fuel price projections.
2) Technology specific hurdle rates are used
3) Includes DECC central carbon price projections
4) Gas is unabated combined cycle gas turbine (CCGT); Onshore wind is >5MW in the UK; Offshore wind is Round Three; Nuclear is first of a kind (2020) and Nth of a kind (2030); Gas CCS is first of a kind post-combustion on CCGT; Coal CCS is first of a kind advanced super critical coal with oxyfuel combustion
5) Cost estimates are not provided for all dates because of gaps in the underlying source.

A portfolio approach

An analysis of future levelised costs reveals that nuclear power has a potential to be amongst the most cost competitive forms of low carbon generation during the next decade, and even competitive with unabated gas power, provided it can reverse the long-term trend of cost escalation. However, with technologies at such different stages of cost maturity, it is not yet possible to discern which will be cheapest in the medium or long term.

Given this uncertainty, illustrated by the extent to which levelised cost ranges overlap in Figure 11, even at 2030, policy makers have chosen to pursue a portfolio of options. It is hoped that costs will mature to a point where it is clearer which options are most cost effective, hedging against the risks that some options do not fall in cost or are not economically deliverable at scale.

As a hedging strategy, it is likely to result in UK paying some 'hedging premium' by investing in developing, demonstrating and deploying options that turn out not to be best suited for the UK. For example, if deploying some new Generation III nuclear power as part of a mix of low carbon technologies over the next decade and a half results in continued cost escalations rather than reductions, then the UK might have been better off in hindsight to focus its resources on renewables, carbon capture and storage or alternative nuclear technologies. This is a risk facing many of the large scale low carbon generation options however, and so paying a premium to support a broad portfolio could be a small price to pay in comparison to backing a single option which then turns out to be unsuitable or unaffordable.

Whilst lowering risk, this strategy does give rise to a number of challenges, which are discussed in Chapter 1. These challenges include:

- deciding when to begin narrowing down options in the portfolio, either through Government decisions about resource allocation, or by introducing competition into resource allocation through technology neutral auctions (as is the Government's current medium term aim).
- deciding how to reflect non-price based considerations such as system impacts, public acceptability and differing lead times into technology neutral auctions for revenue support.
- assessing the impact of tensions between options in the portfolio, such as between centralised and decentralised generation technologies, or of spreading resources too thinly across a broad portfolio.

FINDING 15

It is not yet clear which generation technologies will be cheapest in the 2020s, including gas power, because of substantial uncertainty over technology costs, fossil fuel prices and carbon prices. This is the main reason for supporting a broad mix of generation technologies today, including nuclear power.

4.6 Financial support

Feed in Tariff Contracts for Difference

Nuclear power, in common with many other low carbon generation technologies, has very high upfront pre-construction and construction costs, but very low operating costs. These power stations face a greater risk that they will not be able to recoup the initial investment, plus returns for investors, through selling electricity on the wholesale market over the lifetime of the power station. The risk lies in not being able to forecast wholesale electricity prices, and therefore power station revenues, over periods of several decades.

To reduce this risk and reduce the cost of financing low carbon power stations, the Government is introducing feed in tariff contracts for difference. These contracts with low carbon generators effectively fix the price that power stations will receive for electricity that they sell. Generators will continue to sell electricity on the wholesale market but will also receive a 'top up' payment to an agreed 'strike price' from a wholesale reference price (or will make a payment if the wholesale reference price is above the strike price). The contracts last for between around 60 and 75 per cent of the lifetime of the power station, after which generators receive just the wholesale electricity price.

To begin with, strike prices have been set by Government to reflect the cost of technologies that it wants to support. Strike prices for new power stations will fall in line with technology cost reductions and eventually will be set through an auctioning process, rather than being set administratively by Government. The Government intends to transition eventually to technology-neutral auctions for contracts.

Inflation linking strike prices

Within each contract for difference, the Government has chosen to *fully* link strike prices to the consumer price index – a measure of inflation excluding housing costs such as mortgage repayments and council tax. The rationale for including *an element* of inflation linking is that it is more economically efficient for consumers to shoulder inflation risk associated with construction and operating costs that generators will incur. Generators would charge a risk premium otherwise that would be reflected in a higher overall strike price.

The Government's decision to *fully* link strike prices to inflation has been questioned by some[175]. The decision runs contrary to an early assessment made by the Government of the risks of fully linking strike prices to inflation:

> *'Debt repayments are generally fixed nominal costs that do not move with inflation, and the risk of construction costs rising due to inflation is in most cases typically assumed by investors and hedged through existing contractual mechanisms. Full indexation of the strike price therefore runs the risk of over-compensating for the inflation risk faced by investors. Adjusting the full strike price may therefore not be in the best interests of electricity consumers, depending on the extent to which the administrative price setting processes referred to above could factor this transfer of risk into the calculation of a lower up front strike price.'*[176]

The Government has not given a complete justification for its decision to fully link strike prices to inflation. Rather it has stated that the decision to fully link '*should accommodate the requirements of the wide range of different investors [and attract] investors who have not traditionally participated in the financing of low carbon generation in the UK'*[177]. This does not however explain how the risk of over-compensation at the expense of consumers, identified by Government earlier in the development of Electricity Market Reform, has been addressed. This decision could have implications for the value for money of contracts for difference agreed with prospective low carbon generators, including the investment contract with EDF for Hinkley Point C.

Comparing support for nuclear and renewables

Box 2 considers some of the differences in planned support for nuclear and renewables. It shows that the planned arrangements are quite different, but that these differences reflect fundamental characteristics of each. For example, the difference in revenue support contract length reflects the very different power station lifetimes. There are two important points that follow from this. Firstly, it is difficult to compare the 'support packages' for renewables and nuclear because they differ in many ways. Secondly, it will be challenging for the Government to move to technology neutral auctions for revenue support when the support packages for nuclear and renewables are currently so vastly different (see Chapter 1).

Some have been tempted into comparing strike prices for renewables and nuclear, however the differences in commissioning dates and contract length, and the flexibility of the strike price announced for Hinkley Point C all limit the validity and usefulness of doing so. Strike prices on their own are also not a good measure of technology costs. Although they have the same units as levelised costs (pounds per megawatt hour), strike prices are dependent on other factors such as contract length, inflation linking and other support measures. As explored earlier in this chapter, levelised costs remain the best start place for considering technology costs.

---

[175] Liberum Captial (2013) Flabbergasted – The Hinkley Point Contract http://www.liberum.com/pdf/ULkWtp0o.pdf

[176] DECC (2012) Electricity market reform: policy overview, Annex B, Feed-in tariff with contracts for difference: draft operational framework

[177] DECC (2013) Electricity Market Reform – Contract for Difference: Contract and Allocation Overview

Box 2: Comparing support for renewables and nuclear power

Contract length	The lifetime of new nuclear is expected to be 60 years, compared to 22-25 years for most renewables. It therefore takes a correspondingly longer time to recoup upfront capital outlays and so finance requirements are greater for nuclear. There is a trade-off between contract length and strike price, with shorter contracts commanding higher strike prices. On an undiscounted basis, a 15 year contract for renewables covers 60-70 per cent of the asset lifetime, whereas a 35 year contract for nuclear covers around 58 per cent of the asset lifetime. Discounting at ten per cent however means that renewables have around 84 per cent coverage compared to 97 per cent for nuclear. The longer lifetime of nuclear power stations means that there is an additional opportunity cost associated with them. For example, two or three generations of wind turbines could be deployed in the expected lifetime of a single nuclear power station.
Commissioning date	The Hinkley Point C strike price is for a power station expected to commission in 2023. There is no directly comparable strike price for renewables as these only go up to 2018/19, but new strike prices for all technologies can be expected to fall with time. Both renewables and nuclear strike prices are fully index linked but are most often quoted in 2012 prices.
Strike price flexibility	The cost of nuclear power is more uncertain than renewables (see discussion above) and nuclear developers agree contract terms several years earlier than renewables developers because of the long construction time for nuclear. It is therefore understandable that nuclear developers need more flexibility built into contracts. Allowing flexibility over the strike price up or down under defined conditions could benefit consumers by: - reducing the risk of the project being abandoned if project returns become uncommercial (but still judged ‘affordable’ for consumers) - enabling the consumer to benefit from project returns being higher than expected In principle flexibility could benefit consumers, but it is not possible to judge this yet on the basis of public information.
Loan guarantee	In addition to the investment contract for Hinkley Point C, the Government has agreed a loan guarantee facility for the project. This facility, which is paid for by the developer at commercial rates, enables the project to attract low cost finance by using the Government’s AAA credit rating to protect against default risk. The facility is also available to renewables projects, and is being used by Drax power station for its biomass conversion.
Nuclear accident liability cap	New nuclear developers will be liable for the cost of a nuclear accident up to €1.2 billion, beyond which UK tax payers would foot any bill. The Fukushima accident in 2011 has been estimated to cost Japan around €200 billion[178]. For comparison, the peak support for UK banks following the 2008 financial crisis was £133 billion in cash outlay and £1,029 billion in guarantee commitments[179].
Nuclear waste and decommissioning fund	Nuclear operators will pay into a fund which is expected to cover the cost of decommissioning and long-term waste disposal, however the risk that the fund is not enough to meet the eventual costs lies with the UK taxpayer.

---

[178] Reuters (2013) Major nuclear accident would cost France $580 billion: study

[179] National Audit Office (accessed February 2014) http://www.nao.org.uk/highlights/taxpayer-support-for-uk-banks-faqs/

Bills impact

Where strike prices and other features of contracts for difference can be useful is in considering the possible impacts on consumer bills, in terms of both costs and risk. As well as reducing carbon emissions, displacing unabated fossil fuel generation with renewables or nuclear power will also reduce the exposure of consumers to fossil fuel price risk. This lessens both downside risk (high fossil fuel prices), but also upside risk (low fossil fuel prices). Fossil fuel prices have been the main driver of volatility in electricity bills historically and over the past decade, rising gas prices were the primary reason for bills rising. Over the coming decade however, increasing support for deploying low carbon generation, such as renewables and nuclear, is expected to be the primary driver of increasing electricity bills. This rise in bills in the short term is expected to protect consumers from the risk of rising fossil fuel and carbon prices in the medium and long term, as well as contributing towards mitigating climate change. The bill impacts of planned support for low carbon generation is discussed in more detail in the previous report in the *Future Electricity Series*, called *Power from Renewables*[180].

Carbon Price Floor

The UK introduced a Carbon Price Floor in April 2013 as a tax which tops up the price of carbon under the EU Emissions Trading System and is payable by emitters in the UK power sector. The tax was initially set at £16 per tonne of carbon dioxide, well above the EU price which has been at around €5 per tonne over the past year. The Government initially indicated that the price would rise to £30 by 2020 and £70 by 2030, although there has been speculation over a price freeze from 2020.

The Carbon Price Floor is most relevant for existing nuclear (and renewables) operators, as it drives up wholesale electricity prices which dictate their income (see Figure 12 for various impacts). In contrast, strike prices will dictate the income of new low carbon generators with contracts for difference. It is estimated that the Carbon Price Floor will give windfall profits across all existing nuclear facilities of between £1.0 and £2.6 billion between 2013 and 2020, and existing renewables facilities between £0.9 and £2.6 billion (2013 prices)[181].

Figure 12: Effects of the Carbon Price Floor

✓ Increases revenues for HM Treasury by taxing fossil fuel power stations

✓ Improves the commercial case for extending the lives of existing nuclear power stations (see Chapter 3)

✓ Worsens the economics of coal, and to a lesser extent gas, power stations, making renewables, nuclear and carbon capture and storage more competitive

✓ Drives up wholesale electricity prices for UK consumers, improving the economics of existing low carbon generation and energy efficiency

✓ Improves the economics of low carbon power generators after the term of a contract for difference

✓ Displaces carbon emissions from the UK to the rest of the EU.

✗ Has no impact on EU-wide carbon reductions

✗ Has no impact on the economics of new low carbon generation during the term of a contract for difference

✗ Does not give long term confidence to investors in low carbon generation because the tax is subject to review every year

---

[180] Carbon Connect (2013) Power from Renewables

[181] http://www.parliament.uk/documents/commons-committees/energy-and-climate-change/11a%20-%20HMT%20letter.pdf

Some have called for the Carbon Price Floor to be frozen[182] and there has been speculation over whether this will happen[183]. The main impacts of this would be to:

- erode the commercial case for life extensions of existing nuclear power stations (see Chapter 3), which could exacerbate security challenges;
- strengthen the commercial case for keeping coal power stations operating for longer, which poses risks to meeting the fourth carbon budget in particular (see Power from Fossil Fuels[184]) which the Government is already not on track to meet;
- undermine confidence in future tax escalators remaining un-changed, which increases policy risk and costs for consumers;
- reduce the amount of low carbon generation that could be supported under the planned cap for the levy control framework, by lowering wholesale electricity prices and placing more burden on 'top up' payments to low carbon generators which fall under the levy control framework; and
- not increase or decrease carbon abatement at the European Union level.

4.7 Macro-economic impacts

Developing and deploying energy technologies can have substantial economic impacts, beyond consumer energy bills and public spending. For example, pursuing different energy options can affect spending on energy imports, inward investment, export opportunities, and jobs.

Whilst often cited, the results of studies are typically quite uncertain and based upon on a wide range of assumptions that vary between studies. The problem of comparability is compounded by the fact that there are relatively few studies that attempt to assess and compare energy options on a consistent basis. Typical assumptions which contribute to uncertainty and vary between studies include: where to draw the line on what is included/excluded; how to extrapolate indirect employment benefits from direct jobs; what proportion of employment will be met by migrants as opposed to locals; and, how competitive will UK exporters be with businesses abroad. In addition, some assessments do not take into consideration offsetting effects where jobs or consumption are moved around the economy rather than being strictly additional.

Displace spending on fossil fuel imports

As North Sea oil and gas production has declined, fossil fuels imports have increased. Building nuclear power stations could offset future spending on fossil fuel imports, focussing spending on infrastructure investment instead. Although fuel is also currently imported for nuclear power, it makes up a much smaller proportion of the costs of nuclear than fuel does for coal or gas power stations. Instead, spending on nuclear power is concentrated in the upfront construction costs, which creates more opportunity for inward investment (UK content is discussed below). The extent to which nuclear power displaces fossil fuel imports is not straightforward, particularly under a new regime where nuclear power shares a 'pot' of revenue support with renewables and, eventually, power generation with carbon capture and storage. On the other hand, in providing baseload electricity, nuclear power could contribute to limiting the role of fossil fuel power stations to back-up and peaking.

---

[182] CBI (3 February 2014) Press release: Budget should promote investment and exports to rebalance economy
[183] Financial Times (12 February 2014) Osborne set to freeze tax on fossil fuels
[184] Carbon Connect (2013) Future Electricity Series Part One: Power from Fossil Fuels

Employment

As the costs of nuclear power are highly concentrated in the construction phase, so is the employment. Between around 4,000 and 6,000 workers are estimated to be involved at the peak of constructing a twin-reactor nuclear power station[185]. It has been estimated that construction jobs peaked at around 5,000 on Sizewell B and that they will peak at around 5,600 for Hinkley Point C[186]. Between around 330 and 900 jobs are estimated to be involved in the operation and maintenance of new nuclear power stations, over an operating life of between 40 and 60 years. The employment opportunities during decommissioning are less clear because for new build reactors this might not begin until around 2060, but based upon current experience could involve several hundred jobs lasting over a decade[187]. Jobs would also be expected from waste reprocessing and storage, although these are also highly uncertain due to the unknown extent and nature of these activities in around 70 years' time.

UK supply chain content

The Government and EDF and said that up to 57 per cent of the value of Hinkley Point C could be supplied by UK companies[188]. This compares to a Government commissioned study that estimated the UK could between around 44 and 63 per cent of supply chain content for new built nuclear reactors, depending primarily upon the level of Government intervention[189]. Areas of the supply chain where the UK is currently likely to get the most benefit include civil construction and installation, non-nuclear island, pre-licensing technical and design; and, instrumentation and control. The UK will largely be reliant on overseas suppliers for fabrication of reactor pressure vessels, steam generators and turbines, ultra large forgings and reactor coolant pumps[190].

In its Nuclear Industrial Strategy, the Government set out the work it was and was planning to undertake to strengthen the nuclear supply chain in the short term. Beyond this, there is potential for the UK to secure much higher supply chain content, perhaps 80 per cent, for nuclear in the longer term (beyond 2030) through developing or adopting its own native reactor design, or if small modular reactors are pursued.

Export opportunities

The World Nuclear Association estimates that international procurement opportunities arising from planned nuclear new will amount to around £25 billion per year to 2025[191]. Of this, it is estimated that the UK could secure around £600 million per year, totalling around £8 billion up to 2025. Just over half of this custom could come from the Middle East and South Asia region, where around 40 new reactors are planned, if UK companies secure around 10 per cent of international procurement opportunities (see Figure 13). On the other hand, over 100 new reactors are planned in the Far East with a potential market size of around £110 billion – the largest potential regional market. The analysis below assumes that UK companies achieve around one per cent market penetration.

---

[185] Tyndall Centre (2013) A review of recent research relevant the new build nuclear power plants in the UK

[186] DECC (2013) Press release: Initial agreement reached on new nuclear power station at Hinkley – 21 October 2013

[187] There are currently just under 1,000 people involved in decommissioning the site of two Magnox reactors at Trawsfynydd power station which closed in 1991.

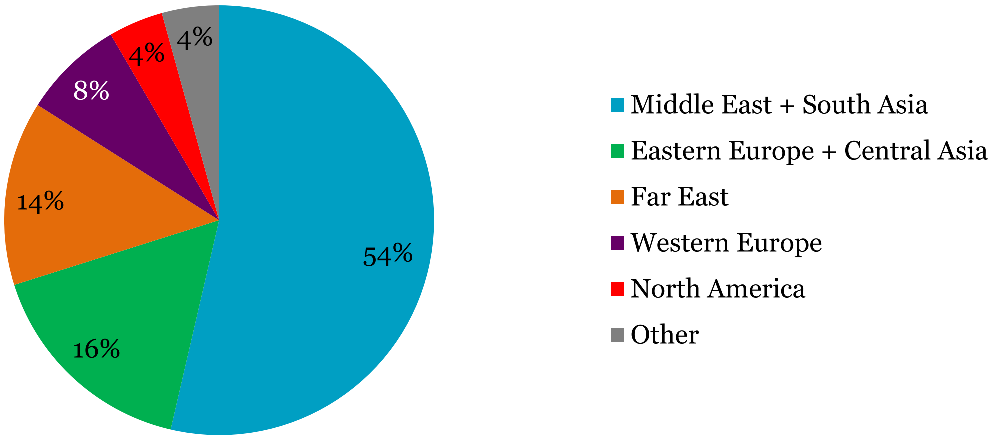
[188] DECC (2013) Initial agreement reached on new nuclear power station at Hinkley. 21.10.13

[189] Oxford Economics and Atkins (2013) The economic benefit of improving the UK's nuclear supply chain capabilities. Note: the upper estimate only applies to the third new reactor onwards.

[190] HoC (2013) Energy & Climate Change Select Committee: Building New Nuclear: the challenges ahead (HC 117)

[191] World Nuclear Association (2012) The World Nuclear Supply Chain: Outlook 2030

Figure 13: Breakdown of £8 billion export opportunities up to 2025



Source: BIS (2013) Nuclear Industrial Strategy: The UK's Nuclear Future

UK Trade and Investments will continue to support UK companies in securing export business in the nuclear sector, with particular strengths noted in research and development, consultancy and decommissioning. The potential for new nuclear power stations to be built in the UK over the coming decade could expand the areas in which UK companies excel, although there is a general view that international competition is strong and UK firms will continue to face significant challenge from overseas companies[192]. In additional, there could be expanding opportunities for UK companies in fields such as finance and law that can build experience in nuclear.

Economic value of new build

Research commissioned by the Government concludes that for 10 gigawatts of new nuclear power deployed by 2030, the UK could expect between £16.6 and £21.3 billion of gross value added (2012 prices) and between around 14,500 and 18,500 jobs on average over this period[193]. The range in assumptions reflects uncertainty over the UK content of the supply chain, itself largely dependent on the level of Government intervention. Of this gross value added, around 40 per cent relates directly to business generated for the UK supply chain (direct impacts), around 35 per cent relates to additional money that the UK supply chain goes on to spend (indirect impacts), and around 25 per cent relates to increased consumer spending as a result of additional employment (induced impacts)[194].

FINDING 16

There are substantial economic opportunities for the UK if it can secure a high proportion of business in the supply chain for new nuclear, both at home and abroad. It is difficult to compare these opportunities with other energy options however, because there are few studies that make comparisons on an equal basis.

---

[192] Oxford Economics and Atkins (2013) The economic benefit of improving the UK's nuclear supply chain capabilities

[193] Ibid

[194] Ibid

5. SUSTAINABILITY

Environmental sustainability is considered in this chapter through carbon[195] impacts and wider, non-carbon, sustainability impacts. Social and economic sustainability are considered as they arise in this report's other chapters. To take full account of all impacts and risks, and to encourage a full assessment, impacts arising throughout the nuclear power lifecycle are evaluated.

Carbon

In response to the threats of climate change arising from man-made greenhouse gases, the UK introduced a statutory target to reduce carbon emissions by 80 per cent on 1990 levels by 2050. Interim carbon budgets are set by Government and serve as a means of holding Government to account in the short and medium term for progress against delivery towards the long term target. Carbon budgets currently extend out to 2027 in five year periods. In 2012, electricity generation was responsible for 32 per cent of total UK carbon emissions[196] and there is general consensus that by 2050 power sector emissions should be virtually zero at most.

There is strong consensus that the power sector is the most practical and cost effective part of the economy to begin carbon reductions[197, 198, 199]. The Committee on Climate Change has recommended that the carbon intensity of the sector be reduced from 531 grams of carbon dioxide per kilowatt hour (gCO2/kWh) in 2012 to around 50 gCO2/kWh by 2030[200, 201]. These measures of carbon emissions are based upon emissions arising directly from combustion at power stations and are narrower in scope than life cycle assessment.

Life cycle assessment is used below as the best means of assessing carbon impacts of different power sector technologies for the purposes of developing strategy and policy. Although life cycle assessment is useful for understanding the full implications of strategy decisions, carbon emissions are measured on a UK production basis for the purpose of the UK's carbon budgets and target. This means that emissions arising outside of the UK, for example through fuel production, are not counted.

Wider sustainability

Whilst carbon emissions are a large part of considering sustainability of electricity, there are additional risks to the environment posed by power production. Power sector infrastructure, like other infrastructure, can cause non carbon pollution, habitat loss and disturb or displace flora and fauna. This chapter looks at the major carbon and non-carbon impacts and risks posed by nuclear power, and compares these with alternative technologies.

5.1 How low carbon is nuclear?

This question can be answered by measuring the amount of carbon emitted to the atmosphere per unit of electricity generated – a measure termed 'carbon intensity'. This measure allows for the contribution to atmospheric carbon dioxide to be quantified and compared across different technologies. To make well-informed decisions about long term power sector decarbonisation, decision makers must consider all carbon emissions arising

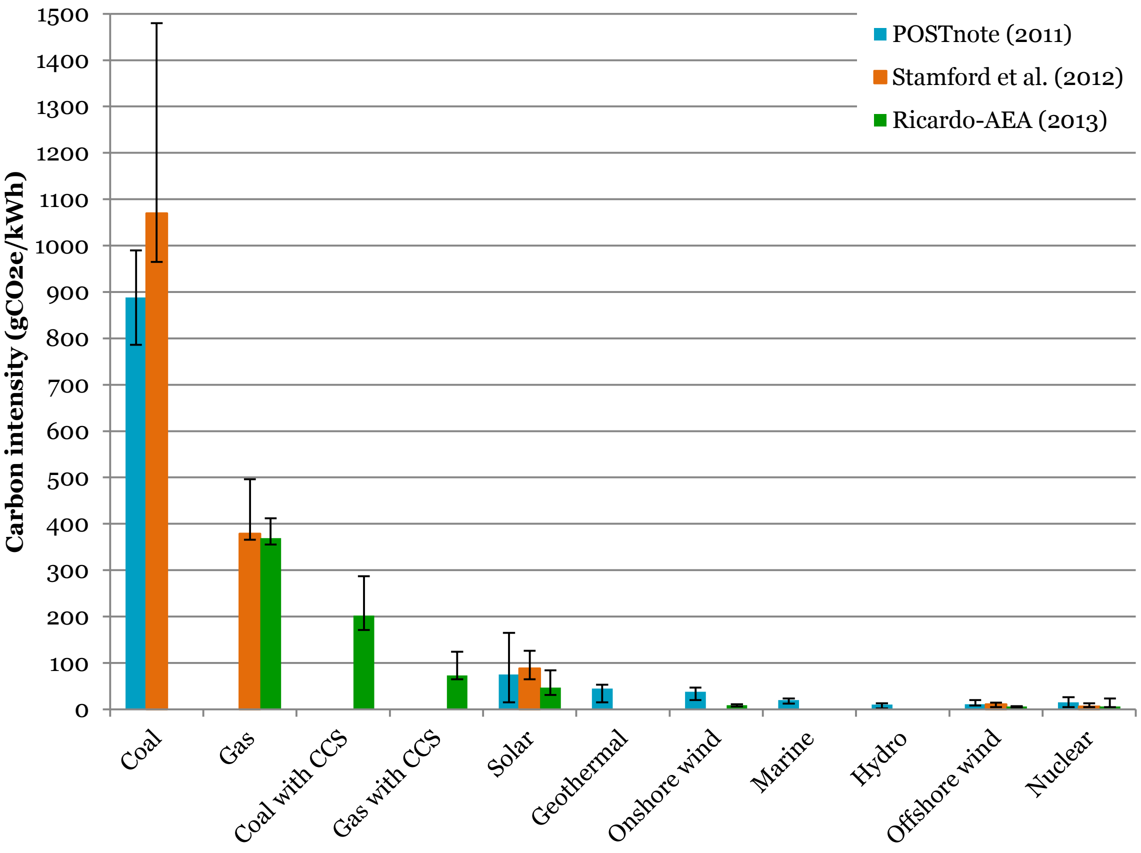
---

[195] Carbon is used as a proxy for all greenhouse gases throughout
[196] DECC (2013) UK greenhouse gas emissions, provisional figures
[197] CCC (2008) Building a Low Carbon Economy: The UK's Contribution to Tackling Climate Change
[198] ETI (2011) Modelling the UK energy system: practical insights for technology development and policy making
[199] UKERC (2013) The UK energy system in 2050: Comparing Low-Carbon, Resilient Scenarios.
[200] CCC (2011) Fourth Carbon Budget
[201] CCC (2013) Next steps on Electricity Market Reform

from energy production. For this reason, carbon emissions arising across the nuclear fuel cycle (described in Chapter 2) are examined. There are however a number of challenges in calculating and using life cycle carbon intensity information. Although standardised methodologies exist, results are highly dependent on measures (or estimates) of actual carbon emissions arising from particular activities. Care should be taken when reaching general conclusions on carbon intensity for individual technologies where results can be very circumstantial.

For the reasons listed above, life cycle assessment of carbon intensity is difficult to do and differences exist between sources and the ranges around central estimates are often wide. It is also notable that there are few single studies that assess a comprehensive range of technologies and adopt a common methodology. To attempt to combat this, three sources are drawn upon in Figure 14, two of which draw on data from a wide range of studies.

Figure 14: Life cycle assessment of carbon intensity for different technologies



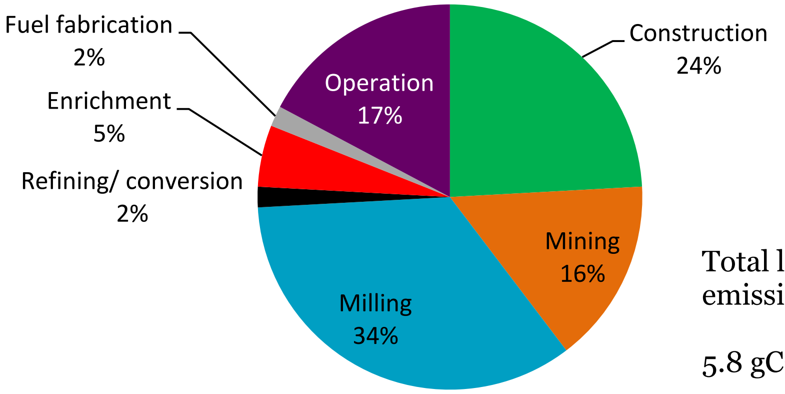
Sources: 1) POSTnote (2011): based upon 30 published peer-reviewed sources of the total life cycle carbon emissions for technologies deployed internationally.
2) Stamford et al. (2012): based upon the CML method, one of the most widely used life cycle impact assessment methods, adjusted for UK deployment. Impacts were assessed using global or European data.
3) Ricardo-AEA (2013): conducted for the Committee on Climate Change based on a review of existing literature. Life cycle assessments were made for deployment of technologies in the UK.

Notes: 1) All numbers are grams of carbon dioxide equivalent per kilowatt hour (gCO2e/kWh).
2) Gas is Combined Cycle Gas Turbine.
3) Coal with CCS includes pulverised coal and integrated gasification combined cycle. The central estimate is an average of the central estimates for each.
4) The Ricardo-AEA solar figures are the combined results of their analysis for poly-crystalline, mono-crytalline and CdTe solar. The central estimate is an average of central estimates for each.
5) Hydro is river hydro.
6) CCS is carbon capture and storage.
7) For detailed assumptions, refer to each source.

Useful conclusions can be drawn however despite these limitations. Lifecycle emissions values illustrated in Figure 14 for nuclear power range from 5 to 25 gCO2/kWh, which compare similarly or favourably with other low carbon technologies. Two of the studies (Stamford et al. and Ricardo-AEA) provide estimates for nuclear power in the UK, with technology assumptions based on Pressurised Water Reactors, which are similar to those proposed for Hinkley Point C. The POSTnote study uses estimates for a wide range of countries and technologies. Although imperfect, comparing a range of studies and contexts provides an indication as to the range of carbon intensities that can result from different lifecycle characteristics.

Figure 15 breaks down the central estimate lifecycle emissions estimate from an analysis by Ricardo-AEA. This scenario assumes generation is from a Pressurised Water Reactor, operating an open fuel cycle where new uranium is used as fuel and spent fuel is directly disposed of. Other assumptions have been selected to reflect a likely UK context. The breakdown highlights the significant contribution that uranium mining and milling make towards total lifecycle emissions, largely due to the relative energy intensity of these processes.

Figure 15: Breakdown of lifecycle emissions from UK nuclear power



Total life cycle carbon emissions:

5.8 $gCO2_e$/kWh

Source: Ricardo AEA, 2012 (report commissioned by the Committee on Climate Change), Base case scenario

The study tests a range of different sensitivities to the underlying assumptions, resulting in a range of lifecycle emissions of between 5 and 22 $gCO2_e$/kWh. Factors having the greatest impact on lifecycle emissions are uranium milling and mining, plant construction (including intermediate waste storage facilities) and plant operation, which includes encapsulation of spent fuel for waste disposal.

Changing uranium enrichment from the centrifuge method to gas diffusion results in the highest lifecycle value (22 $gCO2_e$/kWh) due to the greater energy intensity (50 times) of this process. The next most important factor is the concentration of mined uranium, which determines how much ore must be extracted and processed. Moving from an ore grade of 0.1 per cent to 0.05 per cent increases lifecycle emissions to just under 9$gCO2_e$/kWh – an approximately 50 per cent increase. The study goes on to estimate future lifecycle emissions by modelling the effect of anticipated reductions in grid electricity (in the UK and abroad) across the lifecycle, suggesting that by 2050, emissions intensity could reduce by 60 per cent[202].

---

[202] Ricardo AEA (2013) Current and Future Lifecycle Emissions of Key Low Carbon Technologies and Alternatives

Available evidence on the lifecycle emissions of nuclear power suggest that it is one of the lowest carbon forms of power generation, and could therefore make a significant contribution towards decarbonising the UK power sector. Some uncertainties remain, including the real life performance of new reactors constructed in the UK and emissions arising from end of life decommissioning activities, although these are unlikely to have a significant impact on overall lifecycle emissions.

FINDING 21

Nuclear power is amongst the lowest carbon generation technologies with a carbon intensity of 5-25 gCO2/kWh, compared to the average from the power sector in 2013 of around 470 gCO2/kWh. Around half of these emissions arise from the mining and milling of uranium ore.

5.2 Wider sustainability

Nuclear power, like other industrial activity, has other environmental and social impacts, such as visual, noise, pollution and biodiversity effects. Nuclear power is not unique among power generation technologies in producing hazardous substances, the most significant of which are radioactive materials, present across the nuclear energy lifecycle. The presence of high concentrations however creates unique risks to nuclear workers and the general public in the event of a reactor containment breach. These risks are evaluated in the following section on radiation. Similarly, the long lived nature of some radioactive nuclear waste, and the dual use potential of nuclear technology for civil and military applications, creates social and economic sustainability challenges which are examined in the following sections on nuclear waste and proliferation.

Fuel and material inputs

Environmental impacts vary between each stage of the nuclear energy lifecycle. As with lifecycle carbon analysis, assessment of other lifecycle environmental impacts is highly dependent on the boundaries of the assessment and input assumptions.

Nuclear power has some similar-in-nature upstream environmental impacts to fossil fuel power such as impacts on air, land and water quality from fuel extraction and processing, as well as during the production of power station materials and components (as with all technologies). Coal and uranium are extracted by mining, whereas natural gas is extracted from wells drilled into underground deposits, although there may be increasing use of hydraulic fracturing in future. Uranium is mined using conventional open cast or underground extraction or, increasingly, in-situ leaching in which uranium is separated from ore by chemicals pumped underground[203]. Impacts from fuel extraction are greatest for coal, and significantly less for gas and uranium. Mining activities and impacts, per unit of energy delivered, are much lower for uranium versus coal due to the significantly higher energy density of uranium[204].

Again, because of the higher energy density of uranium, the quantity of materials required to construct nuclear power facilities is similar to that for fossil fuel power plants and can compare favourably with some renewables, typically those with a lower energy density such as solar photovoltaic[205]. As a result, the air, land and water pollution impacts of non-fuel

---

[203] World Nuclear Association (2013) World Uranium Mining Production (Accessed February 2014)

[204] Stamford & Azapagic (2012) Life cycle sustainability assessment of electricity options for the UK; Int. J. Energy Res. 2012; 36:1263–1290

[205] Vidal, O., Goffe, B., Arndt, N. (2013) *Metals for a low carbon society: Supplementary Information*. Nature Geoscience, Volume 6 2013

inputs for nuclear power are similar to those of coal and gas plant, and lower than some renewables[206].

Local impacts of power generation

Many of the effects of nuclear power stations on their local environment are much like those from other types of large infrastructure. Nuclear power stations have a relatively small land footprint per unit energy output compared with other technologies, although the comparison is not straightforward for example with dispersed renewables such as wind power. This is of relevance for both ecosystem and biodiversity impacts, and effects on human communities such as noise and visual impact. Nuclear power stations can occupy land for a significantly longer period of time than other technologies due to their longer operational lives and the considerable duration of decommissioning (around 20 years) and waste storage activities (up to around 100 years[207]). Eligible sites for new build reactors were assessed for their environmental impacts, and therefore these impacts are relatively more known and quantified, and on this basis one site was excluded[208].

Hazards posed by radioactive materials at nuclear power sites in the UK (which include fuel production facilities, reactors, spent fuel processing and waste storage) are regulated to ensure that the risks of harm to workers, the public and the environment are kept as low as practically possible[209]. Discharge of radioactivity from these sites is also regulated[210]. The nature of some radioactive waste however creates the potential for low risk but high impact contamination at sites and a potentially larger surrounding area, through accidents or deliberate sabotage (the hazards and risks of nuclear radiation are examined further below).

Wastes

The environmental impacts of wastes depend on their type, volume and how they are managed and controlled. Waste is produced during uranium mining, as a result of the separation of uranium for its ore, which contains low levels of radioactivity. Waste material is normally stored in engineered facilities at mines to prevent contamination of the local environment. Coal mining also produces wastes, although larger volumes are produced relative to uranium mining due to the lower energy density of coal[211]. As with many renewables, little or no atmospheric pollution is directly created during the normal operation of a nuclear power station. This contrasts to coal and gas, which both emit large volumes of carbon dioxide to the atmosphere. Coal combustion also emits significant quantities of other pollutants, such as sulphur dioxide, to the atmosphere[212].

Nuclear fuel, in common with coal and biomass combustion, leaves behind residual waste. Coal combustion leaves behind fly ash which can contain traces of a variety of metals and pollutants[213], and in UK plants is captured and recycled (in material such as concrete) or disposed of in landfill. A one gigawatt coal power station may produce around 375,000 tonnes of ash per year[214]. The principle waste stream from a nuclear power station is radioactive waste, which takes a variety of forms. These can be categorised by their level of radioactivity - low, intermediate and high. The handling and disposal of these wastes is regulated and controlled to keep the risks of contamination and exposure as low as practically possible.

---

[206] Stamford & Azapagic (2012) Life cycle sustainability assessment of electricity options for the UK; Int. J. Energy Res. 2012; 36:1263–1290

[207] EDF (2010) Hinkley Point C – Pre application consultation

[208] DECC (2011) National Policy Statement for Nuclear Power Generation Vol II (EN-6)

[209] ONR (2013) A Guide to Nuclear Regulation in the UK

[210] Sustainable Development Commission (2006) The Role of Nuclear Power in a Low Carbon Economy: Paper 6, Safety & Security

[211] Tyndall Centre (2013) A Review of Research Relevant to New Build Nuclear Power Plants in the UK

[212] Stamford & Azapagic (2012) *Life cycle sustainability assessment of electricity options for the UK*; Int. J. Energy Res. 2012; 36:1263–1290

[213] NREL (1999) Life Cycle Assessment of Coal-fired Power Production

[214] Drax (2012) Environmental Performance Review (Accessed February 2014)

The majority of waste arising from a nuclear power station (around 90 per cent) is low level waste with short lived radioactivity, ranging from worker gloves to building materials. It is not dangerous to handle, but cannot be disposed of as normal waste, and is instead placed in engineered stores at surface level. Disposal in this manner is not considered to pose a threat to the local environment[215]. Intermediate level wastes (about 7 per cent of total waste volume) have higher levels of radioactivity, and require some shielding, and include items such as fuel cladding and reactor components. Lastly, high level waste is defined by its self-heating properties caused by radioactive decay, and includes spent nuclear fuel and the products arising from spent fuel reprocessing. It accounts for around 3 per cent of the total waste volume, and 95 per cent of total radioactivity in all wastes[216]. A current one gigawatt nuclear power station operating on an open fuel cycle can be expected to produce around 200-350 cubic meters of low and intermediate level waste, and 10 – 20 cubic meters of high-level waste per year[217].

Some chemical elements (isotopes) contained within intermediate and high level waste are initially highly heat generating and radioactive, and can remain radioactive for up to hundreds of thousands of years. As a result, they require careful management and isolation from people and the environment now and in the long term. Interim storage of these in the UK takes place at purpose built facilities which are designed to allow the very hot elements of high level waste to cool for 30 to 50 years. There is consensus that the best way to store these wastes in the long term is in a deep repository in a location that will remain geologically stable over the period which it continues to present a radiation hazard[218]. Although such storage is technically feasible, uncertainties remain regarding the suitability of geological environments over the very long term and the effects of the radioactivity and heat output of stored material on their containment environment[219]. The most immediate challenge for the UK is however site selection, with the current process stalled. This process is examined in the later part of this Chapter.

A final consideration to waste and broader environmental impacts is the recyclability of the materials used in power station construction. Although some parts of a nuclear power plant will not be recyclable due to irradiation, these are small in relation to the overall volume of material (estimated to be less than five per cent for Hinkley Point C). As a result, the recyclability of nuclear power is estimated to be similar to that of coal and gas plants (80 – 90 per cent) with estimates for solar and wind slightly higher (above 90 per cent)[220].

5.3 Radiation

Doses of radiation can be received by absorption through the skin and eyes, through the consumption of contaminated foods and liquids and by inhalation. The effects of radiation at high doses include severe and potentially fatal sickness and a range of cancers, of which there may be a risk even at lower doses. These effects vary with the age at which a person is exposed, the organs affected and the level and duration of exposure. Over and above background levels of naturally occurring radiation, everyday sources of higher exposure include CT scans, aeroplane travel and smoking[221].

Current safety standards are based on understanding of the risks of low dose radiation, which are the levels of radiation associated with nuclear power operation or exposure beyond

---

[215] Environment Agency (2011) Low Level Radioactive Waste

[216] World Nuclear Association (2014) What are nuclear wastes (Accessed online January 2014) http://www.world-nuclear.org/Nuclear-Basics/What-are-nuclear-wastes-/

[217] IEA (2010) ESTAP Technology Brief – EO3

[218] Birmingham Policy Commission (2012) The Future of Nuclear Energy in the UK

[219] Tyndall Centre (2013) A Review of Research Relevant to New Build Nuclear Power Plants in the UK

[220] Stamford & Azapagic (2012) *Life cycle sustainability assessment of electricity options for the UK*; Int. J. Energy Res. 2012; 36:1263–1290

[221] Ibid 219

nuclear sites following accidents. Risks to humans depend on levels of exposure. There are background levels of naturally occurring radiation, and an average individual's effective dose is around 2.4 to 6 millisievierts per year (mSv/year). The maximum advised dose for nuclear workers is 50 mSv/year and the annual dose from smoking 20 cigarettes per day is 80 – 90 mSv/year. The World Health Organisation estimated that the effective dose in the high exposure evacuated areas of Fukushima Prefecture at 10 to 50 mSv/year and 1 to 10 mSv/year in the rest of the prefecture[222].

There are uncertainties however regarding the health risks arising from low dose radiation. Human health impacts of exposure are difficult to disaggregate from other sources of radiation and causes of cancers for example. The lack of certainty has prompted the development of the linear no-threshold model of radiation risk that assumes that there is no 'safe' dose of radiation. This model is however itself contested by some who argue that it may overestimate the risks[223]. The model has informed regulation of the nuclear sector, and in the UK radiation risks are managed according to the principle that they should be kept 'as low as practicably possible'[224].

Health risks from nuclear sites

Radiation risks can be understood in the context of the range of health risks that arise from energy technologies such as pollution (including radiological) or occupational accidents. Nuclear power generation, and especially fuel reprocessing activities, result in very low level radioactive discharges to the environment, although these are controlled and regulated. Evidence suggests that, on a per unit energy basis, the rate of occupational deaths arising from the nuclear energy lifecycle compares favourably with renewables, with both technologies having a lower impact than coal and gas, largely due to the effects of pollution and accidents in upstream fossil fuel extraction[225]. These findings are also applicable to a comparison of health impacts across the population as a whole[226, 227].

Concerns have been raised following reports of statistically significant clusters of childhood leukaemia around the Sellafield and Dounreay nuclear fuel reprocessing sites and similar facilities in France and Germany. Although the general link between radiation and the causes of cancer and leukaemia are well established, debate continues regarding the risks of those diseases directly from radioactive releases in the vicinity of operational nuclear installations. Although studies have confirmed higher rates, they have not been able to establish a causal link with the presence of nuclear facilities[228]. A review of UK nuclear power stations by the Committee on Medical Aspects of Radiation in the Environment found no significant evidence of an association between the risk of childhood leukaemia and living near to a nuclear power station[229].

Accidents

A key difference between nuclear power and other forms of generation are the low-probability, high-impact risks of relatively high contamination over a large area in the event of a failure of radioactive containment, as was the case at the Chernobyl and Fukushima reactors in Ukraine and Japan respectively. Events such as these can expose power station workers and emergency response teams to very high doses of radiation – 28 deaths have been

---

[222] Tyndall (2013) A Review of Research Relevant to New Build Nuclear Power Plants in the UK
[223] Ibid
[224] ONR (2013) A Guide to Nuclear Regulation in the UK
[225] Markandya & Wilkinson (2007) Electricity generation and health
[226] Ibid
[227] Spring (2011) Assessing the Sustainability of nuclear power in the UK
[228] Ibid 222
[229] Committee on Medical Aspects of Radiation in the Environment (2011)Further consideration of the incidence of childhood leukaemia around nuclear power plants in Great Britain

attributed to high levels of radiation exposure following the Chernobyl accident[230]. Impacts on neighbouring populations fall into the low dose category, as described above.

Accidents and radioactive releases of this scale are infrequent and are taken into account in the occupational and public mortality rates for nuclear power quoted above, which suggest that nuclear compares favourably with other technologies. There remains debate as to the quantifiable health impacts of such accidents, however. For example, assessments of the human health impacts of the Chernobyl accident on neighbouring populations indicates increased levels of thyroid cancer in children, a conspicuous indicator of radiation health impacts. This disease is highly treatable and therefore does not contribute greatly to mortality rates or life expectancy figures[231], although assessments of health impacts normally take account of quality of life in addition to length of life. The World Health Organisation estimates that the risk for specific cancers in certain subsets of the population in Fukushima Prefecture has increased as a result of the Fukushima accident in 2011. It does not anticipate greater risks for the general population inside and outside of Japan[232].

Reactor safety

The frequency and probability of such events are in part determined by the safety of nuclear reactors. These are designed to cope with a range of potential accidents, for which it must be shown that wider radiation doses and the frequency of these events will not exceed specified limits[233]. A key focus of safety regulation and design is to limit the potential for reactor core damage under accident conditions. Core damage is considered critical because this may prevent the control of a nuclear reaction, which can lead to a core meltdown, where much or all of the fuel and its metal containment melt due to a loss of the capacity to remove decay heat. A meltdown increases the potential for radioactivity to escape containment and into the environment.

There has been a significant drive to improve the safety of reactor designs by the nuclear industry, as a result of increasingly stringent regulation. Two key nuclear events have prompted national regulators to tighten safety approaches. In 1979, technical failure compounded by human error led to a partial core meltdown at the Three Mile Island plant in the USA, leading to reactor containment breach but minimal public health impacts. A second incident occurred at Chernobyl, Ukraine, in 1986 where human error and design led to a loss of reactor containment. An explosion and fire led to widespread dispersion of radioactive materials. As a result of improved design, vendors claim the probability of such events has been decreased by several orders of magnitude[234]. Such approaches to risk assessment have been criticised, however, for failing to account for 'cascades' of events or impacts outside models, such as the earthquake and tsunami that hit Fukushima[235].

UK safety requirements have also been adjusted over the years, for example by requiring reactor containment for new reactors to be resistant to the physical impact of a large commercial airliner following the September 11th attacks on New York. In the wake of events at Fukushima in 2011, the Government commissioned the Chief Nuclear Inspector to examine the incident and draw safety lessons for the UK. The subsequent report indicated that the accident had not revealed any fundamental safety weaknesses in the UK's nuclear industry, but did indicate areas that could be improved[236].

---

[230] Hatch, M., E. Ron, et al (2005) "The Chernobyl Disaster: Cancer following the accident at the Chernobyl nuclear power plant" Epidemiologic Reviews 27: 56-66

[231] Tyndall (2013) A Review of Research Relevant to New Build Nuclear Power Plants in the UK

[232] WHO (2013) Health risk assessment from the nuclear accident after the 2011 Great East Japan earthquake and tsunami, based on a preliminary dose estimation

[233] Sustainable Development Commission (2006) The Role of Nuclear Power in a Low Carbon Economy: Paper 6, Safety & Security

[234] Chatham House (2012) Preparing for High-impact, Low-probability Events

[235] Ibid 231

[236] Office for Nuclear Regulation (2011) Japanese earthquake and tsunami: Implications for the UK nuclear industry

5.4 Managing High-level nuclear waste

High and intermediate level wastes are managed to safeguard human health and minimise environmental damage. There is consensus that the best way to manage these wastes is long term storage in a geological disposal facility. Once built, this facility will accommodate the large volume of legacy waste from 60 years of military and civil nuclear activity, and waste generated by the new build programme. The formulation of a strategy to deal with long term waste is an important part of the justification for the new build programme, with the Government intending that operators should bear their full share of these costs[237]. Although the issue of legacy waste is not necessarily directly relevant to the new build programme, both sets of waste will likely share the same long term disposal facility. There are possible links between some legacy waste and new nuclear power generation however if spent fuel is incorporated into fuel cycles for new reactors. Options for re-use of the UK's plutonium stockpile could fall into this category for example (see Chapter 1 and 2).

Geological Disposal Facility

The Government intends to store legacy and new build intermediate and high level waste in a geological disposal facility (GDF). After a period of 50 to 100 years of cooling, waste will be packaged and placed in a specially engineered geological 'vault' situated between 200 to 1,000 metres below ground, where natural barriers (geology) and man-made barriers (waste containers and engineered vaults) will limit the escape of radioactivity[238]. The repository will likely remain unsealed for 100 years, after which it will be sealed, with the aim that no further active management be required[239]. The scientific and engineering challenges of constructing such a facility will require further research[240]. A number of countries propose to construct underground repositories, and several test facilities have been constructed around the world[241]. The costs of the facility will remain highly uncertain until a suitable site is located, although recent estimates suggest a total cost of £12 billion (at 2008 money values and undiscounted) to house legacy waste (excludes new build waste arisings)[242].

Legacy waste

The UK's legacy waste is constituted of intermediate and high level waste, the majority of which is stored at Sellafield. It includes large quantities of separated uranium and plutonium oxide, a result of historic decisions to reprocess (separate into components) spent fuel. The total volume of legacy radioactive waste that is forecast to result from past and current nuclear activities is about 4.5 million cubic metres (4.9 million tonnes), a volume that could fill Wembley stadium about four times over[243]. Historic management of these wastes has been poor, with facilities allowed to deteriorate significantly over time, alongside rising management costs[244].

Waste from new build reactors

The Government's current policy position is that intermediate and high level waste from new nuclear build, after interim storage, will be directly disposed of in a geological disposal facility. Operators will be required to construct dedicated facilities at their reactor sites to hold spent fuel and other wastes in interim storage for 50 to 100 years, after which they pay the Government to take responsibility of their waste and dispose of it. It is estimated that a reactor fleet of 10 gigawatts operating for 60 years would increase the volume of intermediate and high level waste requiring long term storage by between 8 and 10 per cent[245]. Although

---

[237] Business Enterprise & Regulatory Reform (2008) A White Paper on Nuclear Power
[238] NDA (2011) Radioactive Wastes in the UK: The 2010 Estimate of Radioactive Waste for Geological Disposal
[239] Birmingham Policy Commission (2012) The Future of Nuclear Energy in the UK
[240] Tyndall Centre (2013) A Review of Research Relevant to New Build Nuclear Power Plants in the UK
[241] NDA (2013) Geological Disposal: How the world is dealing with its radioactive wastes
[242] NDA (2012) Options For Accelerating Implementation of the Geological Disposal Programme
[243] NDA (2013) Radioactive Wastes in the UK: A Summary of the 2013 Inventory
[244] Mackerron, G (2012) Evaluation Of Nuclear Decommissioning And Waste Management
[245] National Nuclear Laboratory (2011) UK Nuclear Horizons: An independent assessment

the higher proportion of spent fuel placed in storage will increase the overall radioactivity of the waste inventory, this is not expected to impact greatly on the design of a geological disposal facility[246]. The relatively modest increase in the stock of waste compared with legacy waste is a result of the lower waste volumes produced by new reactors, thanks to improved design and fuel efficiency relative to the UKs past reactor fleet[247]. Vastly improved fuel efficiency and options to reduce the volume and radio toxicity of legacy spent fuel are potential benefits offered by research and development on fast reactors, advanced fuel cycles and alternative fuel cycles (thorium-based) discussed in Chapter 2.

Operators will pay the Government a fee for taking delivery and disposing of high and intermediate level waste. Before commencing reactor construction, operators will be obliged to demonstrate to Government arrangements to set funds aside for this and future plant decommissioning costs[248]. This fee will be calculated according to the operator's share of the variable costs (construction costs that vary with the volume of waste stored) of building the geological disposal facility. Operators will also make a smaller contribution to the fixed costs, (those unrelated to the volume of waste stored) including site selection, surface facilities and access shafts[249]. However the majority of fixed costs will be borne by Government, which will also fund the share of variable costs relating to legacy waste. The costs of the facility will remain highly uncertain until a site is selected, creating risks around agreed pricing. Cost escalation relative to agreed pricing could result in inadequate industry funds being set aside to cover the costs of managing additional waste from new build nuclear facilities. This is not however a risk which nuclear operators have any control over and so is better shouldered by Government.

FINDING 22

The costs of managing waste from new build reactors will be borne by the owners of these power stations. Some uncertainty remains as to whether financial contributions from operators to pay for the use of a future deep geological facility have been set by Government at an adequate level, as the costs of a facility will remain very uncertain at least until a site is selected.

Implementing a solution

The UK's first process to select a site for and implement a deep geological facility was launched in 1982, but ended in failure in 1997 when the body appointed by Government to find a solution unsuccessfully applied for planning approval to conduct further investigation of the geology of a site near Sellafield. In response to this failure, the Government set up an independent committee, the Committee on Radioactive Waste Management (CoRWM) to consider radioactive waste management options and recommend a strategy. The Government accepted its recommendation in 2006 that waste should be placed in a deep geological repository, and that political consent for a chosen site should be achieved by inviting partnership and voluntarism on the part of local communities[250].

The Committee proposed a six stage process, with communities allowed the right to withdraw between stages one to five. Expressions of interest were received from two district councils in West Cumbria, and a vote was held in January 2013 by the District Councils and the relevant County Council, on whether to make a formal 'decision to participate' in the next stage. Both district councils voted in favour, but the County Council voted against, effectively ending the process[251]. The Government issued a new consultation to amend the process at the end of

---

[246] NDA (2010) Radioactive Wastes in the UK: The 2010 Estimate of Radioactive Waste for Geological Disposal
[247] Birmingham Policy Commission (2012) The Future of Nuclear Energy in the UK
[248] National Audit Office (2012) The Nuclear Energy Landscape in Great Britain
[249] DECC (2011) The Government Response to the Consultation on revised Funded Decommissioning Programme: Guidance for New Nuclear Power Stations
[250] Mackerron, G (2012) Evaluation Of Nuclear Decommissioning And Waste Management
[251] DECC (2013) Consultation: Review of the Siting Process for a Geological Disposal Facility

2013, highlighting that the two District Councils remain interested in continuing their participation in the process[252]. Figure 16 sets out the anticipated timeline for construction and operation once a site is identified.

Figure 16: Anticipated timeline for constructing and operating a geological disposal facility

Start date unknown	Construction of storage for intermediate level waste (15 years) and high level waste (90 years).
2040	First emplacement of legacy intermediate level waste
2075	First emplacement of legacy high level waste and spent fuels
2130	First emplacement of spent fuel from existing new build power stations
2175	Commence closure

Source: NDA (2011) Review Of Options For Accelerating Implementation Of The Geological Disposal Programme & NDA (2010) Geological Disposal: Steps Towards Implementation

Further nuclear deployment beyond the new build programme using an open fuel cycle would require additional space in this facility. It has been estimated that a 30 gigawatt programme could increase the size of the facility by a third[253]. The commercialisation of fast reactors and the development of a more closed fuel cycle would open up options to eliminate some of the longer lived elements of high level waste, making it easier to handle for final disposal and reducing the spent fuel volumes requiring long term storage.

FINDING 23

The UK has amassed a large stock of long-lived nuclear waste from 60 years of nuclear weapons development and power generation at 39 reactors. Although the Government has developed a long term strategy for managing this waste, efforts to identify a site for a Geological Disposal Facility have failed to date. Having stalled, the Government must revisit the process for resolving a crucially important challenge.

5.5 Nuclear proliferation

Historic links between civilian nuclear technology and its military uses, and a perceived culture of secrecy, have animated public concerns regarding nuclear power[254]. Technologies to enrich uranium for nuclear reactors can also enrich uranium to higher levels suitable for nuclear weapons use. Fission reactors are the only known way to produce the plutonium used in weapons; spent (uranium) nuclear fuel also contains plutonium which can be separated via reprocessing. Proliferation risks are a function of both the technical nature of the nuclear fuel cycle in use, and decisions relating to the use and production of nuclear weapons.

Although the first nuclear power stations in the UK were designed to produce material for nuclear warheads, there has been a subsequent separation of nuclear weapons programmes and civil nuclear power, both in the UK and abroad[255]. The UK is a signatory of the Nuclear Non-Proliferation Treaty, which requires that countries work towards nuclear disarmament, stop the spread of nuclear weapons and ultimately eliminate them. The UK introduced a voluntary moratorium on the production of fissile material for nuclear weapons or other nuclear explosive devices in 1995, and has not produced fissile material for nuclear weapons

---

[252] DECC (2013) Review of the Siting Process for a Geological Disposal Facility
[253] Tyndall Centre (2013) A Review of Research Relevant to New Build Nuclear Power Plants in the UK
[254] HoC (2012) Science & Technology Committee: Devil's bargain? Energy risks and the public
[255] Royal Society (2011) Fuel cycle stewardship in a nuclear renaissance

or other nuclear explosive devices since then[256]. It is not current policy, however, to eliminate the UK's nuclear weapons deterrent, although Government has committed to reduce the overall size of the nuclear weapons stockpile by 2020[257]. The reactor designs planned for the UK and the proposed approach towards spent fuel suggest a low proliferation risk. Light Water Reactor designs are not well suited to high plutonium yields and the change from reprocessing spent fuel to direct geological disposal would put beyond reach material that can directly be used for weapons manufacture[258].

A significant proliferation risk from the UK's existing civilian nuclear programme is the large stockpile of separated plutonium currently being stored at Sellafield. Although the plutonium is in a form considered less suitable for use in stockpiled nuclear weapons, continued long term storage poses risks to containment materials, requires controlled access and poses potential risks in the event of an accident or attack on storage facilities[259]. The Government is currently exploring options to reduce the proliferation risks from stored plutonium, which are outlined in Chapter 2 and discussed further in Chapter 1.

In the future, the nuclear fuel cycle could be managed to reduce proliferation risks. This involves reducing or eliminating the production of elements within nuclear fuel that are suitable for weapons manufacture. Alternatives fuel cycles, such as thorium-based fuel cycles, have been advocated because the thorium fuel cycles produce less plutonium in spent fuel. An open thorium fuel cycle would however require small amounts of plutonium or uranium to initiate reactor fission. Nuclear reactors developed for civilian purposes are not likely to be the most cost effective routes for states wishing to develop nuclear weapons, although in the past, states have veiled their efforts to obtain nuclear weapons as civilian programmes[260]. Political will is likely to be just as important as developments discussed above in reducing the spread and number of nuclear warheads around the world.

FINDING 24

New reactor and fuel cycle technologies could substantially increase fuel efficiency, reducing both mining requirements and the longevity of long-lived waste. New technologies could also reduce proliferation risks.

FINDING 25

The environmental impacts of nuclear power are comparable to some generation technologies and favourable to others, although the long lived nature of some radioactive nuclear waste and the dual use potential of nuclear technology for civil and military applications create unique but manageable challenges for social and economic sustainability.

---

[256] HMG (2010) UK Statement to the 2010 Non-Proliferation Treaty Review Conference
[257] HMG (2013) Working towards nuclear disarmament (Accessed February 2014)
[258] Tyndall Centre (2013) A Review of Research Relevant to New Build Nuclear Power Plants in the UK
[259] Royal Society (2011) Fuel cycle stewardship in a nuclear renaissance
[260] The Breakthrough Institute (2013) How to Make Nuclear Cheap

METHODOLOGY AND STEERING GROUP

Carbon Connect carried out this inquiry between September 2013 and March 2014. Evidence was gathered by a conference held in Westminster on 11 November 2013, interviews with those working in and around the sector, written submissions, desk-based research and input from our steering group of industry and academic experts. The views in this report are those of Carbon Connect. Whilst they were informed by the steering group and listed contributors, they do not necessarily reflect the opinions of individuals, organisations, steering group members or Carbon Connect members. All mistakes are those of the authors, not the Chairs, Steering Group or contributors.

Chairs

Charles Hendry MP

Baroness Worthington

Steering Group

Adrian Bull	National Nuclear Laboratory
George Day	Energy Technologies Institute
Peter Hardy	Institution of Gas Engineers & Managers
Phil Kirby	Policy Connect Board
Danielle Lane	Dong Energy
Dr Keith MacLean	SSE
Mike Rolls	Siemens Energy
Prof Jim Skea	Committee on Climate Change
Alistair Smith	Costain
Nee Joo Teh	Energy Supply & Generation KTN
Prof Jim Watson	UK Energy Research Centre

CONTRIBUTORS

Guy Anderson	Independent Consultant, Anderson Nuclear Consulting
Prof Adisa Azapagic	Professor, University of Manchester
Terry Ballard	Policy and Public Affairs, RWE Npower
Louis Blake	Senior Media Manager, EDF
Charles Bray	Regional Manager, National Skills Academy for Nuclear
Adrian Bull	Director of External Relations, National Nuclear Laboratory
Jo Coleman	Deputy Strategy Director, Energy Technologies Institute
George Day	Strategy Manager for Economics, Energy Technologies Institute
Alastair Evans	Communications Officer, Nuclear Industry Association
Dr Tim Fox	Head, Environment & Energy, Institution of Mechanical Engineers
Prof Martin Freer	Professor of Nuclear Physics, University of Birmingham
Ian Graves	Power Sector Director, Costain
Grant Harris	Economics & Policy Manager, RES Advisory
Phil Heptonstall	Research Associate, Imperial College London
Dr Christopher Jones	Research Assistant, Tyndall Centre for Climate Change Research, University of Manchester
Nigel Knee	Head of External Affairs, EDF
Phil Lawton	Future System Operation Manager, National Grid
David Martin	Deputy Director of Research, The Weinberg Foundation
Antony Morris	Director, Marketing & Business Developer, Candu
Dr Naser Odeh	Principle Consultant, Ricardo AEA
David Powell	Vice President, GE Hitachi Nuclear Power Plants
Alistair Smith	Nuclear Development Director, Costain
Laurence Stamford	Research Associate, University of Manchester
Paul Willson	Deputy Director of Innovation, Parsons Brinkerhoff

ABOUT CARBON CONNECT

Carbon Connect is the independent forum that facilitates discussion and debate between business, government and parliament to bring about a low carbon transformation underpinned by sustainable energy.

In addition to around 40 member organisations, Carbon Connect works with a wide range of parliamentarians, academics, civil servants and business leaders who give their time and expertise to support our work. For our member organisations we provide a varied programme of parliamentary events and policy research. As well as benefitting from our own independent analysis, members engage in a lively dialogue with government, parliament and other leading businesses. Together, we discuss and debate the opportunities and challenges presented by a low carbon transformation underpinned by sustainable energy.

With special thanks to Laura Wilton, Laura Owen, Geoff Archer, Claudia Jaksch, Peter Barrett and Natasha Adade.

Cover designed by Richard P Chapman Design Associates

For further information, please contact
Andrew Robertson (Manager, Carbon Connect)
Fabrice Leveque (Senior Researcher, Carbon Connect)
Laura Wilton (Head of Sustainability, Policy Connect)

Carbon Connect
Policy Connect
CAN Mezzanine
32-36 Loman Street
London SE1 0EH

020 7202 8571
carbonconnect@policyconnect.org.uk

www.policyconnect.org.uk/cc
www.policyconnect.org.uk

Printed on recycled paper

Future Electricity Series Sponsor

IGEM
Institution of
Gas Engineers & Managers

Power from Nuclear Sponsor

COSTAIN

A Policy Connect Activity

policy connect