TRANSITIONS PATHWAYS AND RISK ANALYSIS FOR CLIMATE CHANGE MITIGATION AND ADAPTATION STRATEGIES

D3.2 Context of 15 case studies:

UK: Nuclear Power

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1 CASE STUDY: NUCLEAR POWER IN THE UNITED KINGDOM

The Queen opens Calder Hall, the world's first nuclear power station in 1956 Source: Sellafield Ltd

1.1 Introduction

The UK Nuclear Power case study will analyse the policy option of investing in nuclear power as a significant part of the UK's electricity mix. Within recent years, the UK government has promoted nuclear energy as a chosen technology to decarbonise the energy system and to secure and diversify the electricity supply at what was expected to be an affordable cost. The government plans to incentivise the building of up to 16 Gigawatts (GW) of new nuclear generation capacity, at 8 sites, most of which are the sites of existing reactors. The first of these is a controversial 3.2GW project at Hinkley Point, to be funded by state-owned French and Chinese firms. The UK Government sees this project as playing a critical role in replacing retiring nuclear power and coal power plants. This case study will explore the main debates associated with nuclear energy in the UK and issues relevant to the controversial nature of nuclear technology including public acceptance, political interests, the investment environment, and environmental impacts.

The aim of this deliverable is to set up the research questions and to provide the context in which nuclear power has been seen as one of the options to decarbonise the UK energy system. This report introduces the overarching research question: "What low-carbon electricity generation options are available to reduce CO_2 emissions while considering UK's economic, political, social and environmental priorities?" in section 2.1. Section 2.2 introduces the UK energy context. It provides an overview of the policy that oversees the UK energy system, and discusses the economic, environmental, social priorities in which UK nuclear power is embedded addressing the conflicts and synergies of these priorities addressing climate change. Section 2.3 then focuses on nuclear power. It provides a historical development of the sector, which has its roots in the post war period. It provides the current 'cradle-to-grave' value chain from sourcing uranium, to building and operating new and existing power plants, through to decommissioning and nuclear waste handling. This section also includes the enabling environment and policies governing for the value chain including the role played by the institutions. Section 2.4 introduces the system of innovation of the nuclear power using a System Map tool developed by NTUA, as a visual aid to show the complexity of the nuclear system. Section 2.5 then introduces the stakeholders list, who has been and/or will be consulted further either through individual interviews or through workshops to engage them in the discussions to support the analysis of the UK nuclear sector. Finally, section 2.6 summarises the case study.

1.1.1 Research questions

This project seeks to answer the overarching research question: "What low-carbon electricity generation options are available to reduce CO_2 emissions while considering UK's economic, political, social and environmental priorities?"

For the UK case study, we have defined four major research questions, shown below. Nested within each research question are a number of sub-questions to guide the inquiry, which are shown in Appendix A.

1. What feasible nuclear power technological options are available in the UK (considering the above mention priorities) within the current decade and in the longer term?
2. What are the social-economic and environmental costs/benefits and risks/uncertainties to supporting the development of new nuclear power electricity generation? (within the timeframe of 10 years and 20 + years' time)
3. To what extent does policy support in nuclear power divert resources (e.g. financial, human resources and capabilities) from the deployment of other low-carbon electricity generation technologies?
4. Are there other motivations beyond climate change to further develop nuclear power?

1.2 Introduction to the case study: UK energy context

This section introduces the essential background context for this case study. The focus is not on nuclear power as of yet (which will be introduced in more detail from section 2.3 onwards), but rather on the overarching political, social, economic and physical landscape in which this case study is situated. Firstly, the section introduces the relevant policy environment in the UK, with an overview of the major energy and climate policies and their evolution. Secondly, the section will outline the physical context, by detailing the UK's natural resource endowment, energy and electricity mix, carbon emissions, and risks of natural events such as extreme weather. The third sub-section outlines the economic context, for example, the UK's Gross Domestic Product (GDP) and the government's economic priorities. The fourth sub-section outlines the social context, for example population and welfare priorities. Finally, the fifth and sixth sub-sections examine the UK's energy policy priorities, and identifies whether there are any major conflicts and synergies between stated energy policy goals.

1.2.1 Policy overview

The UK's energy system is in a major period of transition (Geels et al., 2016), driven by three main factors: the age of electricity generation and network infrastructure, declining indigenous fossil fuel resources, and the imperative to cut carbon emissions.

1.2.1.1 Energy policies

The UK was one of the first countries in the world to privatise its electricity system. The Electricity Act (HM Government, 1989) laid the foundations for a total restructuring of the UK electricity industry, in which the state-owned generation and transmission company was split up and privatised, although some vertical integration remained (HM Government, 1989, Simmonds, 2002). There are now 30 significant power generators, although the market is dominated by the 'Big 6' energy utilities who together supply around 90% of domestic electricity and gas consumers (Ofgem, 2015). The energy systems are highly centralised: heating is mainly provided through a national gas grid, and large generation assets connected to a high-voltage transmission system produce the bulk of electricity. The National Transmission System Operator (National Grid) is a private regulated monopoly, and plays a fundamental role in electricity system management.

The UK energy system is currently in need of significant investment in generation and network infrastructure. The electricity supply infrastructure is ageing and will require a significant proportion of electricity supply capacity to be replaced by the mid-2020s; the retirement of older fossil fuel power plant capacity has led to an erosion of capacity margins in the power sector (Ofgem, 2012, Royal Academy of Engineering, 2013). There are also large parts of the electricity and gas transmission and distribution networks, which are in need of replacing or upgrading (Department of Energy and Climate Change, 2015b, Dodds and McDowall, 2013, Electricity Networks Strategy Group, 2012, Strbac et al., 2014). However, the combination of a highly centralised system and a highly liberalised market has led to some challenges in financing new projects, in particular large capital-intensive generation assets such as nuclear. For example, prior to electricity system privatisation, the UK planned four new Pressurised Water Reactor (PWR) stations, the first of which was built in 1995 at Sizewell B; however, the higher discount rates which resulted from privatisation meant that the next three PWRs were uneconomical and were never built (Parliamentary Office of Science and Technology, 2003). In recent years, it has become clear that existing market arrangements would not deliver energy infrastructure investment at the scale and pace required (Department of Energy and Climate Change, 2011b), and that the government would need to play a significant strategic role (HM Government, 2009). In order to address these issues, the UK proposed a major shift in energy policy by setting up the Electricity Market Reform (EMR) program. This contained four major new policy instruments (Department of Energy and Climate Change, 2012, Pollitt and Brophy Haney, 2013): a Contract-for-Difference (CfD) subsidy for low-carbon generation,[1] a Capacity Mechanism for dispatchable capacity (Department of Energy and Climate Change, 2013b), a carbon price floor, and an Emissions Performance Standard.

Another major shift in UK energy policy stems from the transition from being a net fuel exporter to a net importer. The UK has been a net importer of natural gas since 2004 and of oil since 2013 due to declining production from the UK Continental Shelf, and of coal since the mid-1980s (Energy Information Administration, 2014). Unlike some other parts of Europe, fuel imports to the UK are diverse and are from a relatively stable set of countries (for example, most of the UK's gas comes from Norway and the Netherlands). However, the relative novelty of net importer status has led

[1] "A Feed-in Tariff with Contract for Difference (FiT CfD) is a long-term contract between an electricity generator and a contract counterparty. The contract enables the generator to stabilise its revenues at a pre-agreed level (the strike price) for the duration of the contract. Under the FiT CfD, payments can flow from the contract counterparty to the generator, and vice versa." (Department of Energy and Climate Change, 2011, 38)

to some policy concerns over the external security of UK energy supply, which were compounded by rising oil and natural gas prices from around 2004 until 2014.[2]

The UK is currently part of the European Union (for at least the next two years), and is therefore subject to EU energy policies and legislation. EU energy policy is also in a period of transition for similar reasons to the UK: ageing infrastructure, climate change, and concerns about dependence on energy imports (Eastern Europe in particular is highly dependent on Russia for a significant proportion of their primary fuel demand). In 2009, the European Commission introduced the EU's 'Third Energy Package', which aims to liberalise and integrate the electricity and gas markets of the 28 European Member States (Dutton, 2015). Progress is somewhat patchy, with some tension between the goal of European Energy Union and the rights of Member States to retain sovereignty over their individual energy policies (Siddi, 2016). The EU has set an interconnection target of 10% by 2020.[3] The UK is supportive of increased interconnection with Continental Europe, and is currently planning new interconnectors with France and Norway, but is constrained due to its geographical location because high-voltage undersea cables are considerably more expensive. This could mean that the UK faces greater challenges than mainland Europe in securely integrating low-carbon generation such as intermittent renewables, because it may not be able to exchange as much electricity with its neighbours.

Nevertheless, there is currently high uncertainty surrounding the future of the UK's relationship with the EU, following the referendum decision to leave the EU on June 23 2016. It is unlikely that any major policy changes will be enacted in the near future – at the time of writing, the UK had not yet invoked Article 50 of the European Union Treaty,[4] meaning that the UK will likely remain a member of the EU for at least the next two years. There is currently very little reliable information (and much second-guessing) regarding the likely impact of the exit from the EU ('Brexit') on UK energy and environment policies in the future. However, there has already been a marked impact on the UK economy (discussed in more detail in section 2.2.3), and it is likely that investment in energy infrastructure will be negatively impacted by the uncertainty created by Brexit and the political turmoil which has followed (Energy and Climate Change Committee, 2016, Froggat et al., 2016, Mayer Brown, 2016). The potential impacts of this on energy

[2] These price increases have not been constant and have shown much volatility. Gas and oil prices generally dropped in 2008 as the result of the financial crash, but increased sharply again until the next oil price crash in 2014.

[3] In other words, by 2020 each Member State should have in place electricity cables that allow at least 10% of their electricity generation capacity to be transported across its borders to its neighbouring countries.

[4] Article 50 of the Treaty on European Union allows a member state to notify the EU of its withdrawal and obliges the EU to try to negotiate a 'withdrawal agreement' with that state. Once a state has chosen to invoke article 50, it has two years in which to negotiate a withdrawal agreement. During the two-year negotiation period, EU laws would still apply to the UK. The UK would continue to participate in other EU business as normal, but it would not participate in internal EU discussions or decisions on its own withdrawal (Ruparel 2015)

infrastructure and security are discussed in more detail in section 2.2.6. It is worth briefly mentioning the fact that the UK has been a key voice in Europe pushing for energy market integration, and concerns have been raised that if – as seems likely – the UK will no longer sit at the negotiating table, this could shift the balance within Europe toward greater State intervention, which could impact the implementation of the Third Energy Package (Froggat et al., 2016).

1.2.1.2 Environmental policies

The 1997 Kyoto Protocol set for the first time legally-binding emissions reduction targets, or caps, for 37 industrialised countries. This led to policy instruments designed to meet these targets. In March 2000, the European Commission presented a green paper with some ideas on the design of the EU Emissions Trading System, EU ETS; which constituted basis for numerous stakeholder discussions that further helped shape the system, and the cap on allowances was initially set at national level through National Allocation Plans (NAPs). The EU ETS was adopted in 2003 and the system was launched in 2005 (European Commission, 2016a).

In 2008, the UK established the world's first legally-binding commitment to climate change target stretching to 2050. The Climate Change Act (HM Government, 2008) mandates an 80% reduction in UK Greenhouse Gas (GHG) emissions on 1990 levels by 2050. Nested within this long-term target are shorter-term 'carbon budgets', which are recommended by the UK Climate Change Committee (UK CCC), an independent body set up to oversee the delivery of the Climate Change Act. The UK is currently on track to meet the third carbon budget (35% reduction by 2020), but may be falling behind on the fourth carbon budget (50% reduction by 2025), as shown in Figure 1. Nevertheless, the government has recently opted to adopt the recommendation for the fifth carbon budget, and has committed to a 57% reduction on 1990 GHG levels by 2032 (Committee on Climate Change 2015). The Department for Energy and Climate Change was disbanded in July 2016, but there has as of yet been no indication that this will affect the UK's carbon targets (Watson, 2016).

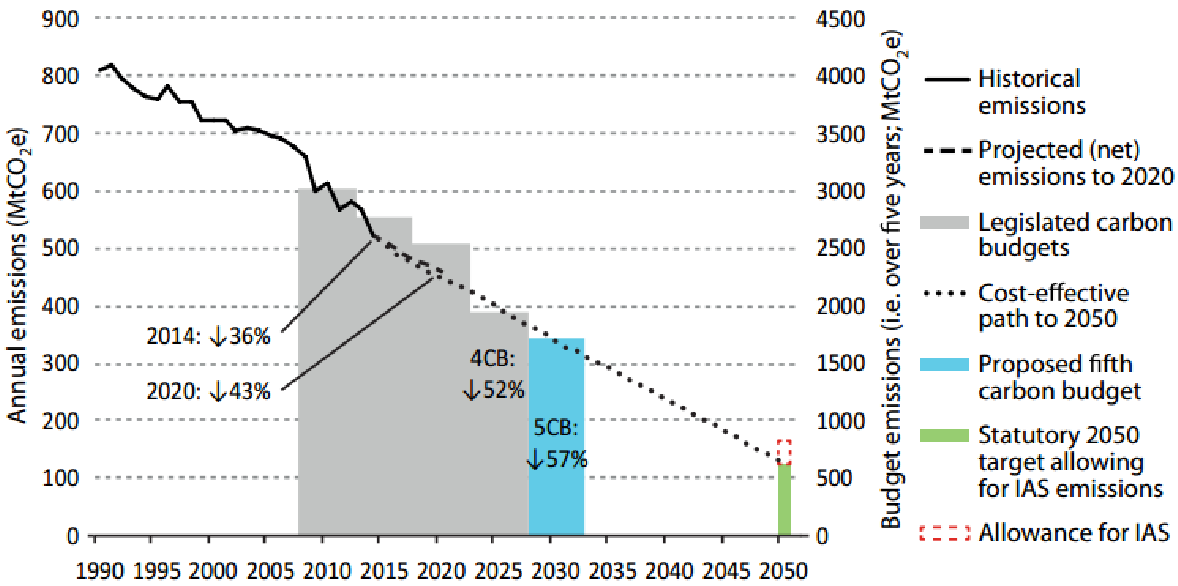

Figure 1: UK historical and projected emissions and the fourth and fifth carbon budgets

Source: Committee on Climate Change (2015)

The UK is also subject to EU environmental policy and legislation. In 2009, the EU legislated a '20-20-20' target: a 20% cut in GHGs, 20% of EU energy from renewables (RES), and a 20% improvement in energy efficiency, all by 2020. Different EU member states agreed differentiated responsibility within this overarching target; the UK was at that time a laggard on RES, therefore agreed to a 15% RES target by 2020. The European Commission has raised concerns that the UK may not be on track to meet this target (EEA Report, 2015, European Commission, 2015).

One of the core policies for achieving the EU's GHG targets is the European Emission Trading Scheme (EU ETS). The ETS is a cap-and-trade mechanism, which operates in 31 European countries and covers around 45% of the EU's emissions (European Commission, 2016b). Set up in 2005, it was the world's first and biggest international emissions trading system. However, the ETS has been subject to problematically low carbon prices, caused by the over-allocation of permits prior to the drop in emissions which resulted from the global financial crash (Laing et al., 2013). The ETS allowance price (EUA) dropped steadily from an initial peak of nearly €35/EUA to around €5/EUA throughout 2013 (Oxera, 2013). The low prices caused the UK to attenuate its own plans for a Carbon Price Floor, which was originally set to increase from £15.70/tonne CO_2 in 2016 to £32/tonne in 2020 and £76/tonne in 2030 (Department of Energy and Climate Change, 2012), but which has since been reformed to be capped at £18/tonne until at least 2020 (HM Revenue & Customs, 2014).

More recently, the EU has agreed to a 2030 target of a 40% cut in GHGs, 27% of EU energy from RES, and a 27% improvement in energy efficiency (European Commission, 2016b). The 40% emissions target is part of the EU's combined INDC ('Intended Nationally Determined Contribution') which was submitted to the UNFCCC Secretariat as part of the Paris Agreement. As of October 2016, 86 signatories have ratified the Agreement (out of 191), which means that the Agreement entered into force on 4 November 2016. The EU ratified the Agreement on the 5th of October 2016, thus enabling its entry into force on 4th November 2016 (European Commission, 2016a). The EU ratification was a particularly complex process, because all member states (including the UK) must ratify individually as well as the bloc itself.[5]

Finally, it is worth mentioning the EU's air pollution policies have had a significant impact on the UK energy sector. The EU Industrial Emissions Directive and its predecessor the Large Combustion Plant Directive (LCPD) have already had an impact on coal generating capacity in the UK, with numerous old coal plants choosing to close instead of complying with the air pollution limits (Parsons Brinckerhoff, 2011). There is also an EU Medium Combustion Plant Directive in process, due to come into force from 2020 onwards (European Commission, 2013); this illustrates that the suite of air pollution controls may get more stringent in the future as legislators attempt to minimise the serious health impacts of airborne pollution.

1.2.2 Natural resources and environmental priorities

1.2.2.1 Primary energy: resources and consumption

In the mid-1960s, the UK began extracting oil and gas from the UK Continental Shelf, a resource base which has provided the main basis for UK energy production ever since. The UK has historically had a strong domestic coal industry, and coal was the main source of UK-produced energy until the 1960s. However, coal production (which had been falling gradually since its peak of 292 Million tonnes in 1913 to 9 Million tonnes in 2015) (Department for Business Energy & Industrial Strategy, 2015) was impacted by the increasing penetration of oil and gas into the UK energy mix. In the 1980s, political struggle between the National Union of Mineworkers and the Thatcher administration eventually led to numerous pit closures and the effective collapse of the

[5] It should be noted that there is currently some uncertainty over the future role of the EU's climate targets in the UK due to the decision to leave the EU; however, at the time of writing there was no indication that this could jeopardise the Paris Agreement.

industry; the UK has been a net coal importer since 1984 (Figure 2), and the last deep coal mine closed in December 2015.

In the 1990s, electricity production shifted significantly towards gas, driven by the privatisation of the electricity industry, changes in electricity regulation, and decreasing wholesale gas prices. Much of this gas was produced indigenously from the UK Continental Shelf, and the UK became, for a fairly short time, a significant gas exporter (Figure 2). However, production from the North Sea has been decreasing rapidly, and the UK has been a net importer of natural gas since 2004 (mostly consisting of piped gas from mainland Europe and liquefied natural gas (LNG) from Qatar). The recent oil price crash has led to a crisis of profitability for many North Sea operators; the UK government has stated its commitment to supporting the indigenous fossil industries, and offered tax cuts in the last Budget (HM Treasury, 2016, Rudd, 2015), but tax cuts are only a benefit if the company is making a profit in the first place. A combination of low oil and gas prices, cheap imports and high costs of a depleting resource mean that the future of the UK oil and gas industry is uncertain. The UK government is keen to exploit the UK's potentially significant shale gas and shale oil resources, although there are considerable uncertainties as to how much of this resource will be economically recoverable, and numerous barriers exist to exploiting onshore shale on any kind of scale in the UK (Stevens, 2010).

Long-term estimates of UK renewable resource potential are shown in Table 1. The UK has significant renewable resource potential, with some of the most abundant wind and tidal resource in Europe, as well as potentially significant solar, wave and possibly biomass resources (Johnstone and Stirling, 2015). However, unlike many other European countries, the UK is not particularly well endowed for hydropower, and is almost fully exploited for both large-scale hydro and pumped storage (Pascall, 2016), meaning a relative lack of flexible renewable electricity. The UK has no indigenous uranium production, and very limited geothermal resource.

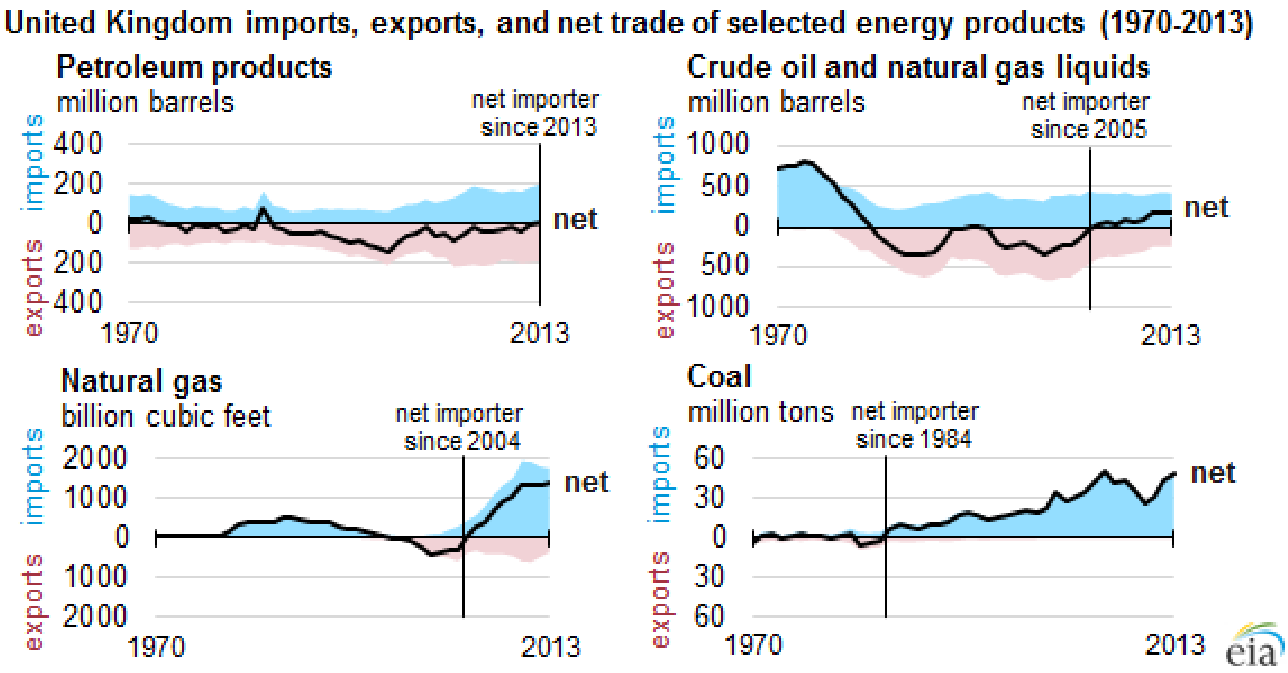

Figure 2: UK imports and exports of major fuels

Source: Energy Information Administration (2014)

Table 1: Approximate UK renewable resource potential

Renewable resource	Resource potential Terawatt hours/year (TWh/y)	Notes
Onshore wind	80	This figure reflects generally-accepted limitations due to public acceptability issues
Offshore wind	400	
Solar	140	
Wave	40	Reflects practical potential; progress on marine energy is slow
Tidal	58-240	Reflects practical potential; progress on marine energy is slow. Tidal stream resource is highly uncertain
Hydro	6	Figure represents current generation; expansion of hydro limited by lack of suitable sites
Bioenergy	?	No data available, because bioenergy resource estimates are highly uncertain due to competition with other sectors for the resource

Source: Committee on Climate Change (2011)

UK primary energy consumption has been decreasing since the early 2000s, mainly driven by a gradual shift of heavy industry to emerging economies and the global financial crash in 2008. However, efficiency improvements and behavioural changes have also contributed to demand reduction. UK energy consumption has been heavily influenced by its indigenous resources, with solid fuel (mostly coal) consumption being replaced by natural gas. Electricity consumption has increased as a proportion of total energy consumption, and is projected to continue increasing especially if the UK pursues electrification of heating and transport in order to cut carbon emissions (Barauh et al., 2014). However, as shown in Table 2, natural gas and oil still make up the bulk of primary energy supply, mainly driven by transport, heating and industrial demand, which are much more challenging to shift away from fossil fuels. Therefore, the main challenge is how to make those sectors change to use cleaner technologies. This change would require a major transformation in the UK energy supply system.

Table 2: Total UK primary energy supply in Q1 2016, in thousand tonnes of oil equivalent

Energy commodities	Indigenous production	Imports	Total primary supply	Total primary supply (%)
Natural gas	10,469	13,698	24,979	42.80%
Primary oil	13,785	13,002	15,694	26.90%
Electricity	5,101	545	5,617	9.60%
Coal and coal products	614	1,772	4,707	8.10%
Bioenergy and waste	3,293	981	4,199	7.20%
Petroleum products	0	9,715	2,943	5.00%
Manufactured fuels	0	204	199	0.30%
Total	**33,262**	**39,917**	**58,338**	**100**

Source: Department of Energy and Climate Change (2016a)

2.2.2.2 Electricity

As this case study focuses on nuclear power, the remainder of this section will focus on electricity. The majority of UK electricity is produced by burning gas and coal, with smaller but significant proportions from low-carbon nuclear and renewables. Table 3 shows the proportions of electricity supplied by each generation type in 2016, in TWh and %.

Table 3: Electricity supplied in the UK in 2016 Quarter, Q1, in Terawatt hours, TWh and %

Energy commodity	TWh	%
Gas	34.40	36.8%
Nuclear	15.75	16.9%
Coal	13.89	14.9%
Wind and solar	12.91	13.9%
- of which offshore	*5.14*	*5.5%*
Bioenergy	7.19	7.7%
Net imports	6.00	6.4%
Hydro	2.03	2.2%
Other fuels	1.07	1.1%
Oil	0.40	0.4%
Pumped storage (net	-0.27	-0.3%
Total	**93.37**	**100%**

Source: Department of Energy and Climate Change (2016a)

Table 4 (below) shows the evolution of the UK's installed electricity capacity from 1996 to 2014 (the most recent year for which these figures are available). In recent years, the gas-fired proportion of the electricity mix has fallen significantly, whilst the coal-fired proportion rose to its highest level since 1996 in 2012 and then dropped again as electricity consumption continued to fall and as coal-fired power stations closed or converted to biomass (Department of Energy and Climate Change, 2015c). The amount of electricity generated from wind and solar has grown enormously in the past few years, from 10.3 Terawatt-Hours (TWh) in 2010 to 36.1 TWh in 2014. Installed generation capacity has grown steadily over the past 20 years, from 82.1 Gigawatts (GW) in 2005 to 96.8GW in 2014; this reflects a decline in conventional thermal generation in favour of an increase in intermittent renewables (DECC 2015b).

Table 4: Installed electricity generation capacity GW

Generation capacity	1996	2000	2005	2010	2012	2013	2014	2014 (%)
Combined Cycle Gas	12.7	21.1	25.9	34.0	35.4	35.1	33.8	34.9%
Conventional steam[1]	43.0	39.7	37.1	37.1	32.6	26.2	25.7	26.5%
Renewable	2.3	4.5	4.5	9.2	15.5	19.8	24.6	25.4%
Nuclear	12.9	12.5	11.9	10.9	9.9	9.9	9.9	10.2%
Pumped storage	2.8	2.8	2.8	2.7	2.7	2.7	2.7	2.8%
Total	**73.6**	**79.0**	**82.1**	**94.0**	**96.2**	**93.8**	**96.8**	**100%**

[1] Mainly coal, includes gas turbines, oil engines mixed/dual fired and co-firing

Source: Department of Energy and Climate Change (2015c)

Finally, table 5 shows electricity consumption by sector in the first quarter of 2016; it shows that the largest proportion of electricity is consumed domestically (for instance, in lighting, electronics and electric heating in homes), with industry also accounting for a large proportion of electricity consumption.

Table 5: Final electricity use by sector in GW, 2016 Q1

Final use of electricity by sector	GWh	%
Domestic	31,191	37.6%
Other final users	25,737	31.0%
Other industries	24,076	29.0%
Transport	1,119	1.3%
Iron and steel	868	1.0%
Total consumption	**82,991**	**100%**

Source: Department of Energy and Climate Change (2016a)

1.2.2.2 Carbon emissions

It is clear that the main sources of emission of CO_2 for electricity generation come from fossil fuels (see Tables 3 and 4). UK carbon emissions amounted 435 million metric tonnes of CO_2 in 2014. They were 6.7 tonnes CO_2 per capita in the same year. This is roughly the same as the EU average, and compares with 17 tonnes in the US, 9.8 in Germany, 7.1 in China and 2.0 in India (Global Carbon Atlas, 2015). It is also interesting to note that the UK has the highest historical emissions in the world, partly due to the coal-driven industrial revolution in the early 1800s (Matthews et al., 2014). Table 6 shows UK carbon emissions by sector; energy supply (including electricity and heat) comprises nearly a third of UK carbon emissions, of which the vast majority is from burning gas and coal. Transport is also a major contributor to UK GHG emissions; most of this is from oil products, as only a small proportion of the UK vehicle fleet is electric (as shown previously in table 5).

UK carbon emissions have been decreasing steadily, although much of this decrease has been due to a shift of industrial processes and manufacturing overseas. Like other countries, the UK measures its carbon emissions on a production basis; however, this may be somewhat misleading as carbon emissions are a global issue and consumption-based emissions may be much higher (Barrett et al., 2013). Projections of future carbon emissions are shown in Figure 1 (section 2.2.1.2).

Table 6: UK carbon emissions by sector, year to Q1 2016

CO_2-emissions per sector	In million ton of CO_2-equivalent	In %
Energy supply	127.0	32.5%
Transport	120.5	30.9%
Business	65.6	16.8%
Residential	62.3	16.0%
Public sector	8.1	2.1%
Other	7.0	1.8%
Total	**390.5**	**100%**

Source: Department of Energy and Climate Change (2016b)

1.2.2.3 Natural and extreme events

Compared to many countries around the world, the UK experiences relatively low risk of disruption caused by natural events. The UK is in a temperate zone and does not experience tropical storms or severe heatwaves – the highest temperature ever recorded was 38.5°C, and air conditioning is not common in private residences, although it is becoming more prevalent in public buildings. The UK experiences relatively little water stress, although droughts do occur occasionally in summer; however, these are mild compared even with France. The UK also does not experience severe freezing or deep snow in winter, although demand for space heating is high in the winter (partly because of poorly insulated buildings). This creates strong seasonal energy demand patterns. Because of the fairly northerly latitude, daylight hours are significantly shorter in winter; the long nights and cold temperatures contribute to a noticeable electricity demand peak at around 6pm on winter evenings, as shown in Figure 3.

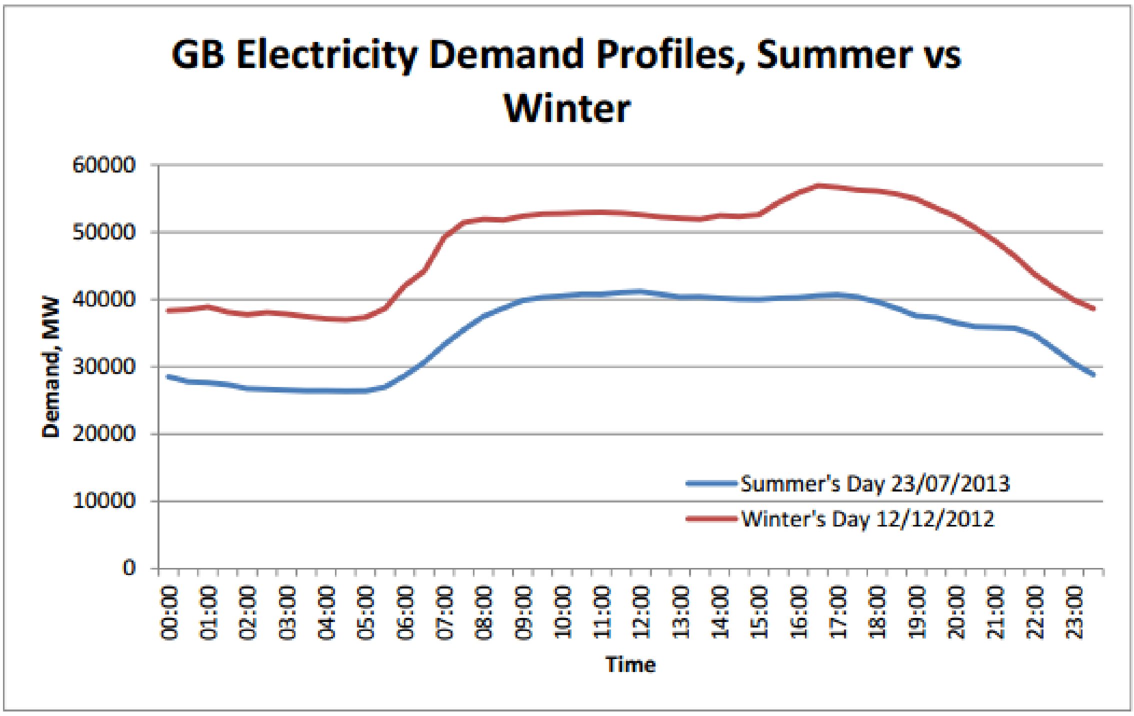

Figure 3: Seasonal variations of Great Britain Electricity demand

Source: (Department of Energy and Climate Change, 2014)

The UK is not prone to large earthquakes: it experiences a magnitude 5 on the Richter scale every 10 to 20 years, and according to the British Geological Survey the largest possible earthquake would be around 6.5 magnitude (British Geological Survey, 2008). The low risk of natural disasters such as earthquakes probably contributed to the fact that the Fukushima nuclear disaster in 2011 had very little impact on public attitudes towards nuclear power in the UK. Although the majority of British public remain of the view that renewable energy is a better way to face climate change than nuclear power, there has been a relative shift in favour of nuclear power (Poortinga et al., 2014).

The areas in which the UK does experience risk from natural events is in rainfall and flooding. For example, storms in December 2013 caused around 750,000 homes across the UK to lose power; around 500 households were without electricity supply for more than five days (Macalister, 2014, Walker et al., 2014). It is also worth noting that the UK is highly subject to coastal erosion. In 2012 the British Geological Survey estimated that across England and Wales 113,000 residential properties, 9000 commercial properties and 5000 hectares of agricultural land are within areas potentially at risk of coastal erosion, with a capital value of assets at risk at around £7.7 billion (British Geological Survey, 2012). This is especially important for coastal power stations; in fact, at one of the existing nuclear power stations in Dungeness, longshore drift is causing the coast to migrate at a significant rate (DEFRA, 2002). Coastal electricity infrastructure could also be at risk of climate change-induced sea-level rise.

1.2.3 Economic priorities

The UK's economy is the fifth largest in the world, at around $2,800 billion in 2015 (Trading Economics, 2016). Recently, the economy has been growing slowly, at a rate of 1.8% in 2015 and 2.0% year-on-year for the first quarter of 2016. The services sector (including finance) comprises around 80% of the UK economy, and is showing economic growth, whereas the industrial sector only accounts for around 15% and is declining (Canocchi, 2016). GDP per capita has increased and is now almost at the same level as before the financial crash in 2008, at around $40,900 per person in 2015 (Trading Economics, 2016). Forecasts for near-term growth are highly uncertain in the wake of the EU referendum result; although the decision had an immediate impact on UK markets and saw the pound drop against the US dollar to its lowest value since 1985. Some credit ratings agencies predicted that the UK economy will shrink by upwards of 1% in 2017 as a result of the decision (Barnato, 2016, Wearden, 2016).

In terms of energy and the economy, probably the most important dynamic is the current program of austerity. The current and previous UK administrations came to power on a platform of reducing public spending and cutting the UK budget deficit, in response to economic concerns since the financial crash in 2008. As part of this agenda, funding for various government departments and for local authorities has been cut significantly. Budget cuts to the Energy Department were met with substantial reductions in funding in several areas. Among them: a) an end to subsidies for onshore wind, b) reductions of up to 63.5% in the feed-in tariff for solar photovoltaics (PV), c) the cancellation of the Green Deal and Zero Carbon Homes demand reduction schemes, and d) the cancellation of a £1 billion competition fund for Carbon Capture and Storage demonstration.[6] Instead, the government announced that the new focus would be on Research and Development (R&D), and announced £500 million in new energy R&D funding. 50% of this is earmarked for research into Small Modular Reactors (SMRs) (HM Government, 2015, World Nuclear News, 2016); which have been argued to have advantage over large nuclear (e.g. delivering Combined Heat and Power, CHP, if adequate infrastructure is already there) (Energy Technologies Institute, 2016).

[6] The Department for Energy and Climate Change had its budget cut by £70 million. The Department (which has now been merged with the Business Department) is relatively constrained in its expenditure, with 74% officially ring-fenced for nuclear decommissioning and international climate finance commitments, and a further 8% unofficially ring-fenced mostly for nuclear waste management (Green Alliance, 2015).

There are significant concerns over how to incentivise infrastructure investment in the wake of such dramatic policy changes; for example, investor confidence dropped significantly in the wake of the cut in Carbon Capture and Storage (CCS) funding (Energy and Climate Change Committee, 2016). Investor confidence has been further impacted by the UK's decision to exit the European Union, and will potentially be impacted by the decision to disband the Department of Energy and Climate Change.

1.2.4 Societal priorities perspective on climate change:

The UK has a population of 64 million, with a fairly high population density of 269 people per square kilometre (compared to 122 in France, 146 in China and 35 in the US). The UK, as a wealthy developed economy, does not experience the same levels of social vulnerability as some other parts of the world: a very high proportion of the population has access to basic food and shelter, and there is a functioning welfare state. The UK provides universal free education from ages 4 to 16, and has high levels of literacy. Income inequality, measured by the Gini coefficient, was slightly above the OECD and EU averages from 1990 to 2012 (Snowden, 2015); however, it has recently increased to 0.404, making the UK the most unequal country in Europe (compared to an EU average of 0.346) (Fernández-Macías and Vacas-Soriano, 2015). Recent budget cuts and changes to welfare and taxation policies may have negatively impacted poorer members of society (Beatty and Fothergill, 2013), and reliance on emergency subsistence charities such as food banks has increased (Trussell Trust, 2016). Interestingly, 60% of the population identify themselves as 'working class' (a figure which has barely changed since the 1980s), even though only 25% of the population are employed in manual or routine jobs (Evans and Mellon, 2016).

In terms of energy access, connection to the mains electricity grid and access to advanced cooking fuels is near 100%. However, fuel poverty (wherein citizens struggle to meet basic fuel requirements from their income) is a concern, driven by a number of factors: the exceptional age and inefficiency of the UK's housing stock; cold winters; income inequality; increases in fuel prices relative to incomes from 2008 onwards; and low levels of connectivity to heating systems in some regions and rural areas. Fuel poverty generally affects poor social groups who tend to live in low-quality housing, especially single parents, the elderly, private rental tenants and some rural populations (Hill, 2012).

In terms of public perceptions of environmental issues, the vast majority of the UK population believe that the climate is changing, although only around 35% believe that this is mainly caused by human activities (Capstick et al., 2015). As of 2015, around 10% believed that climate change is one of the top three most important issues facing the UK today, a comparable proportion to those referring to crime and education (ibid) (although it is worth noting that immigration concerns have surged up the agenda since the start of the Brexit debate). Moreover, surveys have found that around three-quarters of the public support national reductions in energy use and decreased reliance on fossil fuels (Demski et al., 2013, 2015). However, popular backing for specific carbon reduction policies is highly variable and is dependent on numerous project-specific factors (Cohen et al., 2014, Devine-Wright et al., 2009). There is some evidence of an attitude-behaviour gap, in which abstract support for carbon reduction does not translate into support for specific projects or into a change of energy behaviours (Anable et al., 2006, Devine-Wright, 2007). Regard for fairness and social justice are found to be important for public appraisals of energy transitions, alongside concerns for affordability, environmental protection and energy security (Demski et al., 2015).

1.2.5 Politics of energy development priorities

Clearly, political priorities are numerous and varied, and it would be an extremely challenging task (and outside the scope of this section) to attempt to unpick which priorities have an impact on decision-making. However, the past 18 months have been an eventful time for UK energy policy, with numerous major policy changes in a short period helping to highlight some of the political priorities at play. Most notably, in November 2015, the new Energy Minister announced a major 'energy policy reset', in which she made it clear that energy security is now the government's main priority, with affordability and climate change as secondary concerns (Rudd, 2015). The new energy policies outlined in this speech and in the later Budget include:

- Phase-out of unabated coal generation by 2025 (subject to sufficient gas generation being available to replace it)
- End to subsidies for onshore wind and solar
- End to several demand reduction schemes
- Support for onshore unconventional and offshore conventional fossil fuel production
- End to funding for CCS demonstration (HM Treasury, 2016, Rudd, 2015).

The government also strongly reiterated its support for new nuclear power, citing motivations such as climate change, cost and energy security (Rudd, 2015). However, some have pointed out that the conditions for supporting nuclear have become progressively less favourable due to delays and cost overruns, thus suggesting that underlying political or even military motivations may play a significant role in this policy (e.g., Thomas, 2016b, for an overview of the possible military link, Johnstone and Stirling, 2015, Cox et al., 2016).

It is also important to consider the potential impact of the abolition of the Department of Energy and Climate Change in July 2016. The Department was reshuffled into a new 'Department of Business, Energy and Industrial Strategy'. At the time of writing, it was too early to predict the possible impacts that this could have. The UK Energy Research Centre was cautiously optimistic, suggesting that the new department could present an opportunity to integrate industrial and energy strategy in a more coherent manner (Watson, 2016). However, former opposition leader Ed Miliband stated that the decision was "just plain stupid" and pointed out that the new department doesn't actually have the word 'climate' in the title (BBC, 2016b).

Finally, it is interesting to consider political priorities at different spatial scales. The end to onshore renewables subsidies reflects a translation of local antipathy toward onshore wind into national policy. The manifesto of the Conservative administration, which came to power in 2015, pledged to ban new onshore wind farms from 2020; in late 2015, planning laws were changed to give local communities a right to veto new renewable developments. The proposed subsidy cut has since been rejected repeatedly by the House of Lords, and is currently passing back and forth between the Lords and the Commons (Murray, 2016).

On the subject of spatial scales, Scotland (a Devolved Administration) has been pursuing a set of energy policies, which increasingly diverge from that of England and Wales. For example, Scotland has set a target of 100% net renewable energy by 2020, and has an ambitious energy efficiency and microgeneration strategy (Scottish Government, 2015). It is also important to note that the Scottish National Party (SNP) is the only major party to oppose nuclear power development. This is a reflection of a wider divergence, in which Scottish voting patterns are increasingly out of step with England and Wales (BBC, 2016a, Lambert and Monk, 2015), and in which there are repeated calls for Scottish independence. This of course introduces considerable uncertainty to energy planning and policy across the UK, especially because Scotland contains a disproportionately high percentage of the UK's energy resources (both renewable and non-renewable) (ibid). There is also some movement toward more devolution within England – under the Devolution Act 2016, cities such as Manchester and Bristol now have elected mayors with powers over planning, policing, housing and transport. However, compared with some other European countries such as

Scandinavia, the UK (and especially England) is still extremely centralised, and the vast majority of budgetary and decision-making power lies in Westminster.

1.2.6 Conflicts and synergies of priorities

Along with many other nations, the UK is attempting to achieve three energy priorities: security, low cost of energy and carbon reduction. There may be unavoidable trade-offs between these three objectives (Cox, 2016). The EMR illustrated some of the conflicts which can occur, for instance by subsidising diesel generation through the Capacity Mechanism whilst simultaneously taxing it through the Carbon Floor Price. However, since the energy policy 'reset' in November 2015, the government has attempted to ameliorate the delicate balancing act between these three objectives by explicitly prioritising energy security (largely defined as promoting a reduction in imports and increased domestic energy investment); this may result in trade-offs with the UK's fairly stringent and legally-binding carbon target. Ironically, the very act of an energy policy 'reset' may actually result in problems for energy security, because the uncertainty caused by the scale and pace of recent policy changes may be highly off-putting to investors (Energy and Climate Change Committee, 2016).

Thus probably the overarching policy conflict is between the stated primary aim of ensuring energy security and the ongoing uncertainty in UK policy-making more generally, especially in the wake of the political chaos following the EU referendum. There is currently very little information regarding the future of the UK's relationship with the EU or of the future of the devolved administrations (with Scotland potentially pursuing independence), meaning that investors are less willing to invest in UK markets at present. This will likely have a negative impact on energy security, which requires considerable and timely investments in generation and network infrastructure (Cox, 2016a). Furthermore, the Brexit may delay the progress of the European Energy Union and the internal energy market, and may impact the status of the UK's electricity interconnection with Europe (Froggat et al., 2016, Grubb and Tindale, 2016). Increased interconnection and an integrated electricity market could act as a valuable tool for achieving the UK's stated policy aims of secure, affordable and low-carbon electricity (Cox, 2016a, Booz & Company et al., 2013), and the Brexit will perpetuate fears that there are fundamental conflicts between these stated aims and the UK's increasingly autarkic approach to policy-making (Newbery and Grubb, 2014).

1.3 Nuclear power in the UK

The previous section set out the overarching context of the UK energy system. Now, this section turns the focus toward UK nuclear power. The section begins with an overview of the development of the UK's nuclear power sector, beginning with the UK's (and the world's) first nuclear power station in 1956, right up to the latest policy commitment to build a new 'fleet' of nuclear power stations, potentially comprising up to 16GWe of new nuclear power. The second sub-section outlines the complete 'cradle to grave' value chain for nuclear power, from uranium mining, through generation, transportation and storage, to consumption and decommissioning. Finally, the third and fourth sub-sections focus in more detail on the enabling environment for this value chain, by showing the policies (section 2.3.3) and institutions (sections 2.3.4) which act as key 'enablers' for the development of new nuclear power in the UK.

1.3.1 Overview of the development of UK nuclear power

The UK's nuclear power sector goes back to the immediate post-war period, a time which saw dynamic industrial renewal in several areas of UK technology and infrastructure (Cocroft, 2006). In 1956, the Calder Hall power station at Sellafield in Cumbria became the world's first operational nuclear power station. The prototype Magnox reactor at Calder Hall had emerged out of military research programs, and was designed to produce plutonium for the UK and US nuclear weapons programs (Leveque and Robertson, 2014). At the time, there was vast optimism around nuclear power, exemplified by The Lord Privy Seal, Richard Butler, who stated "It may be that after 1965 every new power station being built will be an atomic power station." (BBC, 2005) Nuclear power was seen as an important clean source of electricity in a country dominated by coal and its associated drawbacks of smog and pollution; furthermore, new technologies such as nuclear power were seen to embody national prestige and pride (Cocroft, 2006).

From 1964 onwards, Calder Hall ceased to be a dual-purpose site, and production of weapons-grade plutonium was confined to other facilities at Windscale. Subsequent Magnox reactors, designed primarily as civilian power production facilities, were scaled up; in total, 4200MW of Magnox capacity was built in the UK throughout the 1960s and 1970s (World Nuclear Association, 2016b). Then in 1964, a second government White Paper on nuclear power was produced, announcing the next phase of the UK's nuclear power program featuring the new Advanced Gas-Cooled Reactors (AGRs). In total, 7 AGR stations were built (shown in Table 7).

As of September 2016, the UK had 15 operational reactors at 7 sites, providing around 21% of UK electricity capacity. However, almost half of this capacity is due for closure by 2025. The last Magnox station closed at the end of 2015, and most of the existing AGRs are operating at significantly less than original or design capacity.

Table 7: Operational AGR and PWR reactors

Plant	Type	Present capacity (MWe net)	First power	Expected shutdown
Dungeness B 1&2	AGR	2 x 520	1983 & 1985	2028
Hartlepool 1&2	AGR	595, 585	1983 & 1984	2024
Heysham I 1&2	AGR	580, 575	1983 & 1984	2024
Heysham II 1&2	AGR	2 x 610	1988	2030
Hinkley Point B 1&2	AGR	475, 470	1976	2023
Hunterston B 1&2	AGR	475, 485	1976 & 1977	2023
Torness 1&2	AGR	590, 595	1988 & 1989	2030
Sizewell B	PWR	1198	1995	2035
Total 15 Units		**8883 MWe**		

Source: World Nuclear Association (2016a)

There were numerous problems with the original design of the AGR, which came to light during the construction of Dungeness B. There were significant delays and financing problems, and this led to another long debate on reactor design. Several designs were considered, and the government originally opted for the Steam Generating Heavy Water Reactor (SGHWR) design, but this program was put on hold in 1977 in response to public spending cuts and increasing cost projections of the SGHWR. In 1978, Tony Benn announced his support for the Pressurised Water Reactor (PWR) design, and in 1979, the new Thatcher administration gave the go-ahead for a Westinghouse PWR at Sizewell B (World Nuclear Association, 2016a).

Sizewell B, which began exporting power to the Grid in 1995, is the UK's most recently-built nuclear station. It was originally planned to be the first of four new PWR power stations; however, it was only economic at the 5% discount rate made possible by low-interest government finance. Following the privatisation of the electricity industry, the nuclear sector was advised that the lowest possible commercial discount rate for a nuclear plant would be 11%, making further PWRs uneconomical (Parliamentary Office of Science and Technology, 2003). The economic challenges of building extremely capital-intensive projects such as nuclear power stations in a liberalised market is one of the main reasons that Sizewell B currently remains the UK's newest nuclear power plant.

At its peak in 1997, nuclear power provided 26% of UK electricity demand. This has since dropped to around 18% due to plant closures and unexpected power plant outages. With the exception of Sizewell B, the UK's existing nuclear plants are all due for closure by around 2025-2030 (World Nuclear Association, 2016a), because the graphite cores of the AGR reactors are limited in their life extension capability. The long lead times associated with nuclear power capacity mean that discussions over whether to replace some or all of this old capacity began around the year 2000. An Energy White Paper in 2003 stated simply "the current economics of nuclear power make it an unattractive option for new generating capacity" (MacKerron, 2009, p 82). However, in November 2005, Tony Blair announced an urgent need for a further major energy policy review. The subsequent consultation (reviewed in more detail in MacKerron, 2009; also Cox et al., 2016, Taylor, 2016, Thomas, 2016b), and the 2006 Energy Review Report which followed was much more positive about nuclear power, stating:

> *"Nuclear power is a source of low carbon generation which contributes to the diversity of our energy supplies. Under likely scenarios for gas and carbon prices, new nuclear power stations would yield economic benefits in terms of carbon reduction and security of supply. Government believes that nuclear has a role to play in the future UK generating mix alongside other low carbon generating options." (Department for Trade and Industry, 2006:113)*

In 2008, the UK Government decided to facilitate the construction of 8 new power stations to generate up to 16GW by 2025 (since amended to 2030). The sites chosen for the new power stations are shown in Figure 4 (Black, 2009, Department of Energy and Climate Change, 2011a). For the most part, these comprised existing nuclear sites, which reduce the regulatory complications which would be encountered in building on a green-field site, and which may reduce local opposition. Figure 4 also shows the sites of existing nuclear plants, all of which apart from Sizewell B are due for closure before 2030.

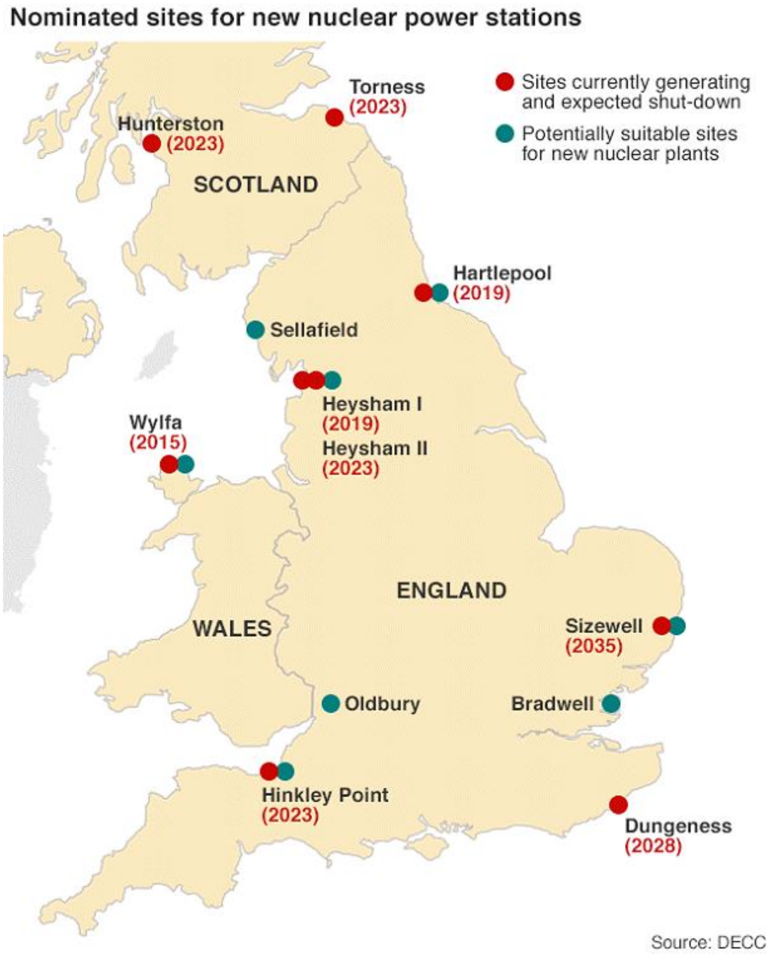

Figure 4: Nominated sites for new nuclear power stations

Source: Black (2009)

Despite nuclear power being "back on the agenda with a vengeance" (Blair, 2006, cited in MacKerron, 2009), the 2006-8 policy papers assert repeatedly that nuclear power would be dependent on favourable economics in a liberalised market. This policy of 'no subsidies for nuclear power' continued into the Coalition administration in 2010, in which the Coalition Agreement stated that nuclear new build would be permitted "provided that they receive no public subsidy" (HM Government, 2010). However, it became apparent in the design of the Electricity Market Reform that building a new nuclear power station would probably require public financial support of some sort, and the proposed new reactors at Hinkley Point C became one of the first energy projects to be awarded a Contract-for-Difference (CfD) subsidy. In a non-auctioned deal, the project was awarded a 'strike price' of £92.50/MWh for 35 years, more than double the electricity wholesale price at the time (see Table 8), meaning that the owners of the plant would receive this price for their electricity irrespective of market conditions. This agreement was also notable for the long duration of the contract: most other supply-side projects can only compete for 15-year CfD contracts, and demand-side-response is limited to 1-year.

All other forms of low-carbon generation must compete in auction for CfD agreements. Because of this, the strike prices can provide a good basis for comparing revealed costs across various types of low-carbon power generation. The results of the first CfD auction in February 2015 are shown in Table 8 (Department of Energy and Climate Change, 2015a). It shows that onshore wind, solar PV and energy from waste were all cheaper in the CfD auction than Hinkley C. The strike prices also illustrate one of the fundamental challenges of the nuclear power sector in the UK. Since the decision to encourage new nuclear power back in 2005-6, the costs of some other sources of low-carbon generation (and also electricity storage) have dropped far faster and further than expected, aided in part by rapid decreases in manufacturing costs in places such as China. Meanwhile, as shall be shown in the next paragraph, the costs of new nuclear plants have consistently been higher than planned (Grubler, 2010).

Table 8: CfD strike prices, first auction, February 2015

Type	No. of projects	Average price/MWh
Onshore wind	15	£81.95
Offshore wind	2	£117.14
Solar PV	5	£67.54
Energy from waste	2	£80
Advanced conversion tech	3	£118.05
New nuclear	1	£92.50

Source: Department of Energy and Climate Change (2015a)

It seems likely that three or more different reactor designs will be used for the proposed new nuclear power programme. A consortium led by EDF (and including a state-owned Chinese company) is planning to build two EPR reactors (a 3^{rd}-Gen PWR design) at Hinkley C, a project which was initially planned for completion by 2017 but which is now scheduled for completion in 2025. EDF also plan to build another two EPRs at Sizewell, although this project is still at consultation stage. The two other EPR reactors under construction in Europe are both extremely late and experiencing cost overruns – the Olkiluoto 3 reactor in Finland is 9 years late and around €6bn over budget (Yeo, 2015), and the Flamanville Unit 3 reactor in France is at least 6 years late and around €7.2bn over budget (De Clercq, 2016). In 2015, the French nuclear safety inspectorate announced that "very serious anomalies" had been found with the reactor vessel at Flamanville, creating yet more delays and concerns about the safety of other EPR reactors under construction (Thomas, 2016a). Importantly for the UK, the £2bn in loan guarantees offered by the UK government to EDF for the Hinkley C project are conditional on the Flamanville reactor being operational by 2020, a completion date which is looking increasingly challenging for EDF to meet (Tickell, 2015).

In 2012, RWE and E.ON pulled out of the UK's nuclear programme in the aftermath of the Fukushima disaster and the subsequent decision by Angela Merkel to phase out nuclear in Germany. Their 'Horizon' consortium was purchased by Hitachi, and is planning up to 6000MW of new nuclear capacity, comprising between four and six Advanced Boiling Water Reactors (ABWRs) at the Oldbury and Wylfa sites. Horizon originally planned to start work at Wylfa in 2015, but financing discussions between the UK government and Hitachi were still ongoing at the time of writing. The third reactor design, the Westinghouse AP1000, is proposed for two or three new reactors at Moorside near Sellafield, in a project run by NuGen, a joint venture between Toshiba and ENGIE (formerly GDF Suez). The project is currently at site assessment stage, and NuGen are hoping to take a final investment decision in 2018. Finally, the state-owned Chinese energy company CNNC is considering a Chinese reactor design at Bradwell, and the state-owned Russian utility Gazprom may aim to certify the Russian VVER-1200 for use in the UK (NEI, 2013).

It is important to note two more crucial aspects of nuclear power. Firstly, nuclear accidents (including core meltdowns of the type experienced at Fukushima, or less serious accidents involving reactor shutdowns and incidents in which safety has been comprised for a variety of other reasons), are extremely costly. The number of such accidents is highly uncertain because transparency is very low; it is not possible to find reliable data even from countries such as the UK with relatively advanced transparency and regulatory regimes, let alone from countries such as China and Russia (Rose and Sweeting, 2016). However, the available data does indicate that there are likely to be more severe nuclear accidents than have been expected by official sources (ibid.), and also that nuclear accidents have been more economically costly than accidents from any other type of power generation (Sovacool et al., 2016, Sovacool et al., 2015). It is worth noting that the 2011 Fukushima accident, which had a transformative impact on the nuclear power sector in places like Japan, Germany, Switzerland and Italy, had very little impact on the plans for new nuclear or on public perceptions in the UK. A large survey by Poortinga et al. (2014) found that there were no marked changes in public concern about nuclear power and the perceived risks associated between 2011 and 2013. There may be multiple reasons for this: the UK has very low levels of risk of natural disasters (ibid.); new reactors will be built on existing reactor sites, where opposition is likely to be lower (Butler et al., 2011); and nuclear opposition in the UK tends to be more closely associated with the waste issue than with concern about accidents.

Secondly, and as shall be elaborated on in the following section, nuclear electricity generation produces nuclear waste primarily in the form of spent fuel, within which Plutonium (Pu239, which has a half-life of 24,000 years), Uranium (U235), and a variety of trans uranium wastes are the main constituents. Work on economic solutions for long-term disposal is still ongoing. Currently, most of the UK's nuclear waste is stored at Sellafield, and numerous safety concerns exist (Blowers, 1999, Tickell, 2014) and have been made highly public (BBC, 2016c). Before the abolition of the Department for Energy and Climate Change, 74% of the department's budget was officially ring-fenced, most of which was for the Nuclear Decommissioning Authority, and a further 6% unofficially ring-fenced for nuclear liabilities (Green Alliance, 2015).

These two important issues are extremely important to take into account when discussing nuclear power, because they represent potentially serious risks and because they are unique to nuclear power and thus set it aside somewhat from other forms of power generation. However, these risks are not discussed in this report in detail, because they will be analysed in more depth throughout the remainder of the 3-year TRANSrisk project.

1.3.2 Nuclear Power life cycle value chain: a cradle to grave analysis

This sub-section outlines the cradle-to-grave value chain for UK nuclear power. In a simplified way, it describes the following processes: a) fuel extraction and conversion, b) electricity generation, c) transportation of fuel, d) storage of fuel and electricity, e) distribution of electricity and end-users, f) decommissioning of power plants, and g) reprocessing and waste of spent fuel.

a) Fuel extraction and conversion

Nuclear electricity requires uranium fuel, which is mined. Many countries (including the UK) have uranium reserves, but in most cases, these are not exploited for commercial purposes. Uranium fuel is mined in a number of countries, and the UK imports all its uranium. The NERA/OECD 'Red Book', the most authoritative source of information on nuclear fuels, suggests that there are sufficient known, relatively low cost uranium reserves to be adequate for world consumption for at least 100 years (OECD et al., 2014). Because uranium is very cheap and easy to store, it is believed that most countries that import uranium (including the UK) keep around 2 years' worth of stocks to ensure security of supply. The major uranium exporting nations are: Kazakhstan, Canada, Australia, Namibia, Niger, Russia, Uzbekistan, USA, China and South Africa (World Nuclear Association, 2015). Rather unsurprisingly, it is not possible to obtain data showing where the UK imports its uranium from, for security reasons. Berkemeier et al. (2014) suggest that most of the UK's uranium comes from Australia.

The fuel cycle is conventionally divided into the front end (everything that happens before fuel is loaded into reactors), and the back end (everything that happens after fuel is removed, including the costs of decommissioning reactors). According to the NEA/OECD the total cost of the entire fuel cycle is characteristically between 15% and 25% of total generating costs (Nuclear Energy Agency and OECD, 1994). Within the front end, the cost of the uranium is just under 25% of costs, or generally no more than around 2% of the total generating cost. Therefore, the cost of the nuclear fuel cycle is a relatively small part of the total generating cost of nuclear electricity, both because the capital costs of nuclear plant are high, and because uranium fuel volume required for the operations is low.

Uranium leaves mines as 'yellowcake' (U_3O_8) and this needs to be converted into UF_6 before the next stage, 'enrichment'. The UK used to have a conversion facility but this was closed in 2014. There might be security reasons for which it is not clear which plant or plants overseas process the uranium used in the UK.

The costs of conversion are however very low (less than 1% of total generating costs.) When uranium as UF_6 arrives in the UK it is then 'enriched'. This involves raising the naturally occurring proportion of U235 (0.7%) to around 4% in a centrifuge plant at Capenhurst (privately owned by Urenco) (World Nuclear News, 2012). This process can in principle be used to make the uranium suitable for making nuclear weapons – it simply means continuing to enrich uranium until its U235 content reaches around 90%. The enriched uranium is then manufactured into fuel elements, combined together in fuel rods, and is then ready for insertion into reactors. Fuel rods are then delivered to reactor sites around the UK by train.

The UK's history of commercial reactors is that, with one relatively recent exception, it has relied on indigenously designed gas-cooled, graphite-moderated reactors. The first generation of such reactors, termed Magnox, which used natural uranium, are now all closed, while the 14 Advanced Gas-Cooled Reactors (AGRs, amounting to some 8 GW and all owned by EDF Energy), using enriched uranium, are still operational, though all are due to close in 2025-2030 period. The most recent UK reactor, Sizewell B, is a Pressurised Water Reactor (PWR, of 1.2 GW) of Westinghouse design and due to close around 2035 (see Table 7).

b) Electricity generation

Enriched uranium is used to generate high-voltage electricity in nuclear power plants. An overview of the UK's existing nuclear plants is given in the preceding section. As it is has already noticed, the UK Government hopes that a further 16GW of nuclear plant may be built over the next decade or more, but this programme has been subject to severe delays. The first new planned station at Hinkley Point C (EPR, 3.2 GW) has just been given formal approval some eight years later than originally planned, with investment from EDF and Chinese state investors (The Guardian, 2016). In principle, two more EPRs may be built at Sizewell C, three AP1000 reactors at Moorside and ABWRs at Wylfa and Oldbury. There are also plans to build a Chinese-designed reactor at Bradwell. Financing has proven difficult and it is not clear whether and when these further reactors will be built: all depend on negotiation with the UK Government over a long-term fixed price for power well above current wholesale electricity prices.

c) Transportation of fuel

As mentioned previously, uranium in the UK is all imported. Most of the transportation is carried out by ships, using specially-designed containers for transportation. Within the UK, it is likely that nuclear fuels are transported either by train or by road freight, using public roads and railways – this is common in nuclear fuel cycles around the world, and safety is heavily regulated. However, there is little publically available information on specific nuclear transportation routes and modes, because of security concerns.

d) Storage of fuel and electricity

In terms of the raw fuel, uranium is cheap and easy to store, because a physically small amount of uranium contains a huge amount of energy. The UK has undisclosed stores of uranium, believed to be roughly 2 years' worth of supply. In terms of the energy generation, nuclear plants produce electricity, which is relatively challenging to store; for this reason, the UK electricity market at present requires constant and instantaneous balancing (Chaudry et al., 2011). However, significant technological and cost improvements have been occurring in storage technology, with the first Grid-scale storage array (owned by Tesla) connecting to the Grid in September 2016 (Clean Energy

Live, 2016). Finally, nuclear power requires specific processes for the reprocessing and storage of nuclear waste; which will be discussed in sections 'f' and 'g' below.

e) Distribution of electricity and end-users

Electricity from nuclear plants goes into the UK-wide high-voltage transmission network. This network is owned and managed by a regulated monopoly company, the National Grid, which has responsibility for balancing supply and demand in order to maintain voltage quality. The high-voltage electricity is used directly by some large industrial users; for all other users, the voltage is stepped down to the low-voltage distribution network, which is owned and maintained by 14 regional Distribution Network Operators. Because of the highly centralised nature of the UK electricity system, electricity users all consume the same mix of electricity generation sources. Moreover, the UK has near-100% electricity access, meaning that almost every UK citizen uses the electricity produced by nuclear power plants. Those who do not have a mains electricity connection generally do so by choice. In is important to note, that the UK has a high reliability standard for electricity, meaning that consumers are accustomed to instantaneous and continuous electricity availability, in the quantity and quality required at any time of day.

f) Decommissioning of power plants

Since 2005, public sector waste and decommissioning have been the responsibility of the Nuclear Decommissioning Authority (NDA), a public body which now owns all public sector UK civilian waste and decommissioned reactors. It spends roughly £2.5 bn. annually on waste and decommissioning (House of Commons Committee of Public Accounts, 2013), the bulk of it at Sellafield, which houses a very large range of wastes, some of them in poor condition. Reactor decommissioning is proceeding slowly, in the sense that decommissioned reactors are subject to long periods in so-called 'Safestore' conditions, with eventual complete dismantling postponed for many decades into the future (Nuclear Decommissioning Authority, 2016). The total future undiscounted bill for public sector liabilities is now £117 bn (ibid.). In the private sector, EDF has financial responsibility for decommissioning and waste management at operating reactors. There is a Nuclear Liabilities Fund, managed by a trust, which vets applications by EDF to draw down this fund, currently valued at £9 bn (Nuclear Liabilities Fund, 2015).

g) Reprocessing and waste of spent fuel

When fuel is removed from reactors it has, after a period of on-site cooling, historically been sent to Sellafield by train where it has normally been 'reprocessed' (see below). Such transport of spent fuel to Sellafield continues from all the AGR reactors on long-term contracts between EDF Energy and Sellafield Ltd, but the fuel is now all stored under water at Sellafield and it is now expected that it will be treated as waste (Nuclear Decommissioning Authority, 2016). For Sizewell B however, a large on-site spent fuel store has been built and there are no current plans to move spent fuel from the reactor site. In much the same way, future reactor sites will also be required to store spent fuel on-site, pending an (expected) availability of a deep geological repository (see below).

Early UK policy for spent fuel was that it was to be reprocessed – that is, undergo a complex mechanical/chemical process in which unburned uranium and plutonium are separated from a variety of waste products. Reprocessing had its origin in a military programme, which required plutonium for weapons production (MacKerron, 2012). The Magnox reactor was an adaptation of a military design, and produced relatively large amounts of plutonium. When this design was adopted for power production it was decided that spent fuel would be reprocessed. This had two justifications: it was expected that uranium would become scarce and expensive, and that a large stock of plutonium would be needed as start-up fuel for fast-breeder reactors (ibid.); and Magnox fuel is metallic and corrodes dangerously if left in water for extended periods. When the fast-breeder justification disappeared in the early 1990s, reprocessing seemed desirable despite the lack of demand for plutonium. Magnox reprocessing, at the 54-year old B205 plant, will in principle by 2020, by which time there will be no more fuel to reprocess (Hyatt, 2016).

When the AGR reactors were built from the early 1970s onwards, it was officially assumed that reprocessing would be desirable because of the apparent need for plutonium. In the same decade it became apparent that some foreign Governments and/or utilities, especially from Japan, would be willing to pay to have their spent fuel reprocessed in the UK (MacKerron, 2012). Therefore, the THORP oxide fuel reprocessing plant was built, and has reprocessed both AGR and overseas fuel. It has had a mixed operating history and is due to close in 2018, as there is no further demand from EDF Energy for further reprocessing in the UK or overseas; reprocessing is much more expensive than treating spent fuel as waste (ibid.). AGR fuel is still delivered to Sellafield but it is now stored rather than reprocessed. There seems little doubt that all future spent fuel will be treated as waste, involving a period of wet storage and the strong likelihood that longer-term dry stores will provide appropriate storage for many decades.

The UK will, as a consequence of reprocessing, soon have some 140 tonnes of separated plutonium stored at Sellafield, constituting the world's largest civilian stockpile of plutonium (Hyatt, 2016). There was a plan to send back foreign-owned plutonium in MOX (Mixed oxide, plutonium-uranium) fuel for use in current reactors. To this end, the former company BNFL built a pilot and then a full-scale MOX fuel fabrication facility at Sellafield. The full-scale plant proved to be a major technical failure and closed in 2011 having operated at only 1% of design capacity in its short lifetime. The NDA and UK Government have been considering disposition strategies for plutonium since 2009 (MacKerron, 2012). Current contending possibilities include building another MOX plant and using the fuel in future reactors in the UK, incinerating the plutonium at a fast reactor to be built at Sellafield, or immobilising the plutonium ready for deep disposal. No decision seems likely for several years (Hyatt, 2016).

Low level radioactive wastes are currently shallow-buried at Drigg. Policy for higher activity wastes has taken several decades to develop, but since 2008, policy has been to find a deep geological disposal site after initiating a volunteering process from potential host communities and offering them a right of withdrawal up to a defined point. Discussions with communities near Sellafield were pursued but in 2012 Cumbria County Council vetoed the process (BBC, 2013), and while voluntarism remains policy, there is no current sign of a willing volunteer community.

1.3.3 Enabling environment and policy mixes

In short, it would be easier to ask which policies *don't* directly or indirectly impact nuclear power in the UK, because the projects are large and highly regulated, and cut across many sectors. Within the energy sector, policies relating to all forms of energy supply and demand have an impact on nuclear power, because nuclear power is dependent on the energy mix and the supply-demand balance: for example, all policies relating to renewables will impact nuclear by determining how much nuclear is required to meet demand. Therefore, drawing the boundary is extremely challenging. Table 9 shows the policies, which have a *direct* impact on nuclear power in the UK; for brevity, indirect policy impacts are not included.

It is important to note that nuclear power has a history of strong cross-party support within the UK government. The only parties, which oppose nuclear power, either historically or in the present day, are the Scottish National Party and the Green Party (who respectively hold 69 and 1 parliamentary seats, out of 650).

Table 9: Complete list of policies / legislation, which directly impact the UK nuclear power sector

	Nuclear	Energy (general)	Climate	Environment	Planning	Other
UK	Nuclear site license requirements	Electricity Act 1989	Climate Change Act 2008	Environmental Protection Act 1990	Planning Act 2008 and NSIPs	Infrastructure loan guarantees
	Nuclear Installations Act 1965	Energy Act 2013	UK INDC	Environment Act 1995	Planning reform 2011 and 'National Policy Statements'	Official Secrets Act: and 'prohibited places'
	Radiological Protection Act 1970	Energy Act 2004				Anti-terrorism Crime and Security Act 2001
	Health and Safety at work Act 1974	Electricity Market Reform				Defence policies (Cox et al. 2016)
	Ionising Radiations Regulations 1985	National Policy Statements for Energy (2011)				Education policies
	Radioactive Substances Act 1993	Energy policy 'reset' (2015)				Trade and foreign policy (e.g. diplomatic relations with China, France)
	Health Protection Agency Act 2004	Abolition of DECC (2016)				Devolved Administration policies
	Generic Design Assessment process (established 2006)					Brexit
	Nuclear Industrial Strategy (2013)					
	Nuclear skills strategy (including Skills Workstream and Nuclear AMRC) (2013)					
	Nuclear Generating Stations (Security) Regulations 1996					
	Waste disposal framework (2008): published in the 2008 White Paper 'Managing radioactive waste safely'					

	Environmental permitting (England and Wales)					
	Radioactive Substances Act 1993					
	Special Waste Regulations 1996					
	Safety Assessment Principles					
	Various regulations governing nuclear transport					
	Scottish nuclear policy (vote 2008)					
EU[7]	Euratom Nuclear Safety Directive		EU 20-20-20 targets	Environmental Impact Assessment Directive		EU Competition Law
	Euratom Radioactive Waste and Spent Fuel Management Directive	Third Energy Package	EU 2030 Energy and climate framework	Water Framework Directive 2000		
			EU Emissions Trading Scheme			
Global	Nuclear Non-proliferation Treaty 1968		Paris Agreement 2015			

All the above policies and regulations have a direct impact on nuclear power stations in the UK, whether in terms of operating or decommissioning an existing power station or planning a new one. However, in order to simplify the policy mix for analysis, table 10 below shows a specific set of policies, which act as part of the *enabling environment* for the continuation and expansion of nuclear power in the UK. Many of these policies were put in place specifically to enable the building of a new fleet of nuclear power stations, starting with the Hinkley C project and potentially extending up to 16GW of new nuclear generation capacity. The table includes both policies and policy instruments, because in many cases, the enabling policy instruments are contained within the relevant policies; for example, the Contracts-for-Difference feed-in tariff for

[7] Note: the future impact of all EU policies on UK energy infrastructure are currently uncertain following the 'Brexit' decision

new nuclear power stations was introduced as part of the Electricity Market Reform, which in turn was introduced as part of the Energy Act 2013. More detail on these policies is given in Appendix B.

Table 10: UK policies and policy instruments to enable nuclear power development

Nuclear	Energy (general)	Climate	Planning
2008 nuclear White Paper	Electricity Market Reform	Climate Change Act 2008	Planning reform 2011
Nuclear Industrial Strategy	Energy Act 2013	EU ETS	
Generic Design Assessment process	National Policy Statements for Energy		
Creation of the Office for Nuclear Regulation and Nuclear Decommissioning Authority			

1.3.4 Enabling environment: government institutions

Figure 5 shows the major public institutions involved in nuclear power in the UK, and the relationships between them. As can be seen, there are a large number of public institutions with a direct involvement in the nuclear power sector in the UK, and relationships between them are somewhat fragmented. The most important government departments are shown on the left: the Department for Business, Energy and Industrial Strategy (formerly DECC and BIS), and the Treasury, which controls the public finances. Since the financial crash in 2008, and the subsequent program of austerity, the Treasury has played a more active role in energy and environment decision-making in the UK. As can be seen, there are also a number of publicly owned yet non-governmental bodies, responsible for regulation, advice and research. The chart also shows that the relevant institutions for nuclear power extend beyond the energy sector, for instance into health, transport, planning, foreign policy, and defence. Finally, it is worth emphasising that this chart shows just the *public* institutions; there are a huge number of privately owned institutions such as utilities and industry bodies which have a crucial role in the nuclear power sector, and which shall be elaborated in the system map in the following section

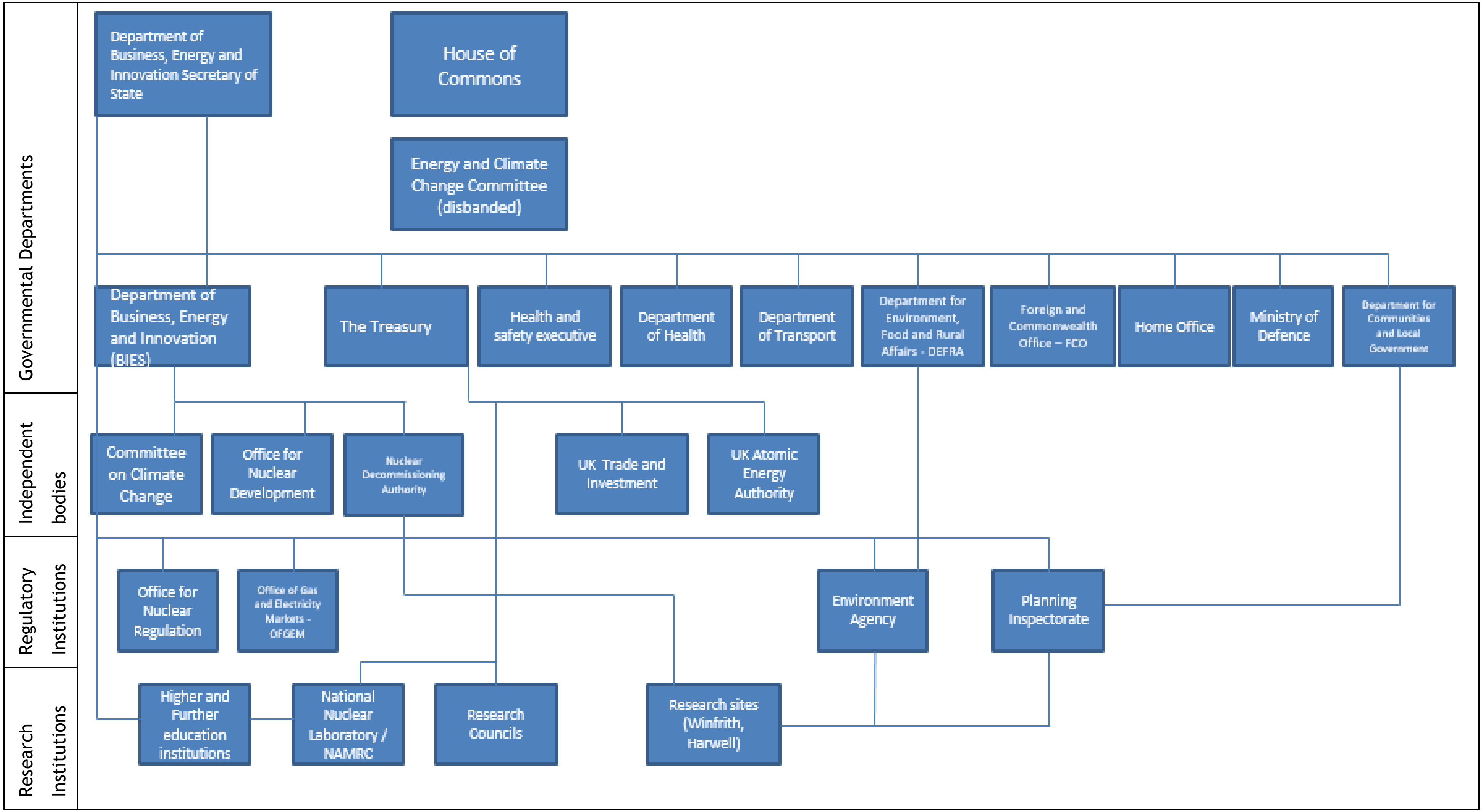

Figure 5: Major public institutions in the energy and nuclear power framework in the UK

1.4 The innovation system map

Figure 6 below shows the system map for UK nuclear power, developed using a dedicated system map tool developed by NTUA. The system map, despite being a somewhat simplified representation of the actors and institutions involved, nevertheless illustrates the considerable complexity of the UK nuclear power system. Some of this stems from the complexity of the technology itself: as shown in the 'Nuclear power plants' section on the left-hand side (and as shown in the lifecycle overview in section 2.3.2), the nuclear power life cycle involves a large number of processes, with a large number of different actors involved at each stage. It is worth noting that the actors listed in the TIS lifecycle section of the system map (e.g. 'supply chain', 'vendors' and 'developers') are by no means comprehensive. The map shows the major suppliers, vendors and developers in the UK supply chain, but there are also a large number of companies not shown which have some lesser involvement. For instance, in providing services such as consultancy, construction, safety management, computer systems, technologies and components. For example, the number of components manufacturers involved in the UK supply chain alone is probably in the hundreds. It is also worth noting that many large companies operate at multiple stages of the supply chain simultaneously, for instance in designing and selling technology, developing and managing new and existing projects, and decommissioning.

Previous sections of this report have also demonstrated the number and fragmented nature of the government departments and policies, which are all directly involved in the nuclear power system, because of the complex, large-scale and highly regulated nature of the technology. This is reflected especially in the 'institutions' and 'policy mix' sections of the system map. Nuclear power also affects many non-energy sectors, as shown by the facilitating services and infrastructure, which are involved: finance, planning, health and defence.

One of the key aspects of this system map is the huge number of specific contextual factors, which are critical for enabling nuclear power, especially nuclear new-build, in the UK. Some of these relate directly to nuclear power (e.g. accidents and waste disposal prices), whereas some relate to the wider energy system (e.g. energy resilience, intermittency, renewable energy pricing). However, there are also many contextual factors from other sectors – for example, the actions of trade unions (even in France), military interests, a contested issue regarding the R&D investment of the UK government, building investor confidence, and minimising the uncertainties created by Brexit. This illustrates the fact that, where complex, long-term and large-scale energy infrastructures are involved, sometimes-key risks may arise from sectors or geographical areas which are distinct from the energy sector and therefore mapping such relationships is a complicated task. This task will be carried out in the next stage of this research. It is expected, further changes and elaboration of the roles and interlinkages of the actors' activities influencing the nuclear power sector will be found and then they will be presented and tested in a second stakeholders' engagement. Therefore, a more coherent system map will be the result of deepen understanding of the enabling and barriers of the nuclear power sector as a way to pursue decarbonisation of the UK energy system.

It is important to notice that this current system map was elaborated with inputs provided by the stakeholders' workshop in October 2016 as it is explained in 2.5.

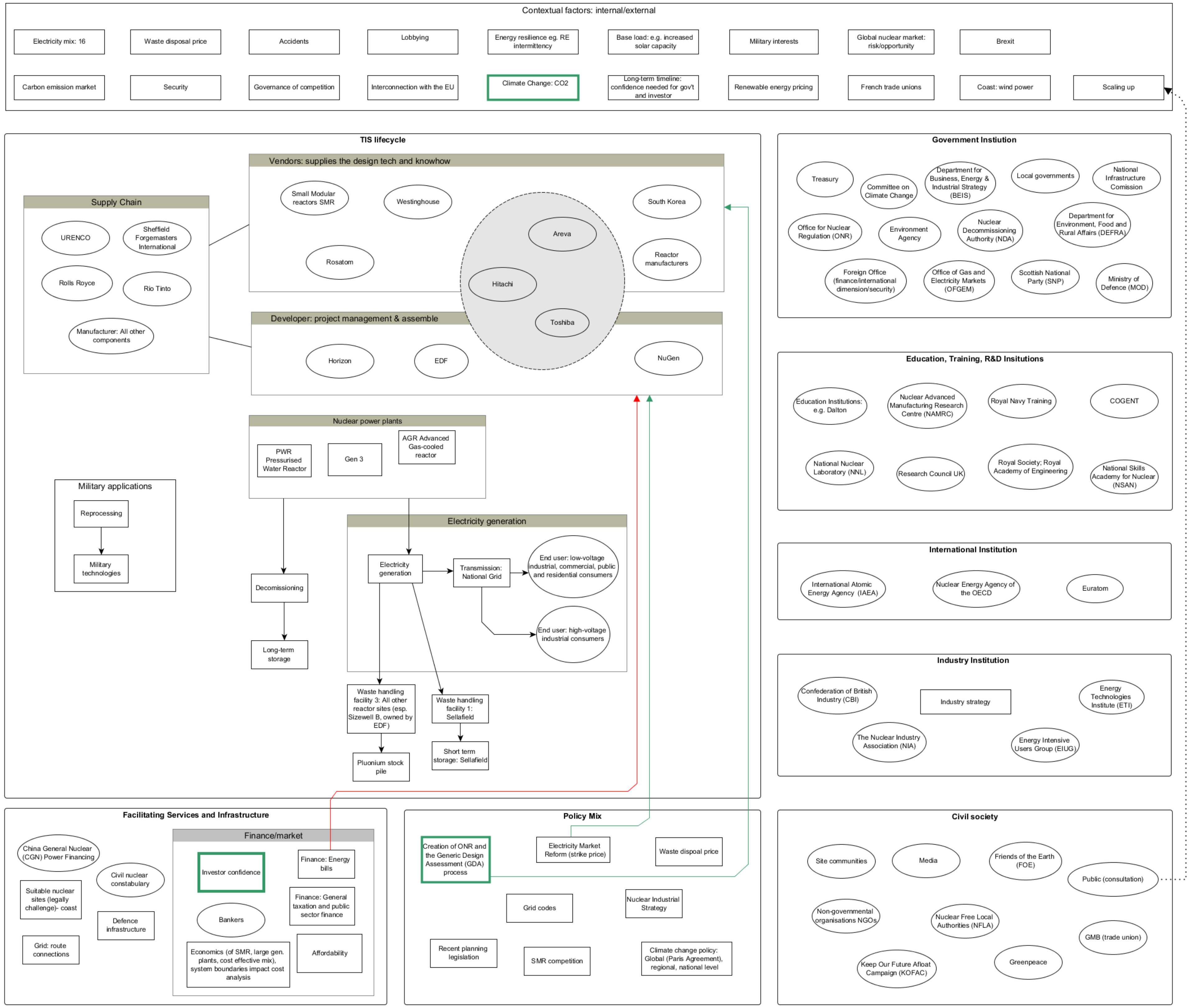

Figure 6: UK nuclear power system map

1.5 Stakeholder engagement

Table 11 below gives details of all the stakeholders who were contacted for this stage of the research. Stakeholders were targeted for their involvement in key organisations or for their knowledge and expertise in nuclear power and energy systems. A variety of engagement methods were used (focus groups, interviews, and a workshop).

It is important to notice that some of the inputs provided by stakeholders are included in this report covering:

a) the debate in nuclear power and its underlying policies and institutions,

b) the development of the nuclear sector,

c) the development of the system map and its main interlinkages,

d) the contradicting expectations of stakeholders to pursue the expansion of nuclear power sector,

e) the identification of the main risks and uncertainties to pursue the development of the nuclear sector as a way to decarbonise the UK energy system.

However, future interviews and workshops will be carried out and together with further analysis of the stakeholders' inputs got at this stage will be the bases for the full case study in the following stages of this project for the final deliverable D3.3.

One important input coming from the stakeholders' engagement was their contradicting views on the future of UK energy mix in the following years, 2030 and 2050. This input will be used in the creation of scenarios and trajectories to mitigate climate change in the next stage of the project.

Table 11: Stakeholder engagement

	Type of stakeholder	Position in the organisation	Economic sector	Type of engagement	Month & year contacted
1.	Research	Professor	Energy/environment	Focus group	July 2016 / Nov 2016
2.	Research	Professor	Energy/environment	Focus group	July 2016 / Nov 2016
3.	Research	Senior researcher	Energy/environment	Focus group	July 2016 / Nov 2016
4.	Research	Junior researcher	Energy/environment	Focus group	July 2016 / Nov 2016
5.	Advisory body	Economist	Energy/environment	Interview	Oct 2016
6.	Research	Senior researcher	Energy / financial	Interview	Oct 2016
7.	Research and business	Senior advisor	Energy / financial	Interview	Nov 2016
8.	Research / consultancy	Senior researcher	Energy	Interview	Oct 2016
9.	Public body	Top level	Energy / environment	Interview	Nov 2016
10.	Government / research / business	Senior advisor	Energy / industry / transport / financial	Interview	Nov 2016
11.	Research	Senior researcher	Energy / industry	Interview	Nov 2016
12.	Advisory body	Strategy Manager	Energy / industry	Workshop	Nov 2016
13.	Advisory body	Analyst	Energy / environment	Workshop	Nov 2016
14.	Research	Senior researcher	Energy / environment	Workshop	Nov 2016
15.	Business	Head of strategy	Energy / industry	Workshop	Nov 2016
16.	Research	Economist	Energy / environment / financial	Workshop	Nov 2016
17.	Research	Economist	Energy / environment / financial	Workshop	Nov 2016
18.	Research	Professor	Energy / environment	Workshop	Nov 2016

1.6 Summary

1.6.1 Context of the UK energy system

The UK's energy system is in a period of major transition, driven by declining domestic fuel reserves, the need to replace ageing energy infrastructure, the need to cut carbon emissions in line with unilateral, European and international agreements, and changing energy markets. These pressures have led to calls for new sources of low-carbon electricity, one of which could be nuclear power.

The UK has a highly centralised electricity system, also tends to lean toward centralised and supply-side-centric energy policies. It was one of the first countries to privatise its electricity and gas systems in the late 1980s, and since then has long been an advocate of liberalised energy policy. However, the new pressures facing the energy system mean that targeted support for particular technologies is now undertaken. Historically, the electricity system has relied extensively on gas and coal (and nuclear to a slightly lesser extent), which in the past were sourced largely from domestic reserves which are now in steep decline. The UK also has abundant wind and solar resources, but rather limited potential for hydropower, geothermal, and electricity interconnection. It is also worth noting that the UK's overall energy consumption is decreasing, although longer-term plans to decarbonise heating and transport could mean that consumption of *electricity* actually increases in the future. The UK has a unilateral, legally-binding target to reduce GHG emissions by 80% on 1990 levels by 2050, and is also party to European climate targets and environmental initiatives, although the recent decision to leave the EU has created uncertainty over the future of these commitments.

The context-setting part of this case study (section 2.2) also noted that the UK is at relatively low risk of the majority of natural catastrophes such as earthquakes, hurricanes and droughts. However, the UK is at high risk of flooding, sea-level rise and coastal erosion, which could all worsen due to climate change and could put energy infrastructures at risk. However, at present, the main concerns facing UK policy-makers are related to the economy, rather than natural events or climate change. An ongoing program of economic austerity has led to significant cuts to public funding for energy, and the Department for Energy and Climate Change has been merged into a new Department for Business, Energy and Industrial Strategy (BEIS). Finally, section 2.2 of the case study argued that probably the main conflict within UK policy priorities is between the stated primary aim of ensuring energy security, and the ongoing uncertainty in UK policy-making more generally, especially in the wake of the political chaos following the EU referendum. There is currently very little information regarding the future of the UK's relationship with the EU, meaning that investors may be less willing to invest in UK markets at present. There is also uncertainty over the future of the devolved administrations, with Scotland potentially pursuing independence and an increasing disparity between UK and Scottish energy policies; this is important because Scotland opposes nuclear power, and possesses a disproportionate amount of the UK's fossil and renewable energy resources.

1.6.2 Nuclear power

The development of nuclear power in the UK began in the 1950s, with the world's first civilian nuclear power station at Calder Hall and an initial total of 4.2GW Magnox capacity. Then during the 1970s and 80s a fleet of AGR reactors was built; for the most part, these AGRs are what provides the UK's nuclear electricity today. During the 1980s, four PWR reactors were planned, but after the privatisation of the electricity industry these were no longer profitable, and only one was built – this remains the UK's newest nuclear plant. With the exception of the PWR at Sizewell, all the UK's existing nuclear reactors (representing around 18% of current UK electricity consumption) are due to close by 2030.

During the 1990s and early 2000s, the challenges of building such a capital-intensive technology in a liberalised market made nuclear power economically unattractive. However, in 2005 Tony Blair announced that nuclear power was "back on the agenda with a vengeance", and the government subsequently announced their intention to support a fleet of new nuclear power stations, comprising 16GW generation capacity at 8 sites around the UK. Since then, nuclear power has enjoyed cross-party support from all the main political parties (with the exception of the Scottish National Party), and nuclear power is currently touted as a favourable option for cutting carbon emissions whilst maintaining energy security.

However, this ambitious new-build program may encounter multiple risks and uncertainties. Nuclear power is an especially complex and highly regulated technology, and financing such projects within the UK's liberalised electricity market remains highly challenging. Furthermore, there have been numerous delays, cost overruns and safety concerns with similar projects already underway elsewhere in the world. The investment environment is highly uncertain, especially in the context of rapidly changing electricity markets in many countries due to the growth in renewables and shifting patterns of demand. UK energy policy has also seen some rapid and unexpected changes in recent years, and the future of the UK's relationship with EU energy markets is highly uncertain. All this makes investors wary of making long-term commitments in such an uncertain policy and investment environment. Nuclear power also experiences particular risks, which set it apart from other generation technologies, because of the challenges of nuclear waste disposal and the catastrophic nature of nuclear accidents.

This report has carried out some initial mapping of the nuclear power life cycle, the policies and institutions involved, and the stakeholders in the supply chain and enabling environment. The privatisation of the electricity system in the late 1980s led to the proliferation of multiple private and public actors, which makes the system highly complex. For example, the system map illustrates the considerable number of major suppliers, vendors and developers in the UK supply chain, and yet there are hundreds more who are also involved to a lesser degree. Nuclear power is a large-scale politically visible and highly-regulated technology, which means that it cuts across many sectors, and hence has a considerable number of government departments and non-governmental bodies involved in its development and regulation. There are also a considerable number of policies which directly impact nuclear power, therefore this case study has focused on a set of policies which have been put in place to actively help enable the development of *new* nuclear power in the UK, including subsidies, market reform and planning reform.

The system mapping carried out in this report has also illustrated the huge number of facilitating services and contextual factors which are critical for enabling nuclear power, especially nuclear new-build, in the UK. Many of these relate directly to nuclear power or to the wider energy system; however, many relate to other sectors and countries: for example, investor confidence, planning and siting, health policy and regulation, military interests, the actions of trade unions (even in France), and Brexit. This illustrates the fact that, where complex, long-term and large-scale energy infrastructures are involved, sometimes key risks may arise from seemingly distant sectors or spaces.

Appendix A: Detailed Research Questions

Overarching question: What low-carbon electricity generation options are available to reduce CO_2 emissions while considering UK's economic, political, social and environmental priorities?

5. **What feasible nuclear power technological options are available in the UK (considering the above mention priorities) within the current decade and in the longer term?**
    a. EPR; GE Hitachi ABWR, Westinghouse AP1000 (currently deployable)
    b. Feasibility of Chinese Hualong design and/or small modular reactors? (local adaptations of technological innovations deployable in X years)
    c. What nuclear power technologies (listed in 1a & 1b) are viable for contributing to UK's electricity generation capacity?
        i. Questions to ask for specific nuclear power technologies:
            1. How much would it cost? (capital costs, operation cost etc.)
            2. What is the life span of the nuclear power plant?
            3. How fast can it be ramped up and down?
    d. What is the threshold (maximum capacity) for nuclear power in the electricity generation mix in the UK before it becomes impossible to run all nuclear plant at full load throughout the year)?
        i. If nuclear power was to exceed the threshold, what changes to the electricity mix or energy economy is needed? (e.g. could nuclear investment be justified if its availability was restricted?)
        ii. What are the potential knock-on effects if the threshold for nuclear power was surpassed? Would it for example encourage growth of electricity use e.g. charging electric cars at night)
        iii. What would be the public's perception of the changes required?
6. **What are the social-economic and environmental costs/benefits and risks/uncertainties to supporting the development of new nuclear power electricity generation? (within the timeframe of 10 years and 20+ years' time)**

a. What are the possible construction costs of nuclear power per kWh, cost of decommissioning, of nuclear waste management, etc.

i. If costs are above market prices, who pays? Consumers, taxpayers, industry (upfront investment, pass on costs to consumers)? What are the socio-economic implications of different payment options?

ii. How easily can nuclear power plants be financed?

b. How does nuclear power support sustainable job creation, support other sectors such as medical and military etc.

i. How can the industry attract talent?

c. What is the cost of CO_2 emissions savings related to nuclear power compared to other technologies?

i. What are the risks and potential impacts of accidents and natural disasters (e.g. coastal erosion, storm surges, flooding)

ii. Financial impacts, environmental impacts etc.

d. What is the role of public opinion on the feasibility of nuclear power?

7. **To what extent does policy support in nuclear power divert resources (e.g. financial, human resources and capabilities) from the deployment of other low-carbon electricity generation technologies?**

a. Such as readily available renewable energy technologies (e.g. solar PV, wind, biomass, etc.)

b. Other renewable energy technologies in development (e.g. tidal, new solar technology etc.)

c. Carbon capture and storage

8. **Are there other motivations beyond climate change to further develop nuclear power?**

a. Such as improving the security of supply (electricity generation)?

b. Are there regional interests, industrial, military motivations, air pollution?

Appendix B: Policy detail

This appendix gives further detail on the policies listed in table 10 (section 2.3.3), the 'enabling policies' for the development of new nuclear power in the UK.

Energy policy review (2006) and 'Meeting the energy challenge' white paper (2008): The energy policy review in 2006, and the subsequent white paper 'our nuclear future', reversed the government's previous opposition to building new nuclear power stations. The review contained many measures to remove barriers and obstacles to nuclear new-build, in particular in the energy market and in planning legislation; these are outlined in more detail below.

Nuclear Industrial Strategy (2013): This strategy, and its supporting documents, sets out the government's proposals to assist industry in building a 'fleet' of 16GW of new nuclear generation capacity and to ensure that the UK nuclear sector is competitive in the global market. It also sets out plans for significant public spending on education, training and R&D.

Generic Design Assessment (GDA) process: This was one of the facilitating measures introduced in the 2008 White Paper. The GDA ensures that the regulators are equipped to pre-license designs for new build proposals, thus streamlining the design process. The process is operated by the ONR (see below).

Creation of the ONR: The ONR (Office for Nuclear Regulation) is responsible for regulating the nuclear industry and running the GDA process; it is a statutory corporation, which charges fees to the nuclear industry. It was created following the 2008 White Paper; the legislation to establish the ONR is part of the Energy Act 2013 (see below).

Creation of the NDA: The NDA (Nuclear Decommissioning Authority) is a non-departmental public body, which delivers the decommissioning and clean-up of the UK's nuclear legacy. It was set up in the 2004 Energy Act. The NDA also owns the Sellafield site, and funds a large amount of research across the UK's nuclear estate.

Electricity Market Reform (EMR): EMR was designed to reform the UK's electricity market in order to help the market deliver the government's goal of 'secure, affordable, low-carbon' electricity supply. It was set up as part of the Energy Act 2013 (see below). The four policy instruments contained within EMR are explained in section 2.2.1 of this report. Of particular importance for nuclear power are the Contracts-for-Difference, under which new nuclear plants can bid for feed-in type subsidies, and the Capacity Mechanism, which offers existing nuclear plants a payment for providing reliable generation capacity at peak times.

Energy Act 2013: The Energy Act 2013, and its precursor the 2011 Electricity White Paper, explained that current market mechanisms were not sufficient to deliver secure, affordable and low-carbon energy. The Energy Act legislated for EMR.

National Policy Statements for Energy: The NPS (National Policy Statements) provide guidelines which the Infrastructure Planning Commission must consider when making decisions on planning applications for 'nationally significant' energy projects. EN-6 is the NPS for nuclear power, and states that: "given the urgent need to decarbonise our electricity supply and enhance the UK's energy security and diversity of supply, the Government believes that new nuclear power stations need to be developed significantly earlier than the end of 2025."

Climate Change Act 2008: This is the UK's unilateral, legally-binding carbon reduction target, which requires an 80% reduction of UK GHG emissions by 2050 compared to 1990 levels. As part of this, the UK Climate Change Committee sets interim carbon budgets, which the government can either accept or reject (although the government has never thus far rejected a recommended carbon budget).

EU Emissions Trading Scheme (ETS): This is an EU-wide cap-and-trade system for emissions reduction, which has been in operation in the EU since 2005. It operates in 31 countries (the EU-28 plus Norway, Iceland and Lichtenstein), and covers more than 11,000 energy-intensive installations (e.g. power plants and industrial sites), accounting for about 45% of the EU's total GHG emissions. The Energy Policy Review 2006 (see above) set out plans to work towards reforming the ETS in order to make it more effective; Phase 3 of the ETS (2013-2020) has removed the free allocation of emissions permits, and introduced a single EU-wide emissions cap. This has assisted the nuclear power sector by making it more expensive for carbon-intensive power plants.

Planning reform: The reform of the Planning laws from about 2011 onwards included the setting up of the NPS (see above). Effectively, the planning reform removed the need for a public enquiry when deciding on planning applications for new nuclear power plants. The planning law was also reformed in order that EDF could begin pre-construction work on the Hinkley C site before the project had been given final approval.

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