

A Review of Research Relevant to New Build Nuclear Power Plants in the UK

Including new estimates of the CO₂ implications of gas generating capacity as an alternative

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All views contained within are attributable to the authors and do not necessarily reflect those of researchers within the wider Tyndall Centre, University of Manchester, University of Sussex, Friends of the Earth or the report's reviewers.

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2 Introduction

This report has been commissioned by Friends of the Earth England Wales and Northern Ireland (FoE) to independently review evidence on key issues relating to the potential new fleet of nuclear power stations that may be built in the UK over the period 2017 to 2030. The report draws primarily on peer-reviewed academic literature although this is supplemented with “grey” literature from credible government, consultancy and policy sources. It is not an exhaustive review of all the issues and writing concerning civil nuclear power but has a specific scope outlined below (see Annex 1 for full Terms of Reference).

2.1 Structure

Nuclear power is quite unlike both fossil fuels and renewable sources of electricity generation with a particular set of characteristics that may be beneficial or problematic. The main purpose of this report is to provide a succinct appraisal of key issues relevant to the plans for a new generation of reactors in the UK, namely:

- safety
- radioactive waste disposal
- proliferation of nuclear weapons
- economics of nuclear power
- siting and planning of low carbon generation
- employment
- issues in managing a low carbon grid
- interactions between nuclear power and other low carbon technologies

These issues are presented in separate sections as reviews of existing primary research and not as new research findings. The penultimate section, Chapter 11, presents new work by Tyndall Manchester on the carbon dioxide emissions implications of using gas rather than building a new series of nuclear power stations. We calculate the emissions output if the shortfall in electricity generation were to be met by the use of combined cycle gas turbines (CCGT). Alternative renewable energy sources are not considered as their direct emissions are negligible and similar to those from nuclear stations. A range of scenarios is presented for different combinations of rates and extent of nuclear construction and the availability and performance of carbon capture and storage technology.

This report is intended for detailed consideration by the staff and members of Friends of the Earth and does not include an executive summary. Direct recommendations as to the appropriateness of a new fleet of nuclear stations in the UK have not been made by the authors. It is also important to note that some key aspects are highly contextual and contingent upon future circumstance.

2.2 Scope

There are a number of related issues that are outside of the scope of this report. Firstly, in relation to a new build nuclear programme, we do not consider plant designs other than the Westinghouse AP-1000 and the Areva EPR. These were the only reactor designs undergoing generic design assessment (GDA) for possible deployment in the UK at the time of this report being commissioned.

Both are variations on the pressurised water reactor (PWR) design concept. Life extensions to existing plants, the longer-term development of Generation IV reactor designs (e.g. fast breeders such as GE-Hitachi Prism) and alternative fuel cycles, such as thorium, may be included in other subsequent pieces of work, but are not directly investigated in this report. Some reference is made to the ABWR design proposed by Hitachi, however, the announcement of this reactor in the UK market was made too late in the preparation of this report to investigate in depth.

Secondly, only nuclear power for grid electricity is considered. Although nuclear plant may be technically able to act as an energy source for shipping, domestic heating and to provide heat for industrial processes (either directly or through combined heat and power (CHP) systems), these uses have not been identified by the UK Government as priority areas and, in the current policy environment, are unlikely to be deployed to a significant extent over the time period of interest.

Thirdly, other than in the specific questions examined in Chapters 11 & 12, climate change and emissions budgets are not explicitly considered. The analysis developed here is premised explicitly on the level of emission reductions and electrification outlined by the respective scenarios. The approach and conclusions, whilst potentially of wider significance, nevertheless are for this particular framing of electricity within the UK energy system.¹ If mitigation were aligned with the UK's international obligations under the Copenhagen Accord and Cancun agreement (i.e. to hold below 2°C, with the UK's budget founded on science and equity) the rate and urgency of reductions would be markedly higher (Anderson and Bows, 2011), as discussed in Chapter 12.

Finally, emphasis is placed on the implications for, and evidence from, the UK. As such, international precedents, other national circumstances and research not specific to the UK are considered only where there is no alternative source or where a directly transferable point is made.

2.3 Research methodology

The research presented is a “desk based” critical examination of published material, supplemented with personal communications with researchers where required. All sources are fully referenced. Key word searches in science citation databases (Scopus and Web of Knowledge) identified candidate literature that was then screened for relevance to UK proposals.

A workshop was held at the Friends of the Earth local groups' conference in September 2012 where the process and scope was outlined and participants were invited to identify issues of key concern and relevant sources of evidence. Notification of the research was sent out to nuclear power campaigners and posted on the FoE local group members' intranet with details of an email address to send material for consideration. The authors are grateful to all those who took the time to submit information. Although we have not cited all references supplied they have all been considered. We did not enter into discussion or individual correspondence with any contributors.

Where possible we have tried to provide a concluding paragraph to each section outlining the consensus position in the literature. However, in some cases we have found that no clear conclusion

¹ Whilst we have reservations as to the adequacy of these UK Government targets in avoiding dangerous climate change associated with a 2°C temperature rise, reasons for which are discussed in Anderson and Bows (2011), we take the targets as given to maintain consistency with other UK Government proposals.

could be drawn, where empirical research is not available or evidence contradictory or ambiguous, and from which no consensus emerged.

The final report has been peer-reviewed by two external academics identified by the Tyndall Centre research team; Malcolm Grimston of Imperial College London and Dr Paul Dorfman of Warwick Business School. Their comments and the authors' responses to them have been provided to FoE. The reviewers' participation should not be interpreted as their endorsing or otherwise commending the contents of the report.

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3 Safety

Safety is a key issue for nuclear power technology, with the 2011 disaster at Fukushima Daiichi in Japan recently highlighting some of the potential risks. Concern over radioactive materials released by nuclear reactors, in both operation and in the event of a major containment breach, is central to discussions of a new build programme. The safety of new build reactors is discussed, in terms of the likelihood of a nuclear accident, followed by a literature review of human health impacts associated with ionising radiation from nuclear facilities.

3.1 Reactor safety

Improvements in safety have been a key focus for the nuclear industry between the previous stage of reactor design (Generation II) and the proposed reactor iteration (Generation III) such as the EPR, the AP-1000 and the ABWR. This has primarily been driven by increased scrutiny from national nuclear regulators prompted by two² key nuclear events (Butler and McGlynn 2006; Suzuki 2011):

- Three Mile Island, USA (1979). Technical failure, compounded by human error led to a partial core meltdown at one of the Three Mile Island facility reactors (reactor 2). There was a containment breach, although public health risks were minimal. The Three Mile Island site continues to generate electricity, although reactor 2 has been permanently defueled. Of the reactors that have been involved in nuclear accidents, this PWR reactor design is the closest in terms of design concept to the EPR and AP-1000 types planned for the UK.
- Chernobyl, Ukraine (1986). Human error and reactor design (graphite core moderator and light water coolant) were implicated in an accident that led to a loss of reactor containment. An explosion (caused by pressure build up in the containment vessel) and fire at the facility lead to widespread fallout of radionuclides into water and land at a continental scale. Light water reactors (EPR, AP-1000 and ABWR) do not have the same design characteristic that produced the destructive power surge (a positive void coefficient in the core) from the reactor.

The response to these events was a ratcheting up of regulation and an increased requirement on reactor vendors to demonstrate safety protocols to meet regulatory requirements (Butler and McGlynn 2006). Identified risks and mitigation measures include:

- Passive Residual Heat Removal. The AP-1000 and ABWR designs have secondary cooling systems that are gravity driven and pressure activated. Water storage tanks above the reactor core provide cooling in response to a change in core pressure caused by a primary cooling failure, with inner containment water storage tanks near the bottom of the structure acting as a heat sink (Sato and Kojima 2007; Sutharshan, Mutyala et al. 2010). A reduced reliance on mechanical equipment should avoid the risks of mechanical failures and requirement for operator intervention within the first 72 hours of a shutdown (Sato and Kojima 2007).

² The Windscale reactor fire in 1957, although a significant nuclear accident did not prompt as noticeable a change in nuclear regulation.

- Back-up (Redundant) Cooling: The EPR has five self contained and sealed back up cooling systems to meet core cooling safety requirements (Weightman 2011).
- Focus on human factors to avoid human error. Sovacool (2011) highlights numerous (2,400) incidents since the 1950s where human error or technical failures have forced safety shutdowns. There has been a significant move to design out the potential human error impacts on reactor operation (Reed and Shaffer 2008; Lee, Hwang et al. 2009; Song and Zhang 2010; Papin 2011).
- Improved resistance to core melt impacts: The EPR includes a core capture systems which is in effect a large concrete basin (Areva 2012). The alternative employed by AP-1000 and ABWR reactors is enhanced water cooling capacity to prevent core melt (Sutharshan, Mutyala et al. 2010; Weightman 2011).
- Hydrogen Control: It appears likely that a build up of hydrogen gas, produced by steam interacting with the zirconium cladding of the nuclear fuel at high temperatures (1000°C) led to explosions in three of the Fukushima Daiichi reactor units (Weightman 2011). The three reactor designs considered for the UK have design features that specifically address hydrogen explosion risks. The AP1000 has hydrogen igniters to prevent a build up of gas within the containment structure. In the EPR UK design, catalytic convertors are used to remove hydrogen. The ABWR design uses nitrogen inside the containment structure to make hydrogen inert and prevent an explosion (Sato and Kojima 2007).

Generation III reactors are also required to demonstrate resilience to aircraft impacts within the UK Generic Design Assessment (GDA) (Health and Safety Executive 2009; Office for Nuclear Regulation 2011). Reactor outer containment walls should be able to withstand the impact of a large commercial airliner, a subsequent high intensity fire from burning aviation fuel and the vibrations caused by the impact (Frano and Forasassi 2011). 3D modelling of modern outer containment walls show that with the correct thickness they can withstand impact from a Boeing 747 and be resilient to a subsequent fire caused by such a crash (Frano and Forasassi 2011; Jeon, Jin et al. 2012). Similar 3D modelling shows that damage caused to components within the nuclear reactor can be avoided through the design of the reactors foundation to allow vibrations to dissipate (Petrangeli 2010).

The above enhanced safety features are required to meet the criteria set out by the GDA that assesses new reactor designs against different risk probabilities (Bredimas and Nuttall 2008). The Office for Nuclear Regulation implement the GDA and Safety Assessment Principles on the basis of an 'as low as reasonably practicable' (ALARP) approach to risk (Health and Safety Executive 2006). To progress through the GDA, reactor developers must be able to show they have design features that meet assessment standards; the ONR does not prescribe how they should do this but tests whether design issues are met by amendments (Weightman 2011). A Design Basis Analysis (DBA) process investigates the effectiveness of reactor safety measures to withstand faults and extreme events. Probabilistic Safety Analysis (PSA) modelling from DBA is used to assess whether the overall reactor design represents a low risk. For instance, reactor developers, such as Westinghouse claim that the frequency of a core melt is 4.2×10^{-7} /year, implying event occurrence once every 42 million years. Probabilistic approaches to reviewing nuclear reactor safety have however been criticised; Ramana (2009) summarises these critiques. Pertinently, it is argued that such abstract models are unhelpful and do not account for events or 'cascades' of events outside of the model's parameters, such as the tsunami and earthquake that hit Fukushima Daiichi (Dorfman, Fucic et al. 2013).

Further reviews of nuclear safety have followed the Fukushima Daiichi nuclear disaster in Japan 2011. Containment was breached at three reactors on the Fukushima Daiichi nuclear site in Japan as the result of a large tsunami destroying the operator's ability to control reactor core temperatures.³ The core meltdowns and an explosion in one of the reactor containment vessels released radionuclides into the air and water, leading to land contamination.⁴ This led to mass evacuations within 25km of the reactor, displacing around 100,000 people.⁵ In this case, contamination of marine life in coastal areas near Fukushima appears to be the most pronounced effected within 18 months of the event, with high dose and increased mortality for marine life expected (Brumfiel 2012).

As a result of the Fukushima nuclear disaster, the UK Health and Safety Executive has reviewed nuclear safety and published several recommendations. This HSE report by Weightman (2011) is broadly confident that new build reactors have sufficiently high safety features and that the probability of extreme environmental risks (e.g. a factor 9 earthquake and a tsunami) in the UK is low. A key aspect of the failure to maintain core temperature within safe limits was damage to the auxiliary diesel generators required to drive cooling circulation after loss of power. The Fukushima Daiichi reactors are Generation II, built in the 1970s. This is an issue Generation III cooling systems are much less susceptible to (Suzuki 2011; Weightman 2011). Weightman (2011) also points that the tsunami event that led to the nuclear disaster was outside the DBA used by the Japanese regulator. The report recommends improved disaster response protocols, organisation and a transparent and communicative regulator (Weightman 2011).

3.2 Nuclear power and ionising radiation

This sub-section considers the peer reviewed epidemiological literature from the past ten years on nuclear safety and ionising radiation. The principal focus is on low dose radiation (<1000mSv) which is of particular interest for health studies of nuclear power. The levels of radiation associated with nuclear power operation and radiation exposure beyond reactor sites following a nuclear accident typically fall into this category (Brenner, Doll et al. 2003). The human health impacts relating to such exposure has however so far proved difficult to disaggregate from other sources of radiation and causes of cancers, making issues such as whether there is 'safe dose threshold' contested (Brenner, Doll et al. 2003)

Doses of radiation can be received by absorption through skin and eyes, through ingestion of foods and liquids contaminated by radionuclides, and through inhalation. Radiation effects include severe, potentially fatal sickness and nausea at high doses and a range of cancers, of which there may be a risk even at lower doses. Effects vary based on the age of the person when the dose is absorbed, under 18 year olds may be more susceptible, the organs effected, for instance the thyroid is particularly sensitive, as well as the level and duration of exposure. Radiation levels absorbed by organisms are measured in Grays (Gy). As radiation types and their effects differ between sources,

³ See IAEA, (2012), *One Year On: The Fukushima Nuclear Accident and its Aftermath*, Available at: <http://www.iaea.org/newscenter/news/2012/fukushima1yearon.html> (Accessed July 2012).

⁴ *Ibid*

⁵ *Ibid*

the effective dose, which accounts for the biological impact of radiation exposure and is measured in Sieverts (Sv), is frequently used to compare human radiation doses. Because a Sievert is a large dose, millisieverts mSv (one thousandth of Sv) are typically used to measure the health risks from radiation exposure from a range of sources including CT scans, aeroplane travel and smoking.

The average individual's effective dose from natural background radiation is 2.4 to 6mSv/yr, largely dependent upon the altitude of day to day residence. The maximum advised annual dose for nuclear workers is 50mSv/yr (ICRP 2007) and the annual dose received from smoking 20 cigarettes per day is 80-90mSv/yr (Zaga, Lygidakis et al. 2011). The World Health Organisation estimates the effective dose in the high exposure, evacuated areas in Fukushima Prefecture as 10 to 50mSv/yr and 1 to 10mSv/yr in the rest of the Prefecture (WHO 2012). People living in and relocated from areas affected by the Fukushima disaster have so far been found to have received very low doses that make health impacts difficult to detect according to two preliminary reports by the WHO and the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) (Brumfiel 2012).

3.2.1 Radiation dose and safety

The lack of certainty about health risks from low dose radiation has prompted the linear no-threshold (LNT) model of radiation risk. LNT assumes that any dose of radiation may be harmful to humans and that there is no 'safe' dose of radiation (Martin 2005). This approach has informed regulatory approaches to the nuclear sector, but is contested. Reports by the International Commission on Radiological Protection (ICRP 2007), the US National Academies' Biological Effects of Ionizing Radiation (BEIR VII) (National Research Council 2006) and the French Academies of Science and Medicine (Tubiana, Aurengo et al. 2006) have reviewed biological epidemiological data to explore this issue, including radiation doses caused by the Hiroshima and Nagasaki nuclear bombs. The reports however differ in their conclusions about the safety implications of low dose radiation. The BEIR VII report suggests that the risks of developing cancer from low radiation doses is small, however it does support the LNT approach, concluding that;

"current scientific evidence is consistent with the hypothesis that there is a linear, no-threshold dose-response relationship between exposure to ionizing radiation and the development of cancer in humans (National Research Council 2006)."

The ICRP (2007) report that there is still not sufficient evidence to support a *universal* threshold for safe radiation doses, which they consider a requirement for instituting policy. As with the BEIR VII it upholds the LNT approach on the basis of precaution. This perspective does not conclude that nuclear power is unsafe, but that risks should be acknowledged and there should be limits for planned exposure, for example for nuclear power plant workers. They advocate 'optimisation of protection' whereby "individual dose should be kept as low as economically and socially possible (ICRP 2007, p. 14)." This is similar to the UK Health and Safety Executive's 'as low as reasonably practicable' (ALARP) approach which underlies UK nuclear regulation.⁶

In contrast the French Academies of Science and Medicine, summarised in Tubiana, Aurengo et al. (2006) suggest that the extrapolations used to assess low dose impacts (drawn from impacts at

⁶ HSE (2012), *ALARP at a Glance*, Available at: <http://www.hse.gov.uk/risk/theory/alarpglance.htm> (Accessed 03/11/2012).

doses that can be observed more readily) are flawed and lead to an overestimation of low dose risks. Tubiana, Aurengo et al. (2006) use the French Academies findings to contend that overestimation of dose risk from the LNT approach leads to negative consequences driven by insufficiently substantiated fear of low doses radiation, such as unnecessary displacement of populations in areas with very low doses. They also suggest that the fear of radiation framed around the LNT may itself lead to physical and mental health impacts that are greater than the effects of the radiation itself (Tubiana, Aurengo et al. 2006).

Recent publications have suggested that the LNT model overestimates low dose radiation risks, for instance as argued in Mobbs, Muirhead et al. (2012), Siegel and Stabin (2012) and Harbron (2012). They do not however provide research that clarifies the impact of low dose radiation on human health and Brenner and Sachs (2006) and Martin (2005) contend that there is not strong enough evidence about the safety of low dose radiation to abandon tight regulation premised on LNT.

3.2.2 Health risks from nuclear sites

In their review of the human health impacts of the nuclear lifecycle, Markandya and Wilkinson (2007) state that occupational deaths attributed to the nuclear industry, relative to its size, are very low, particularly in comparison with coal and natural gas. As a significant proportion of health impacts for coal and gas are upstream (extraction, processing etc), electricity generated by carbon capture and storage (CCS) plants was found to have greater lifecycle health impacts than from nuclear plants, with the additional fuel required to run capture equipment likely to offset the benefits from reduced local air pollutants (Markandya and Wilkinson 2007). They conclude, in relation to nuclear power, that the “numbers of deaths through cancer, severe hereditary effects, and non-fatal cancers caused by normal operations are extremely small (Markandya and Wilkinson 2007, p.982).”

This perspective is also reflected in the SPRIng Nuclear Sustainability report into a new UK nuclear programme, which concluded that; “*Even when the radiological consequences of a large accident are taken into account, nuclear power remains one of the safest sources of electricity*” (Azapagic, Grimston et al. 2011, p.19). This report goes on to conclude that when full lifecycle health impacts are considered per MWh of generated electricity, nuclear compares favourably with renewable energy technology (Azapagic, Grimston et al. 2011). The exception to this is solar PV, which on a health impacts per MWh basis performs worse than other renewables and nuclear, although it is still significantly ‘safer’ than coal and gas (Markandya and Wilkinson 2007; Azapagic, Grimston et al. 2011). This is largely due to mineral input and the manufacturing process, coupled with the low efficiency per-cell of previous PV technologies. If PV efficiency improves it should perform better in this indicator.

The human health safety implications of living near to a nuclear facility have primarily focused on incidences of childhood leukaemia. This followed the reporting of statistically significant clusters of childhood leukaemia cases around the Sellafield and Dounreay nuclear reprocessing sites in the UK, similar facilities in France and the Krummel nuclear power plant in Germany (Kinlen 2011).

In Germany, the Federal Office for Radiation Protection (BfS) *Kinderkrebs in der Umgebung von Kernkraftwerken (KiKK)* study reported a statistically significant increase in childhood leukaemia

within 5km of nuclear power plants in Germany, although radiation doses for areas studied were found to be too small to explain the findings (Kaatsch, Spix et al. 2008).

Reviews of UK nuclear power stations however have not found evidence of elevated cancer incidents around UK nuclear power stations (Committee on Medical Aspects of Radiation in the Environment 2011; Kinlen 2011). The same findings were reported for French nuclear power stations in White-Koning, Hemon et al. (2004) and for Finish nuclear power plants in Heinavaara, Toikkanen et al. (2010). The elevated cases of childhood Leukaemia near Sellafield and Dounreay may be related to the reprocessing activities that distinguish these sites from other nuclear sites in the UK. However, Kinlen (2011) and the Committee on Medical Aspects of Radiation in the Environment (2011) both report that past leaks of radioactive material from Sellafield and Dounreay do not correlate with leukaemia cases. Kinlen states that; “although initially seen by some as an obvious explanation, radioactive discharges have not been implicated in any CL [childhood leukaemia] excess near a nuclear site (Kinlen 2011).” Sermage-Faure, Laurier et al. (2012) suggest further study is needed on cancer incidences near nuclear power plants, but concluded from their own study of French nuclear sites that “the absence of any association [of leukaemia] with the DBGZ [dose-based geographic zoning] may indicate that the association is not explained by NPP gaseous discharges.” This study also recommends further research in this area. In a meta-analysis of childhood leukaemia studies around nuclear facilities, Baker and Hoel (2007) found that although in a number of cases there were statistically significant higher rates of leukaemia there was not sufficient evidence for a causal link to the radiation from nuclear facilities. They note that in several studies which compared childhood leukaemia rates from before the construction of nuclear facility that “rates generally remained unchanged before and after start-up [of a nuclear reactor], even in regions with elevated rates (Baker and Hoel 2007, p. 362)”

3.2.3 Health risks for nuclear workers

The health implications specifically related to nuclear reactor operation can prove difficult to differentiate from ‘background’ health issues, particularly certain forms of cancer. A US study by Kubale, Hiratzka et al. (2008), a British study by McGeoghegan, Binks et al. (2008), a French study by Guseva Canu, Garsi et al. (2012) and a German study by Kindler, Roser et al. (2006) were examined to review the human health impacts of long-term radiation exposure. The studies focus on nuclear power plant and research workers who are in close proximity to reactors on a daily basis. In these cases the incidences of a majority of cancers and autoimmune thyroid disease were not statistically significant. Furthermore McGeoghegan, Binks et al. (2008) reported that socio-economic factors had a greater impact on employee health than radiation dose in their study sample. However, the following increased incidences of disease in workers were observed that could be attributed to reactor operation:

- A statistically significant increase in multiple myeloma deaths in female employees at a US nuclear research laboratory (Kubale, Hiratzka et al. 2008).
- Significant elevation in leukaemia in employees serving for over 20 years (Kubale, Hiratzka et al. 2008).
- Preliminary findings that suggest that there may be a link between radiation dose and incidence of circulatory disease, however, cause isolation is difficult with this type of health impact (Guseva Canu, Garsi et al. 2012).

- Some evidence of higher incidence of elevated serum thyrotropin, which can be an indicator of thyroid problems (Kindler, Roser et al. 2006).

As with the other aspects of nuclear power health impacts, the incidences of harm to workers can be difficult to detect. As discussed in Azapagic, Grimston et al. (2011) and Markandya and Wilkinson (2007), potential health risks should be considered in relation to risks in other industry sectors that may be higher.

3.2.4 Health risks from nuclear accidents

Failures in nuclear reactor containment can lead to widespread radioactive contamination, such as at Chernobyl in 1986 and Fukushima in 2011. Power station workers and emergency responders may be exposed to very high doses of radiation. In the case of Chernobyl high radiation exposure led to severe radiation sickness in 134 workers, resulting in 28 directly attributable deaths from high radiation doses (Hatch, Ron et al. 2005).⁷ Zablotska, Bazyka et al. (2012) found “significant associations between protracted radiation exposure at low doses and leukaemia incidence (p.14)” in Ukrainian Chernobyl clean-up workers (of 137 cases of leukaemia identified from the cleanup worker sample, 16% attributed to radiation exposure from Chernobyl site). As of November 2012 no deaths have been attributed to radiation exposure from the Fukushima emergency response and cleanup.

The level radiation exposure of the public after disasters such as Chernobyl (Hatch, Ron et al. 2005) and Fukushima (WHO 2012) and for nuclear power station workers fall into the low dose (<100mSv) category (Brenner, Doll et al. 2003). However, according to Moysich, McCarthy et al. (2012), the quantifiable safety risks of a nuclear accident for human health remain unclear. An example of this is the assessment of human health impacts of the Chernobyl disaster on the populations of Ukraine, Belarus and Russia through a number of epidemiological studies over twenty years. Incidences of thyroid cancer, particularly in children, are the most conspicuous indicator of radiation health impacts (Hatch, Ron et al. 2005; Higson 2010). Successive epidemiology studies of the Chernobyl disaster show elevated thyroid cancer incidents, yet, because of its high treatability, it does not contribute greatly to deaths or lower life expectancy indicators (Higson 2010). The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR 2011) concluded that so far there had been 15 fatalities from the 6,000 cases of thyroid cancer that are assumed to predominantly relate to childhood (pre-18years old) radiation doses in the areas affected by Chernobyl. Another health implication is an increased likelihood of leukaemia and bone marrow disease, particularly in children, however there is not currently sufficient evidence to suggest an increase against the baseline in studies of areas affected by Chernobyl (Hatch, Ron et al. 2005; Cardis, Howe et al. 2006; UNSCEAR 2011).

Cardis, Howe et al. (2006) suggest that even twenty years following the Chernobyl accident it remains too early to evaluate the full human health impact of the incident (Cardis, Howe et al. 2006). However, epidemiological studies of the populations in areas affected by the accident so far suggest “no clearly demonstrated radiation-related increases in cancer risk” apart from thyroid cancer (Cardis, Howe et al. 2006, p.127).

⁷ Health impacts from lower radiation doses experienced by clean up works is discussed later in this section.

3.2.5 Mental health impacts of nuclear accidents

The mental health impacts of the Chernobyl nuclear accident are considered by the Chernobyl Forum to be most significant public health consequence for residents in affected areas (The Chernobyl Forum 2005). Incidences of post-traumatic stress, anxiety, depression and 'unexplained physical symptoms' were twice, and for some conditions 3-4 times higher for exposed populations than for control groups studied (The Chernobyl Forum 2005). The fear of the effects on health from radiation exposure and the trauma of rapid relocation and loss of social contacts were considered particularly significant. Feelings of helplessness and fatalism related to exposure and perceived health impacts by groups in the study were noted. This is supported by studies such as Loganovsky, Havenaar et al. (2008) and Bromet, Havenaar et al. (2011) looking at the long term mental health effects on Chernobyl clean-up workers and first responders that identified higher incidences of anxiety, depression and low regard of own health.

Initial studies of the mental health impacts of the Fukushima disaster suggest elevated incidences of post-traumatic stress, anxiety and depression in clean-up workers and first responders to the reactor site (Matsuoka, Nishi et al. 2012; Yasumura, Hosoya et al. 2012). In addition to fear of health impacts from exposure and stress from the work involved, social stigma of working for the nuclear company who own the site and discrimination as a consequence has been suggested as heightening mental health impacts (Matsuoka, Nishi et al. 2012; Shigemura, Tanigawa et al. 2012). Matsuoka, Nishi et al. (2012) found a statistically significant elevation in psychological impacts for male clean-up workers in their study. Vazquez, Jordan et al. (2010) suggests that 'radio-nuclear emergencies' produces psychological traumatic stress and that those not directly affected by radiation can also suffer from mental health problems attributed to an accident. This article postulates that the inability of humans to sense (by sight, smell, sound, taste or touch) radiation, particularly at low and medium dose levels is a key factor (Vazquez, Jordan et al. 2010).

3.3 Nuclear safety and climate change adaption

As with all infrastructure, nuclear power stations will need to be resilient to potential changes in the UK's climate as global temperatures rise. The impacts of sea level rise and coastal erosion need to be accounted for given the location of proposed new build nuclear sites. Assessments of the resilience of nuclear and other thermal power stations have focused on European and US contexts, predominantly with inland power stations. Studies including Rubbelke and Vogeles (2011), Kopytko and Perkins (2011) and Van Vliet, Yearsley et al. (2012) assess the impact of heat waves and droughts on power stations cooled by lakes and rivers. Fewer studies are relevant to the UK case, where nuclear stations are typically located on the coast. For UK new build reactors, the key climate change impacts affecting safety relate to their coastal locations and include sea level rise, coastal erosion and storm surges (Wilby, Nicholls et al. 2011). Wilby, Nicholls et al. (2011) explored the impact on UK nuclear sites in an 'upper-end' climate change adaptation scenario (8°C global mean temperature rise by 2200), with localised sea-level rises up to 3.3 metres. This study suggests limited impacts on the operation of a nuclear power station during the early/mid 21st Century as a result of design features already being incorporated at developments such as Hinkley Point C. These impacts include an increase in fouling from a changing marine environment and more frequent storms that may impair operation and increase maintenance and operational costs (Wilby, Nicholls et al. 2011). It does however suggest that, in the longer term, potentially more abrupt climate changes may occur

towards the end of the century, and these could compromise decommissioning where stability of the reactor site for around 100 years post operation is necessary (Wilby, Nicholls et al. 2011). The report concludes that with sufficient monitoring and a flexible approach to coastal defence, extreme climate change impacts would not necessarily compromise new build reactor safety during the 21st Century (Wilby, Nicholls et al. 2011). Further research is required to increase the evidence base for climate change affects for all infrastructure including nuclear power stations.

3.4 Summary

Safety is a central concern in debates about the future of nuclear power in the UK. Accidents at Three Mile Island (1979) and Chernobyl (1986) have led to more stringent safety requirements from regulators and improvements to reactor design. These design changes in new, Generation III, reactors have included attempts to design out human error and improve resilience in the event of a reactor failure or an incident such as an aircraft crash. The Fukushima disaster in 2011, involving a Generation II reactor, led to further safety reviews. In the UK, the Health and Safety Executive concluded that the safety requirements for new reactors set out in the UK Generic Design Assessment were adequate. Nonetheless, recommendations were made on improving responses to disasters.

There are uncertainties about the effects of radiation at low doses on human health that raise issues about how safe nuclear reactors are during operation, what the risks of a loss of radiation containment are and what the impacts of this would be. The health impacts of nuclear accidents are hard to determine with any certainty. The consequences for site workers exposed to high doses of radiation may be relatively clear but low dose impacts are harder to identify conclusively. Evidence from the aftermath of the Chernobyl disaster shows an increase in thyroid cancer in the area although mental health disorders are thought to be a significant public health consequence for evacuated residents. Evidence of other health impacts such as childhood leukaemia is currently weaker.

Studies from the UK, Finland and France on the health consequences of living close to nuclear sites, particularly on the incidence of childhood leukaemia, suggest that there is no discernible increased risk for local populations during normal reactor operations. However, it should be noted that the study by the German Federal Office Radiation Protection (BfS) Expert Review Group found higher rates of childhood leukaemia in the vicinity of German nuclear facilities, although without a causal link to radiation.

Overall the safety risks associated with nuclear power appear to be more in line with lifecycle impacts from renewable energy technologies, and significantly lower than for coal and natural gas per MWh of supplied energy.

Climate change does not appear to present a severe risk to the safety of reactors on the UK's coasts. However, in the long-term, changes to sea level, erosion rates and storm surges may have implications for site stability, particularly during decommissioning phases. More research in this area is required.

4 Radioactive waste management

4.1 *Radioactive waste from nuclear power*

There are several sources of radioactive waste, including waste materials produced by military and medical equipment and naturally occurring radioactive materials (NORM) from industries such as hydrocarbon extraction, coal power stations and fertiliser production (McGinnes, Alexander et al. 2007). The largest contributor to the UK's radioactive waste inventory, both in terms of volume and radioactivity, is the nuclear power sector (Chapman and Hooper 2012; MacKerron 2012). Radioactive waste is produced at each stage of the nuclear cycle. In addition to the waste produced by nuclear reactors and ancillary equipment that are included in national waste inventories, there are also radioactive waste products from uranium mining and nuclear fuel fabrication.

4.1.1 Waste from mining and milling

A 1GWe light water reactor's fuel requirements may be expected to produce between 43,000 and 48,000 tonnes of waste uranium 'tailings' following mining and milling per year (McGinnes, Alexander et al. 2007). Tailings are radioactive and contain heavy metals that require monitoring and management (Vandenhove, Sweeck et al. 2006; Voitsekhovitch, Soroka et al. 2006; McGinnes, Alexander et al. 2007; Tripathi, Sahoo et al. 2008). According to McGinnes, Alexander et al. (2007) burial at the mining site with continued monitoring is the preferred management option for this waste. The environmental and human health impacts from this appear to vary by mine location and may be susceptible to changes over time. The Tripathi, Sahoo et al. (2008) study of uranium mining in India showed no ground water contamination and 'marginal impacts' on the local environment from the effluent treatment plant used to decontaminate land and materials. A similar study of uranium mining in Kyrgyzstan assessed the impact of uranium and radon leaching from mine tailings on a local river and surrounding land (Vandenhove, Sweeck et al. 2006). Although the concentration of radionuclides and heavy metals measured were considered still with safe limits, the study highlighted a potential risk of dangerous contamination for local populations if an unexpected event accelerated leaching (Vandenhove, Sweeck et al. 2006). A study by Voitsekhovitch, Soroka et al. (2006) on the environmental impacts of uranium mining on the Dniper river illustrates how poor mining practice can lead to additional contamination and a build up of radionuclides in the local environment over long periods of time. It finds however that the total radiological human health and environmental impacts are low.

The main findings from the studies cited above are that uranium mine tailings do not necessarily have a significant human or environmental impact in the short-term, but that this requires continued monitoring to gauge the effects of long-term build ups of heavy metals and radionuclides. Localised contamination may also be anticipated from other mining operations necessary for energy generation such as for iron and aluminium ores, and indeed fossil fuels themselves, although this is not assessed here.

4.1.2 Radioactive waste products from nuclear power stations

Radioactive waste arises throughout reactor operation and decommissioning. It comprises various materials with differing levels of radioactive contamination, including reactor components and worker clothing as well as liquids that are contaminated by cleaning and cooling processes. The UK

also has radioactive waste emanating from fuel reprocessing, specifically the fission products and transuranic elements separated out from the uranium and plutonium in spent fuel. In the UK radioactive waste has three groupings (McGinnes, Alexander et al. 2007):

- Low level waste (LLW): Irradiated waste up to 4000 Bq/g alpha radiation and 12,000 Bq/g of beta and gamma radiation (McGinnes, Alexander et al. 2007). This is a category that encompasses a wide range of materials that have been irradiated at some stage in the nuclear cycle including clothing and building materials. Previously this waste has been buried in backfilled trenches at Dounreay in Scotland and the LLW repository at Drigg in Cumbria (NDA 2010). The current model for managing LLW is to segregate out metals suitable for recycling and other materials permitted for landfill before super compaction of remaining waste in metal drums (NDA 2010).
- Intermediate level waste (ILW): Irradiated waste over the threshold for LLW but that does not generate substantial heat, defined as emitting less than 2 kW/m³ thermal energy (McGinnes, Alexander et al. 2007). Includes nuclear fuel rod cladding reactor core materials and sludges 'from the treatment of radioactive liquid effluents' (NDA 2011).
- High level waste (HLW): Irradiated waste over the threshold of LLW that generates heat. Includes nitric acid solutions from spent fuel recycling (NDA 2011).

In addition to materials that are classified as waste, the UK also has a large stockpile of plutonium and uranium from reprocessed spent fuel. Further, because of the reprocessing approach, spent fuel (SF) is not classified as radioactive waste in pre-2010 inventories because it was seen as a potential resource. This has changed because of a shift from 'closed' fuel cycle to a 'once-through' cycle where SF is treated as waste. The Birmingham Policy Commission (2012) state that AP-1000 and EPRs can use MOX fuel (although a regulator review would be needed first), and remaining plutonium could be used in this way.

4.2 UK Radioactive waste policy

Radioactive waste has been a long standing issue in the UK, with successive failures of government to develop a viable policy for long-term nuclear waste management (Greenhalgh and Azapagic 2009; MacKerron 2012). MacKerron (2012) suggests that the absence of coherent policy on radioactive waste management between 1956 and 2002 has led to a costly, high volume waste legacy. The large volume of waste, relative to the scale of the UK reactor programme, stems from persisting with the graphite moderated reactor design concept (Magnox and AGRs variants) (MacKerron 2012).

Graphite core technologies are blamed for a high volume of ILW relative to lifetime reactor electricity output. The complexity of AGR designs and variations in design between reactors has meant disposal is likely to be more expensive than if a generic light water reactor design had been used (MacKerron 2012). The graphite moderated reactor cores of existing UK nuclear power stations (excluding Sizewell B) are a significant contributor to the volume of ILW in the inventory. The UK's HLW, which although small in volume (0.3% of total radioactive waste inventory), currently represents the largest proportion of radioactivity (50%) in the waste inventory (Davies 2006).

The NDA states that records of what was placed into cooling ponds during the 1940s to 1960s are incomplete, meaning the contents are not fully known (NDA 2011). This poor management of

interim storage for spent fuel and waste from early experimentation has led to increased costs (MacKerron 2012).

The committee on Radioactive Waste Management (CoRWM) was established by the Government in 2003 to address this and other radioactive waste problems. In 2006 CoRWM recommended long-term geological storage after interim storage. Sites for a Geological Disposal Facility (GDF), would be selected through 'volunteerism' in geologically suitable areas (Greenhalgh and Azapagic 2009).

The GDF concept involves storing/continuing storage of HLW in cooling 'ponds' for around 30-50 years. HLW is produced in liquid form, vitrified with borosilicate glass to take a more stable form that can be encapsulated in a steel container, and placed within a copper (or steel) 'overpack' container (McGinnes, Alexander et al. 2007; NDA 2009). Packaged waste would then be placed in a specially engineered geological 'vault' situated 200 to 1,000 metres below ground where it can be 'isolated from the biosphere' (NDA 2009).

The GDF approach is the option for HLW currently pursued by Finland, Sweden, France and the USA (Chapman and Hooper 2012). The first GDF is at an advanced planning stage for Onkalo in Finland and is estimated construction could begin in 2015.⁸ Scotland has currently opted out of this option and expressed a preference for 'near-surface, near site disposal or storage', which allows for easier monitoring and retrieval (DECC 2010). The IAEA (2003) state however that this approach cannot be used for storing HLW, including spent fuel, securely and safely, and CoRWM (Broughton 2011) have questioned how the proportion of Scottish HLW that is not suitable for this option will be dealt with.

The Birmingham Policy Commission (2012) stated that a UK GDF could be ready to start receiving ILW by 2040. However, this assumes that the outstanding issues relating to a UK GDF are resolved and a later date may be more likely. Nuclear Waste Advisory Associates highlight 101 scientific and technical issues they consider necessary to be resolved before GDF can be considered viable and safe (NWAA 2010). The NDA response to these concerns highlights that further research is needed (NDA 2011). In particular four issues appear most significant:

1. The suitability of the geological environment over long time periods: The GDF requires a geological environment that will remain stable over hundreds of millennia (NDA 2009). In particular this means a geological setting that is unlikely to be disrupted by faults or be susceptible to interaction with ground water (NDA 2009). Geological disposal has the backing of the British Geological Survey, the Royal Society and the Geological Society, suggesting a high level of confidence in the general approach although identifying a suitable geological environment is however a challenge (Powell, Waters et al. 2010). The UK, by opting for hard rock storage, may avoid the corrosion difficulties arising from rock properties encountered in Germany (Gorleben and Asse) and USA (Yucca Mountain) using salt mines as a repository (Rogers 2009; Forsberg and Dole 2011; Hueggenberg, Graf et al. 2011). Identifying suitable rock formations for a GDF also requires avoiding compromising future natural resource extraction (hydrocarbons and metals etc) that could disturb the vault

⁸ Kinnunen, T and J. Rosendahl, *Update-1 Finland expects to begin to bury nuclear waste in 2022*, Reuters (2012), Available at: <http://uk.reuters.com/article/2012/12/28/nuclear-waste-posiva-idUKL5E8NS25G20121228> (Accessed 10/01/2013).

(Powell, Waters et al. 2010) and modelling potential changes in ground water level and earthquake susceptibility (Strom, Andersson et al. 2008).

2. Radionuclide transfer and thermal output during storage: Radioactive waste, including ILW (McKinley and Takase 2010), transfers radionuclides to surrounding material over different periods of time. The transfer properties of these radionuclides, over millennium, need to be understood to ensure that the GDF provides sufficient containment. Altmann (2008), McKinley and Takase (2010) and Pentreath (2009) all express confidence in the GDF approach, but highlight knowledge gaps in the understanding of long-term radionuclide transfer and environmental interaction. Similarly studies by Sundberg, Back et al. (2009), Yang and Yeh (2009) and Min, Rutqvist et al. (2005) suggest further research is needed to fully understand how thermal transfer from HLW and SF will build up over time and affect the GDF.
3. Long-term performance of 'overpack' materials: A key concern for long-term storage is the resistance of the outer casing of packaged fuel to corrosion. Rosborg and Werme (2008) study of the long-term corrosion behaviour of copper for nuclear waste storage suggests that if 'proper environmental conditions are established and maintained' the copper casing will provide long-term containment. It does however indicate that localised corrosion from water infiltration and/or rock movement could lead to a failure and that this needs further consideration (Rosborg and Werme 2008)
4. Governance Issues of site selection: The decision by Government to adopt CoRWM's recommendations for a voluntary application of communities to host a GDF presents additional challenges. Communities are invited to volunteer to host a GDF and have the option to withdraw throughout the development process, which is likely to take decades. This requires a strong match between receptive communities and suitable geological environments. Such a match is reported for the West Cumbrian communities who, in 2012, began considering hosting a GDF (Birmingham Policy Commission 2012). A previous geological study by Nirex, until 2005 the body responsible for developing long term waste storage, of the land around Longlands Farm near Sellafield found this site would be unsuitable for geological storage (Nirex 1997). This has been interpreted by some to suggest that the whole West Cumbrian region is geologically unsuitable (Technical Review Group 2011).⁹ However the British Geological Survey has recommended that the area is suitable, against a suite of high level criteria (Powell, Waters et al. 2010).

In addition to the issues surrounding GDF, there are waste management issues surrounding interim waste storage, particularly in relation to spent fuel. Spent fuel is cooled in 'ponds' near reactor sites for 30-50 years until their heat output lowers. They can then go into dry cask storage, which is considered to be a viable and safe storage format (Bunn, Holdren et al. 2001; Brewer, Hendrickson et al. 2011). However past experience with interim storage has shown how bad management

⁹ The West Cumbrian MRWS partnership reports submissions of evidence based on the Nirex study that suggest the while region is geologically unsuitable for a GDF. This is not however the view held by CoRWM and the British Geological Survey. See Technical Review Group (2011). Preliminary Assessment Report - Geology (Criterion 2).

practices (in logging cooling pond contents etc) and poor maintenance of storage facilities can prove costly and potentially risk radiation discharge (MacKerron 2012; National Audit Office 2012). It may be possible to resolve these issues, but they highlight the risks associated with long term management of liabilities.

4.3 Impact of a new build nuclear programme on radioactive waste management

Radioactive waste produced by a new build programme of AP-1000s and EPRs has been assessed by the NDA's Radioactive Waste Management Directorate (RWMD). This report concluded that the additional storage required as a result of spent fuel from a new build reactor programme (10GW) would increase the internal space necessary for HLW and SF by around 47% (NDA 2011). ILW for disposal, primarily arising from the reactor buildings and fuel casing etc, would have a marginal (~6%) increase on the area needed (NDA 2011). It is not clear either from the NDA (2011) report or the CoRWM report (Hill 2012) what the impact on the overall scale of the GDF would be, as HLW and SF is a smaller proportion of GDFs volume than the ILW compartment. However a CoRWM statement on future radioactive waste inventories resulting from a new build nuclear programme suggests that the overall radioactive waste inventory for storage would only increase by 8% (Davies 2006). The Birmingham Policy Commission (2012) gives this figure as 10%. These figure are however based on a 10GWe reactor programme operating for 60 years, and CoRWM has subsequently asked RWMD to consider the same for a 16GWe reactor programme (Hill 2012).¹⁰ In a scenario with 30GW of installed nuclear capacity, based on the trend for a 10GW programme, the GDF may have to increase by one third.

Although the waste volume estimates suggest that new build would have only a minimal effect on the scale on a GDF (at 10GW capacity), the higher proportion of SF being stored could increase the overall radioactivity of the waste inventory by around 265% (Davies 2006). However, RWMD consider the overall post-closure risks for new build SF sent to the GDF to be lower than for legacy waste, concluding;

“there are no new issues arising from the generic DSSC that would challenge the fundamental disposability of the waste and spent fuel expected to arise from the operation of the AP1000 and UK EPR... [P]otential variations in disposal inventory, including the recent commitment to build up to 16GWe of new nuclear power stations, are not expected to significantly change the conclusions of this review (NDA 2011, p.29).”

While a new build programme might not be expected to impact greatly upon the design of the GDF, Government have proposed a policy mechanism to ensure that future nuclear operators contribute to the cost of long-term waste management (National Audit Office 2012). The Birmingham Policy Commission suggest that the GDF would have to remain open until 2175 if waste from a new build programme in 2020 to 2030 were to be incorporated. The National Audit Office (2012) reports that

¹⁰ The NDA do state that a 16GWe new build nuclear programme would increase the SF sent to GDF by ‘less than a factor of two’ NDA (2011). Geological Disposal: Management of Wastes from New Nuclear Build; Implications of the generic disposal system safety case for assessment of waste disposability, Nuclear Decommissioning Authority. However this is not detailed enough to assess the overall impact on the GDF.

this would be achieved through a ‘Nuclear Liabilities Financing Assurance Board’ based on an established cost of waste disposal. The decision on the price for waste transfer to be paid by operators will be deferred by 30 years until the costs of GDF are clearer. The Birmingham Policy Commission (2012) warns that the costs of a GDF could undergo ‘nuclear inflation’ and rise significantly as other aspects of the industry have experienced in relation to construction and decommissioning.

4.4 Summary

Radioactive waste from the UK nuclear industry is an issue that must be resolved regardless of whether there is a new build reactor programme in the UK or not. The UK has a significant ‘legacy’ waste responsibility that requires a long-term solution. The development of a geological disposal facility (GDF) is the preferred option of the UK Government, although the Scottish Government has taken a different view on this, and involves providing a permanent storage for radioactive waste in an underground vault (NDA 2011).

This section reviewed the issues associated with radioactive waste and geological disposal. It discussed types of radioactive waste and the differences between legacy waste and future waste that would arise from a new build programme. The new build nuclear programme is for example expected to have a ‘once-through’ fuel cycle that would increase the amount of spent fuel for long term disposal. However better techniques for fuel use and reactor designs that are easier to decommission would reduce other high level and intermediate level waste streams. A new build programme would therefore produce far less waste volume per unit of electricity than the previous reactor programme.

Although GDF is a popular option for European governments with nuclear waste, there are a number of issues relating to the long term integrity of the storage containers, their interaction with their environment and the location of a GDF in the UK. In the medium term a UK facility would be expected to be actively managed until 2175. As well as the practicalities of cost and management, the time period also clearly presents ethical quandaries with regards intergenerational equity. This is therefore an issue that requires further research and consideration.

5 Proliferation of nuclear weapons

5.1 Proliferation risk from a new UK reactor programme

There has been a shift within the UK from using civilian nuclear reactors to manufacture weapons-grade material for nuclear warheads, to a drive towards making reactors resistant to further weapon proliferation. The world's first civilian nuclear power station at Calder Hall was designed to support the nuclear weapon programme in the UK (Hewitt and Collier 2000), but a key driver for Generation IV reactor designs is increased proliferation resistance (Abram and Ion 2008).

Radioactive materials for nuclear weapons take the form of highly enriched uranium (85% of the metal is ^{235}U in comparison with $\sim 3\%$ used in nuclear fuel) and plutonium. The enrichment process for producing nuclear fuel can also be used to enrich weapons grade uranium (Hewitt and Collier 2000). Fission reactors are the only known way to produce plutonium-239 (^{239}Pu) and, through reprocessing, plutonium can be separated from spent reactor fuel and processed to attain a high level (weapons grade) of the ^{239}Pu isotope. Consequently civilian reactor development is often a required step in nuclear weapon procurement. For this reason there is strong focus in the literature on states with new reactor programmes, such as Iran, in terms of proliferation (Drell, Shultz et al. 2012; Varrall 2012).

The requirement of a nuclear reactor and uranium enrichment technology to develop nuclear weapon material does not mean those with a reactor and enrichment capability necessarily wish to develop nuclear weapons; as demonstrated by Germany and Japan (Sagan 2011; Varrall 2012). This is particularly evident when nations choose reactor designs other than those best suited to producing greater quantities of ^{239}Pu (Hewitt and Collier 2000; Nifenecker 2011).

The reactor types that have applied for construction in the UK (the AP-1000 and the EPR) and the approach taken to spent fuel suggest a low proliferation risk. The light water reactor design used in the EPR and AP-1000 is not well suited to high plutonium yields (Hogselius 2009; Nifenecker 2011). The change from reprocessing spent fuel to direct geological disposal also reduces proliferation risks (Hewitt and Collier 2000; Hogselius 2009). Reprocessing spent fuel has left the UK with a large (in comparison with other nuclear states) plutonium stockpile (MacKerron 2012). The 'once-through' fuel cycle, as planned for the UK (Hill 2012), means that plutonium produced in the reactor remains un-segregated and therefore not useful for powerful nuclear weapons (Hogselius 2009). For these reasons the Birmingham Policy Commission (2012) and the Sustainable Development Commission (2006) have concluded that the proliferation risks from a new build nuclear programme as proposed for the UK to be low.

5.2 Summary

This section discusses the effect a new build reactor programme in the UK may have of on the proliferation of nuclear weapons globally. It does so from a technical perspective and does not consider the political legitimacy that civilian nuclear programmes may lend to weapons programmes now or in the future. The proliferation risk of a new build nuclear programme in the UK is considered low in the literature. This is because the UK already has a nuclear weapons arsenal, and the 'once through' fuel cycle expected for new build does not produce material that can be easily used by other nations or organisations to develop an effective nuclear bomb.

6 Economics of nuclear power

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The analysis of recent estimates of UK nuclear costs, and those of other large-scale low carbon technologies, in this report highlight a number of important factors that have a significant influence on these costs. These include the cost of capital, the extent to which costs might escalate during construction, what load factors are achieved by plants once they are operating. The analysis also shows that the market and regulatory environment where nuclear investment is planned can have large impact on investor risks – and hence, on costs. The UK’s liberalised electricity market is particularly risky for capital-intensive low carbon technologies like nuclear power. This is one important reason why the government is introducing radical reforms to the market via the Energy Bill 2012. We conclude that it is likely that those studies that provide lower estimates of nuclear costs for the UK have not fully accounted for interest during construction or the historic experience with cost escalations. The most pessimistic study reviewed for this report is more comprehensive with respect to the coverage of these issues, and therefore suggests a more plausible range of potential costs. Furthermore, we conclude that claims that nuclear power is cheaper than all other low carbon options are unlikely to be borne out in reality. It is more plausible to assume that onshore wind will be cheaper than nuclear power under present UK investment conditions. Estimates of generation costs for other large scale low carbon options reviewed here (i.e. CCS and offshore wind) have uncertainty ranges that overlap significantly with the higher cost estimates for nuclear power. Given the amount of uncertainty in these estimates, particularly for CCS technologies, it is not possible to provide a definitive view of which of these options will be cheaper or more expensive than the others.

6.1 Introduction

The purpose of this section of the report is to present and analyse the most up to date cost estimates for nuclear power in the UK. The analysis focuses in particular on what assumptions have driven these cost estimates, how they compare with estimates for other power generation technologies, and why they differ from each other. Since there is no recent experience of nuclear construction in the UK, such estimates need to be treated with particular caution. The most recent reactor in the UK, Sizewell B, was completed in 1995.

The economic analysis within this report is set out as follows. First, the report includes a brief history of nuclear costs, and explains why they have tended to rise over time in most of the countries in which nuclear power has been deployed. Second, it explains some of the most important parameters that affect cost estimates, particularly the way in which estimates of capital costs are used to derive estimates of the cost of electricity generated. Third, a small number of recent studies of nuclear costs in the UK are summarised including, where possible, the assumptions that have been made in each case. Fourth, conclusions are drawn.

6.2 A brief history of nuclear costs

Nuclear power has been in use as a civilian technology since the 1950s. Since that time, a significant number of countries have developed civil nuclear power as part of their electricity mix. In the 20th Century, the majority of nuclear plants were constructed in the OECD (Europe, North America and

Japan) and the former Soviet Union. There are currently over 400 nuclear reactors in operation world-wide. Whilst nuclear power was developed for a variety of reasons, those developing it have often believed that it was an economically competitive source of electricity¹¹.

Despite the significant amount of investment in nuclear power, and in developing improved reactor designs, the costs of nuclear power in many countries have risen significantly over time. In common with those of many new technologies, the developers of nuclear power have often exhibited ‘appraisal optimism’. In many countries, they have consistently under estimated the costs of nuclear stations. Whilst nuclear power is not the only technology that has experienced cost rises over time (a good recent example in the UK is offshore wind), the economic record of nuclear power is particularly poor.

As Gordon MacKerron demonstrated in a paper in 1992 (MacKerron 1992), nuclear costs rose in many countries during the boom years of the 1960s and 1970s – including in the USA, UK, France, Canada and South Korea. His paper demonstrated that the reasons for the rise in nuclear costs were complex, and some of these reasons were outside the control of the nuclear or electricity industries. However, he also showed that the primary reason for such increases was increases in construction costs. His paper and another paper by Cohen (Cohen 1990) show that these costs rose due to increasing design complexity (in response to tightening regulations), increasing labour costs (partly in response to an increasing need for regulatory compliance), high inflation in the 1970s and early 1980s (which exacerbated cost escalations due to construction delays) public opposition and a lack of feedback and learning due to long construction periods and bespoke designs in some countries.

For example, the empirical evidence shows that US capital costs trebled in real terms between the mid 1960s and the mid 1970s. This was before the Three Mile Island accident which led to much tighter safety regulation and public opposition which, in turn, drove up costs further. Even in France, which had one of the more successful nuclear programmes in the OECD, costs rose during the 1970s. MacKerron’s paper showed that plants entering service in the 1980s had capital costs that were around double the costs of France’s first plant that entered service in 1974. A more recent analysis of the French experience by Arnulf Grubler confirmed that French nuclear costs rose through the latter half of the 1970s and 1980s, albeit more slowly than the MacKerron paper indicated (Grubler 2010).

More recent experience suggests that rising costs are still a very significant issue for nuclear power, at least in Europe. The two European Pressurised Water reactors that are under construction in Finland and France are both a number of years behind schedule, and are expected to cost at least twice their original budget. The Flamanville EPR plant in France is now expected to cost 8bn Euros by the time it comes online in 2016, whereas the initial estimate of costs was 3.3bn Euros (in 2005 prices)¹².

Independent estimates of the costs of recently constructed plants outside the EU, which have been mainly in China, Russia and other Asian countries, are more difficult to find. It is possible that costs

¹¹ The Chairman of the US Atomic Energy Commission is often quoted as stating that nuclear power would be ‘too cheap to meter’ in 1954, though he may have been referring to electricity in general.

¹² ‘Flamanville costs up €2bn’ World Nuclear News, 4th December 2012; http://www.world-nuclear-news.org/NN-Flamanville_costs_up_2_billion_Euros-0412127.html

have been kept under control more successfully in some of these other markets, particularly in China and South Korea. A KPMG report stated that South Korean capital costs have fallen significantly during the 1990s and 2000s. The source of this data is the reactor vendor Westinghouse which has licensed its technology to Korean firms, rather than an independent body (KPMG 2010).

6.3 Key terms and parameters

There are a number of important factors to consider when calculating and interpreting the projected 'engineering costs' of any power generation technology, including nuclear power. Such costs are often expressed in the cost per kWh or MWh of electricity produced (i.e. in p/kWh or £/MWh). In this section, we set out the most important of these factors and discuss their implications for costs¹³.

At the outset it is important to note that such estimates of engineering costs have significant shortcomings, and should not be used literally to predict real investor behaviour. This is because engineering cost estimates may not fully reflect the relative risks associated with different technological options in a particular market context. Options that appear to be cheap can sometimes be financial unviable because the risks associated with them are higher than those of other options that are, on the face of it, more expensive (Awerbuch 2003). For example, investors in the UK have continued to favour gas-fired CCGT technology even though the cost of gas has risen significantly since the mid 2000s. At the times, the generation cost advantage of this technology over some other options (particularly conventional coal technology) has been significantly eroded or eliminated. One of the reasons for this is that the largest risk these investors face (a risk of gas price increases) is correlated with their income from the sale of electricity (because electricity prices tend to rise when gas prices rise).

6.3.1 Capital costs

For nuclear power plants and most other low carbon technologies, capital costs are a dominant factor in the cost of electricity. Such costs are incurred 'up front' and then need to be paid off by an operator by selling the electricity they generate. For technologies that take significant amounts of time to construct (nuclear power is one of these), it is important to be clear what capital cost figures mean. Many quoted capital costs are overnight costs. As this label implies, they are quoted as if a plant is built virtually instantly. In practice, construction takes a considerable period of time (perhaps 6-8 years), and therefore developers will incur interest on their debt during construction. Such interest payments will be higher if the plant is funded partly by debt (i.e. by borrowing) rather than being financed entirely from a developer's balance sheet (i.e. through equity). This is because borrowing from external sources tends to be more expensive, even for private sector developers. Some capital cost figures include this interest, though many do not.

¹³ For a more detailed discussion of these and other key parameters, see Thomas, S. (2010). *The Economics of Nuclear Power: An Update*. Brussels, Heinrich Bolll Stiftung. or Nuttall, W. (2005). [Nuclear Renaissance: Technologies and Policies for the Future of Nuclear Power](#). London, Inst of Physics Publishing.

6.3.2 The discount rate (or cost of capital)

The discount rate, or cost of capital, is a measure of how much it costs to borrow the capital to invest in a given power plant. The discount rate used includes a number of factors including opportunity costs (what the capital could have been used for instead) and the risks a developer or lender perceives for a given project (e.g. whether the revenues are guaranteed, how likely the power project is to be constructed on time and budget). The cost of capital for private sector developers tend to be significantly higher than those in the public sector – and also tends to be higher in liberalised markets where developers face high risks due to competition. For example, before privatisation the UK's Central Electricity Generating Board used a discount rate of 5% to appraise new investments. This was revised upwards to 8% in the 1980s. Once the electricity sector had been privatised, the new private sector firms tended to use higher rates of 12-15%. These rates reflected their Weighted Average Cost of Capital (WACC). This is the weighted sum of the interest rate on loans and the required rate of return on equity investment.

Higher values for the costs of capital (i.e. of the WACC) have a particularly negative impact on capital-intensive technologies like nuclear power, CCS or offshore wind, especially if they take a long time to construct. This is because any revenue for their developers – which only starts to flow once the plant is in operation – is discounted more (since it occurs further into the future) than any up-front investment costs. Sometimes, appraisals of different technologies use different costs of capital to reflect differences in the perceived risks associated with them¹⁴. For example, Mott MacDonald's recent reports on the costs of low carbon electricity use different discount rates for this reason – including rates that decline over time as technologies are assumed to mature (Mott MacDonald 2011).

6.3.3 Plant lifetime.

All power plant technologies have an expected technical lifetime. However, when lifetimes are used in the estimation of their costs, there are two important factors to consider. First, the lifetime figures used do not necessarily indicate their maximum technical lifetime. Many power plants can be operated well beyond their expected lifetime (for example, nuclear plants are often granted life extensions by regulators), whilst others may be prematurely closed (for example if environmental legislation makes retrofitting to comply too expensive). Second, calculations of the cost of electricity sometimes use financial lifetimes that are more driven by lenders of capital than they are by any technical considerations. Gas-fired plants financed in the UK 'dash for gas' in the 1990s were financed over 15 years, but this does not mean that these plants would be automatically retired after this period. Gas-fired technology is, in principle, capable of operating for much longer periods as long as operators are prepared to invest sufficiently in maintenance and the replacement of critical parts as they wear out.

¹⁴ For a detailed analysis, see a recent report by Oxera for the Committee on Climate Change. See Oxera (2011). Discount rates for low-carbon and renewable generation technologies. [Report for the Committee on Climate Change](#). Oxford, Oxera.

6.3.4 Load factor

The load factor achieved by a nuclear plant (or any other type of power plant) will have a significant impact on costs. If a plant can operate with a high 'baseload' load factor, the capital costs and fixed operating costs can be spread over more units of output, and will be lower per kWh. Nuclear plants are relatively inflexible and are therefore best suited to operating at such high load factors – though in France there is some experience with operation at lower load factors. As noted by a number of studies (e.g. Harris, Heptonstall et al. 2012), actual plant load factors have often been lower than those envisaged when nuclear projects were planned. However, it is also important to note that the average load factors of operational nuclear plants have improved over time (IAEA 2012).

6.3.5 Fuel and operations and maintenance costs

For nuclear power plants, these costs are a relatively minor part of the total cost of electricity. Fuel costs reflect the costs of the raw material (i.e. uranium in most cases), and also the costs of processing and fabrication of fuel rods. A significant rise in the price of uranium, which is the basis of most nuclear fuel, will not have a large impact on generation costs. As illustrated by the data discussed below, fuel costs tend to be lower than operations and maintenance costs. With respect to the latter, it is important to distinguish between fixed costs (which are incurred irrespective of the performance of a particular plant) and variable costs (which depend on the output of the plant).

6.3.6 Waste management and decommissioning.

The costs associated with dealing with nuclear waste can be significant. There are ongoing costs arising from the need to deal with spent nuclear fuel during plant operation. There are also potentially larger costs that will be incurred after plant closure to decommission the reactor and to return the site to a 'green field' state. The latter tend to be incurred many years after a power plant is closed, and therefore have a relatively small impact on electricity generation costs due to discounting. Estimates of the UK's nuclear liabilities (which are mainly due to the costs of cleaning up and dealing with legacy nuclear infrastructure) have risen dramatically over time (MacKerron 2011). Public sector liabilities that are the responsibility of the Nuclear Decommissioning Authority now total over £50bn. This includes liabilities from both civilian and military nuclear programmes.

6.4 Comparing recent estimates for nuclear costs in the UK

This section presents the findings of three recent studies of nuclear power costs, together with their respective underlying assumptions. We have focused on recently published studies since 2010 that have specifically focused on UK nuclear costs. In each case, the analysis has – to some extent – included a comparison with the costs of other power generation technologies. The studies are Parsons Brinckerhoff's *Electricity Generation Cost Model 2011 Update* (Parsons Brinckerhoff 2011), Mott MacDonald's analysis of power generation costs for the Committee on Climate Change in 2011 (Mott MacDonald 2011), and Imperial College's recent report on nuclear costs (Harris, Heptonstall et al. 2012).

We start with a review of the summarized findings presented in the following table, after which we discuss the underlying assumptions individually for each of the studies.

Table 1 Summary of the estimated costs of nuclear power in the UK

	Mott MacDonald 2011	Parsons Brinckerhoff 2011	Imperial College 2012
Levelised cost (£/MWh)	96 – 98 (NOAK**)	62-86 (FOAK**)	164 / 175 *
(Overnight) capital costs (£/kW)	3500	2966-4166	4885 / 5564 *
Operational lifetime (years)	60	40	40
Discount rate (%)	11 (9 - 13)	10	11
Load factor (%)		90	76 - 85
Build time (years)		6 (5 pre-construction)	7.5 (5.5 pre-construction)
Cost escalation (% per year)	None	None	5.4
Decommissioning & Waste Management (£/MWh) included in generation price	2.5	2	2.4 + 0.45 (waste disposal)

* Figures are for two scenarios developed within the ICEPT report

** NOAK = 'Nth' of a kind plant; FOAK = First of a kind plant. Costs for NOAK plants are generally lower than for the first of a kind (FOAK) commercial plant due to learning and experience.

Considering the large variations in the existing estimates, an analysis of the assumptions behind each study's numbers is necessary to understand why they differ.

6.4.1 Mott MacDonald for the Committee on Climate Change

This is a detailed assessment of the costs of different low carbon generation technologies, with medium and long term scenarios for the evolution of those costs. It develops estimates for three technology deployment scenarios: 1) a balanced efforts scenario – where all technologies are supported, 2) a high renewables scenario, where renewables and energy efficiency are prioritized at the cost of nuclear and CCS, and 3) a least cost scenario, where, according to the study's assumptions, support is given to nuclear, gas-CCS, low cost renewables and energy efficiency. The nature of the three scenarios explain in large part the evolution of each technology's costs since the scenarios have direct implications for the favoured technology's learning rate, the familiarity of the UK supply chain with the technology and, particularly important for nuclear, the regulatory and financial environment.

According to the authors' own definition, the capital costs estimates include original equipment manufacturer and the engineering and procurement contractor contingencies, but not the developers' own contingencies. They also exclude land costs and any additional site preparation costs over and above what would be incurred on a 'clean and levelled site', as well as interest during construction. On the other hand, they also take into account a market congestion premium (Mott MacDonald 2011). Mott MacDonald's cost estimates for nuclear power and other, selected low carbon technologies are summarised in figures 1 and 2.

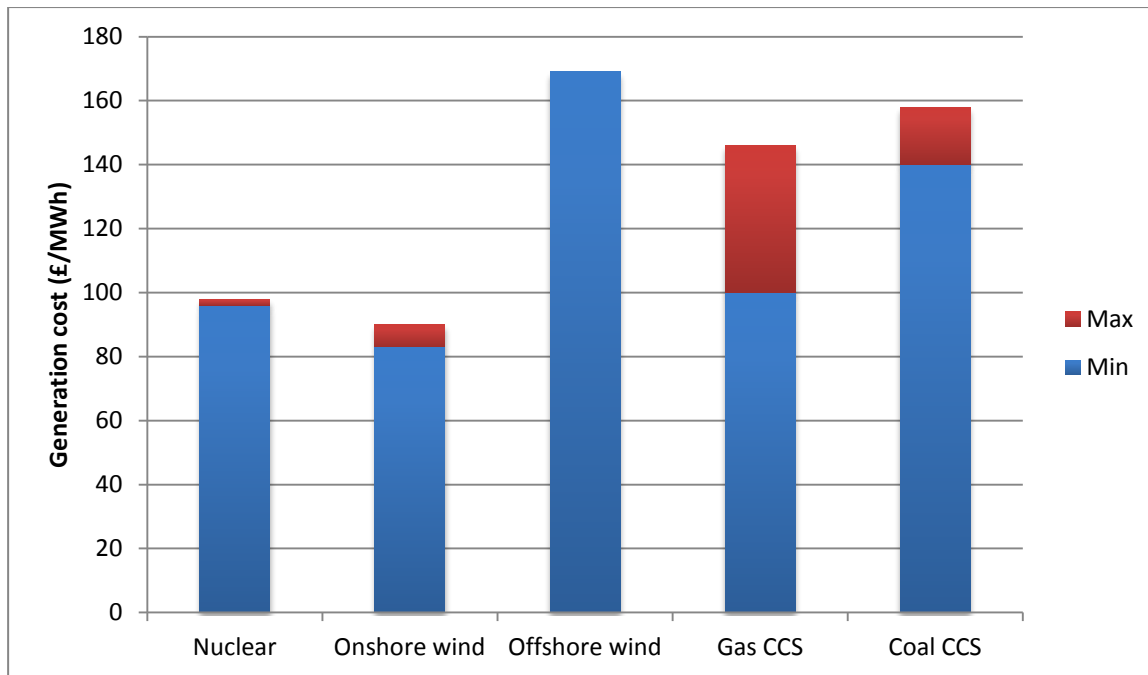


Figure 1 Mott MacDonald estimates of current generation costs
Source: Figure 2 in Mott MacDonald (2011)

According to the results of the Mott MacDonald analysis that are summarised in Figure 1, nuclear energy is a competitive technology, with lower generation costs than other large-scale low carbon options. However, the estimates alone say little about the rationales behind the cost structure. As summarized in Table 1, this number is derived from an overnight capital cost of £3500/kW that is, in turn, derived from a cost of £10bn for 3 GW twin reactor. They use an operational lifetime of 60 years (an industry figure for a Generation III + reactor technology) which is higher than the 40 years used by the other two studies reviewed here. It is important to note that the use of a longer lifetime of 60 years (rather than 40) makes a very small difference to generation costs at an 11% discount rate. We estimate that it reduces generation costs by around 1%. Nevertheless, some critics argue that lifetime estimates of 40 or 60 years are overly optimistic, considering that up to now the average reactor lifetime world-wide has been 22 years (Schneider, Froggatt et al. 2011). Mott MacDonald do not provide details of some of their other cost assumptions. Specific figures for fuel and maintenance costs are not given, and nor are their assumptions about the length of pre-construction or construction periods.

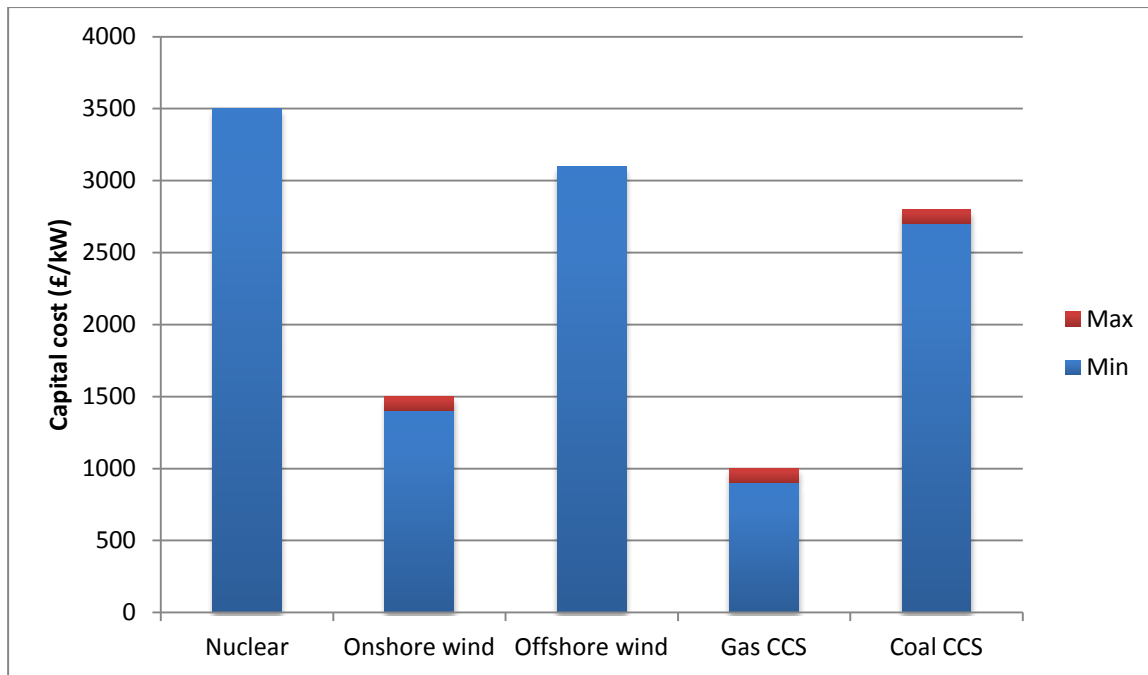


Figure 2 Mott MacDonald estimates of current capital costs
Source: Figure 1 in Mott MacDonald (2011)

The 11% discount rate that has been used by Mott MacDonald for nuclear power is less than that recommended or mentioned by some financial institutions. For example, Citigroup mention a discount rate of 15% as being appropriate in a recent advisory note (Chestney 2011). The discount rate is specifically important to nuclear, relative to other technologies, because of the lengthy construction period – especially if there are delays and cost overruns as there have been with the EPR plants under construction in Finland and France. Therefore, a few points variation can increase the cost considerably. Another important observation is the lack of an escalation factor in the Mott MacDonald costs. As noted below, the ICEPT study includes such an escalation to take into account the empirical evidence from the past (and from current nuclear construction in the EU) that costs tend to rise over time.

In the medium and long-term, Mott MacDonald foresee important potential cost reductions due to learning effects from replication and the refinement of designs. The costs related to the reactor island, the fuel pathways and civil works show the most significant reductions. The downward cost trend in Table 2 is based on a potential contribution from ‘a combination of the GDA (Generic Design Assessment) process, greater focus on project logistics and international competition in nuclear equipment markets’ (Mott MacDonald 2011: 3-69). However, as they acknowledge, historical experience shows that such reductions may not be realised. Even in France, where nuclear power was rolled out on a large scale between the 1970s and 1990s, empirical evidence shows that capital costs rose at a rate of 3.6% per year on average (Harris, Heptonstall et al. 2012).

The capital cost reductions projected by Mott MacDonald lead to falling estimates of generation costs – from £89/MWh in 2011 (which is lower than the £96-98/MWh range they give elsewhere in the same report) to £63 in 2020 and £50 in 2040. The main reasons for this expected reductions are i) falls in expected capital costs; and ii) falls in discount rates due to decreasing risks faced by investors – from 11% in 2011 to 9.5% in 2020 and 7.5% in 2040. Mott MacDonald stress that their

estimate for 2011 ‘must be considered highly uncertain given the limited and troublesome track record of the two reactor models currently being considered for the UK and the lack of recent experience in the UK (among contractors and regulators)’ (Mott MacDonald 2011: 7-3).

Table 2 Capital costs for a nuclear PWR ordered in 2011, 2020 and 2040

Installed capital cost - £/kW					
	2011*	2020	2040	% of 2011 costs in 2020	% of 2011 costs in 2040
Site preparation & licensing	325	278	264	86	81
Reactor island	1000	734	626	73	63
Turbine-island	225	180	167	80	74
Fuel pathways	250	178	154	71	61
Civil works	1400	987	815	71	58
Electrical works	125	106	99	85	79
Balance of plant	175	146	134	83	77
Total	3500	2608	2259	75	65

* Assumes a market congestion premium of £700/kW in 2011

Source: Table 3.34 of Mott MacDonald (Mott MacDonald 2011).

6.4.2 Parsons Brinckerhoff

Parsons Brinckerhoff have also published a series of reports on electricity generation costs, the most recent of which is the update of their electricity generation cost model in 2011 (Parsons Brinckerhoff 2011). This builds on previous work published, for example, in their report *Powering the Nation* which was updated in 2010 (Parsons Brinckerhoff 2010). The electricity generation cost model update covers some, but not all, low carbon technologies.

Their main findings for nuclear power are summarized in Table 1 above. The Table shows that their analysis is more conservative than Mott MacDonald’s about operational lifetime, and that a slightly lower discount rate of 10% has been used. They assume a 6 year construction period (which is shorter than that assumed by ICEPT) and a pre-construction period of 5 years. The lower end of their capital cost range is below figures from other studies, as is the costs included for decommissioning and waste management. The 2010 update of their earlier *Powering the Nation* report was more optimistic still, and included a capital cost figure of £3000/kW rather than a range. The upwards revision since then is in line with the general trend of increasing estimates of capital costs – for nuclear power and for other low carbon options. Given these assumptions, it is not surprising that Parsons Brinckerhoff estimate a lower cost of electricity for nuclear power than other studies (see Table 1). Contrary to the analysis of Mott MacDonald from the same year, they also find that nuclear power is the cheapest of the main large-scale low carbon options. Figure 3 shows the comparison

with coal and gas plants with CCS, but excludes wind power since this was not covered in that particular report. In the 2010 update to *Powering the Nation*, Parsons Brinckerhoff concluded that offshore wind was also significantly more expensive than nuclear power, whereas the range for onshore wind had a higher maximum cost than the range for nuclear power (Parsons Brinckerhoff 2010). However, they are also keen to stress the level of uncertainty inherent in such cost calculations.

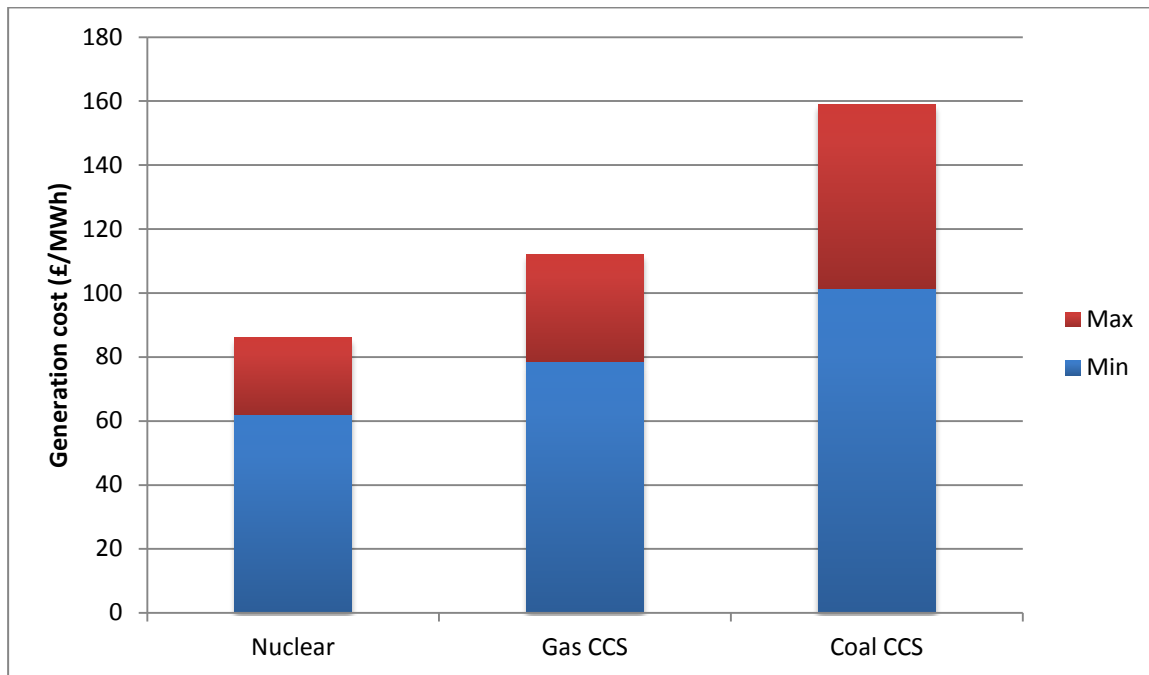


Figure 3 Parsons Brinckerhoff estimates of generation costs
Source: Nuclear and CCS costs from (Parsons Brinckerhoff 2011)

A more detailed breakdown of their nuclear power generation cost estimates are given below in Table 3. They are presented in comparison with a 'Next of a Kind' estimate for 2017 and the earlier range of estimates they published in the 2010 update of *Powering the Nation*. The key driver of the different estimates of generation costs in Table 3 is capital costs. The 2010 report includes a range of capital costs that is lower than the 2011 FOAK estimate, whereas the 2017 NOAK estimate is based on an assumption that capital costs will fall with experience.

Table 3 Parsons Brinckerhoff generation cost estimates (£/MWh)

	2010	2011 FOAK	2017 NOAK
Capital		55.5	48
Fixed O&M		11	9.4
Variable O&M		0.6	0.5
Fuel		5	5
Decommissioning & waste management		2	2
Total		74.1	64.9
Sensitivity range	60-80	62-86	55-80
Capital costs (overnight)	£3000/kW*	£3000-£4200/kW	£2500-£3500/kW

Source: Parsons Brinckerhoff (2011). 2010 figures are from Parsons Brinckerhoff (2010)

* Indicative 'central' projection taken from Parsons Brinckerhoff range by KPMG (KPMG 2010)

6.4.3 Imperial College (ICEPT)

This ICEPT working paper draws on historical experience, and corrects industry estimates by applying lessons from past nuclear construction experience – including that of more 'successful' countries such as France. More specifically, it applies adjustments to previous estimates of nuclear costs. The baseline costs that are used by ICEPT are central cost estimates from Mott MacDonald's 2010 electricity generation costs update (Mott MacDonald 2010). The ICEPT adjustments are summarised in the second row of Table 4, and the original figures from Mott MacDonald are summarised in the first row.

Table 4 Mott MacDonald (2010) and ICEPT UK nuclear new build costs

Annual cost escalation during construction	Build time (years)	Discount rate (%)	Operating lifetime (years)	Overnight cost (£/kW)	Levelised cost (£/MWh)
1.5%*	6	10	60	3,742	95
5.4%	8	11	40	4,885	164

* This rate has been calculated by ICEPT based on Mott MacDonald figures

Source: Figures from ICEPT (Harris, Heptonstall et al. 2012).

Departing from their baseline estimates for nuclear costs, the ICEPT report applies a series of assumptions to provide estimates that they regard as being more in line with current UK market conditions. The rationales for these adjustments are, in broad terms, the relative lack of nuclear new

build (especially in OECD countries) during the last two decades, the historically long time scales involved in planning and construction of nuclear stations and the liberalised market that prevails in the UK (albeit with significant changes proposed under the Energy Bill 2012).

The adjustments to the baseline costs that are made in the ICEPT analysis are as follows:

1. Increasing the pre-construction phase from 4 to 5-6 years, justified mainly by regulatory changes driven by the Fukushima accident and the technical and financial implications of the withdrawal of the sale of the Horizon consortium.
2. Increasing the construction period from 5.5-6 years (as proposed by EDF) to 7-8 years, which is similar to the global median of 7.7. The latter figure is calculated from 381 reactors over the period of 1976 – 2010.
3. Plant operating life is 40 years which is consistent with some independent estimates, but lower than some industry assumptions (which are as high as 60 years)
4. A plant load factor 80.5%, compared with the industry's 90%. This is based on the EDF's average load factor for the past 7 years, and figures provided in the literature.
5. Plant operations and maintenance (O&M) costs that are in line with Mott MacDonald 2010 figures (around £8.5/MWh). There is an adjustment to waste management and decommissioning costs to reflect recent government statements (an increase from £2.1 to £2.4/MWh). The costs associated with the government's price cap on the long-term disposal of waste of £0.45/MWh have also been added by ICEPT to the original Mott MacDonald figure.
6. Financing costs (i.e. the Weighted Average Cost of Capital) of 11%. This is consistent with the assumptions used in the previous two studies discussed above.
7. A cost escalation rate during construction of 5.4% rather than the 1.5% figure that was implied in the baseline costs. The revised figure is the weighted average from the French nuclear new build programme, the 99 reactors built in the United States and capital cost data for the EU reported by IHS/CERA.

The results of ICEPT's analysis are shown in Figure 4, which summarises most of the main adjustments discussed above.

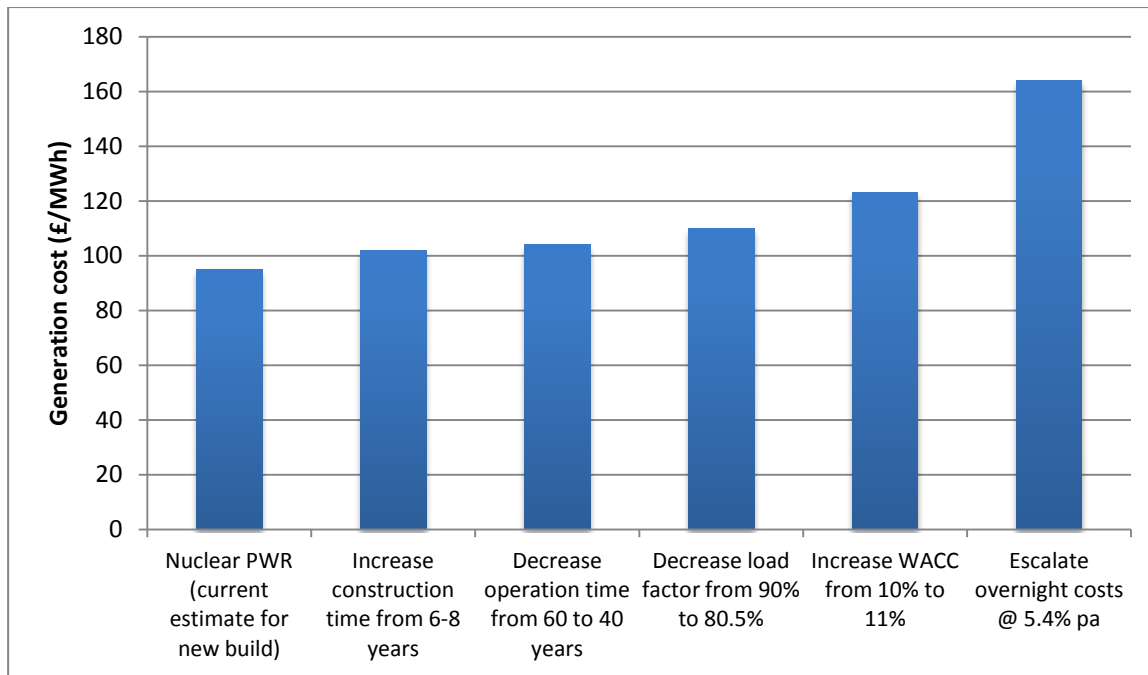


Figure 4 ICEPT estimates of the costs of nuclear power in 2013
Source: ICEPT report figure 1 (Harris, Heptonstall et al. 2012)

It is clear from Figure 4 that the main contribution to the much higher nuclear cost estimates provided by ICEPT is the adjustment to the cost escalation rate during construction. As noted above, this has been increased from an implied 1.5% per year from Mott MacDonald 2010 to 5.4% per year. The 5.4% cost escalation rate is applied to a 5.5 year pre-construction phase and a 7.5 year construction period. Based on this escalation rate, the ICEPT study derives two estimates of capital costs, which are shown in the last column in Table 1. The lower estimate (£4,885/kW) takes the industry estimate of £9bn as the construction cost of a twin (2 x 1600MW) reactor. The second estimates assumes that this industry estimate is an overnight cost, and adds interest during construction as well as the escalation factor.

6.5 Discussion

A comparison of these three studies highlights a number of important issues for the economics of nuclear power. The relative cost effectiveness of nuclear power in a UK context depends on a number of key assumptions. Capital costs and the extent to which these will escalate, discount rates, construction times and load factors are particularly important. Much depends on expectations about whether the developers of new nuclear stations in the UK will be more successful than in the past in their ability to control costs and to deliver projects on time.

The choice of discount rate is not the main driver of differences between cost estimates from these three studies. As noted earlier, all of these studies use a 10% or 11% rate. We estimate that a reduction in discount rates from 11% to 10% will reduce the cost of electricity by around 6-7%. Of more importance are different assumptions (explicit or implicit) about cost escalations and interest during construction. Parsons Brinckerhoff appear to have a particularly optimistic view about interest during construction, which implies that they have assumed that the cost profile during

construction is 'back end loaded' – i.e. that the majority of costs will be incurred towards the end of the construction phase. ICEPT take a much more pessimistic view on cost escalation, though this is a view that is informed by empirical historical experience from within the OECD. Even in France, which has implemented a relatively successful nuclear programme, empirical studies have found significant cost escalations in practice (Grubler 2010). There is some evidence that such escalations have not been experienced in some other countries more recently. In South Korea, it is claimed that costs and build times have fallen for successful reactors in the 1990s and 2000s. For example, capital costs are said to have fallen from around \$2300/kW in 1995 to around \$1600/kW in 2005 (KPMG 2010). However, such claims are based on data from a reactor vendor (Westinghouse) rather than an independent source, and it is not clear whether these costs include interest during construction or any escalations.

As noted above, the use of a lower cost of capital to conduct project appraisals tends to benefit technologies that are capital intensive like nuclear power. Given that one important rationale for building new nuclear plants (though not the only rationale) is to cut carbon emissions, it could be argued that a social discount rate that is applicable to a longer term decision making context is more appropriate. HM Treasury in the UK recommends using a 3.5% rate for decisions that have longer term societal implications (such as decisions about climate change mitigation). If such a low rate were applied to nuclear economics, the cost of electricity would come out much lower than the cost using a 10% or 11% rate – perhaps 50% lower if other assumptions remain constant.

However, the use of a 3.5% rate is not a realistic way in which to appraise nuclear economics, or the economics of any other power plant technology in the UK. Modelling conducted for the UK government (for successive energy White Papers) and the Committee on Climate Change uses this discount rate – but it combines it with individual hurdle rates for each low carbon technology to characterise technology risks facing investors (Usher and Strachan 2010). Appraisals for a societal decision making context do not mean that such risks disappear. A rate of 3.5% is much too low to account for these risks and the opportunity costs of investing in nuclear power rather than another low carbon technology. Given the global nature of capital markets, UK power projects are often competing with projects outside the UK too. Even if the government were to invest in nuclear power itself, using taxpayers money, it would not use a cost of capital that is so low. It would have to justify why public money was being used to fund nuclear power rather than other projects that may be competing for public funds – and it would need to factor in many of the same risks (for example the risk of cost escalations) that a private sector investor would face. Direct government investment may reduce the effective cost of capital by a few percentage points. As noted earlier, the state-owned CEBG used a rate of 8% in the years before it was privatised.

Whatever discount rate (or cost of capital) is used, the estimated costs of new nuclear investment in the UK should be compared with estimates for other low carbon technologies. As Figure 1 shows, many other low carbon technologies are also capital intensive. The capital cost estimates for coal-fired plants with CCS and offshore wind are of a similar order to those for nuclear power. Gas-fired CCS plants are expected to be considerably cheaper to build, whilst experience shows onshore wind power has much lower capital costs. For those technologies with similar expected capital costs, varying the cost of capital will have a similar effect on the capital element of their cost of electricity (in pence per kWh). However, the generation costs of fossil fuel technologies such as coal-fired CCS will tend to fall less in response to reductions in the cost of capital than the generation costs of

nuclear power. This is because the fuel costs of CCS technologies remain significant, whilst nuclear fuel costs account for a small proportion of the total.

For an investor – whether public or private – the costs of most of these competing low carbon technologies are subject to significant uncertainty. The costs of CCS technologies are particularly uncertain since a full-scale power plant with CCS has not yet been completed anywhere in the world (Watson, Kern et al. 2012). There is more experience of offshore wind, much of it in the UK, though capital costs of successive plants are still rising. It is unclear when (or if) costs will start to fall in response to economies of replication and learning effects (The Crown Estate 2012). A common issue for both CCS and nuclear technologies is long-term liabilities – for stored CO₂ for CCS and for radioactive waste for nuclear power. In both cases, these liabilities and the associated management costs are likely to be shared between operators and taxpayers. As noted in the earlier chapter of this report on radioactive waste management, arrangements are being put in place so that developers of new nuclear stations will contribute to the costs of long-term waste management. In addition to this, nuclear developers will continue to benefit from a cap on their liabilities in the event of an accident under international agreements. This is because nuclear power stations could not be insured in the absence of such a liability cap.

A final issue that is important when comparing nuclear costs to those of other low carbon technologies is the extent of any electricity system costs that will be associated with deployment. This issue is explored in more detail in Chapter 11 of this report, but it is important to briefly note the potential economic implications here too. It is often argued that wind power in particular gives rise to significant system costs because wind is an intermittent resource that is difficult to predict and wind power load factors are relatively low. The extent of grid reinforcement and additional power plant capacity that may be required to integrate intermittent renewable generation is heavily dependent on context. As recent work by Poyry for the Committee on Climate Change shows, the costs per MWh are will increase as the share of intermittent renewables in the UK power system increases (Poyry 2011). The extent of these costs will depend heavily on the existing levels of intermittent generation on the system, what other power plant technologies are deployed, what the capacity margin is, and what combination of measures are used to balance the system (e.g. additional conventional capacity, interconnections, demand side response and so on). An independent assessment of the evidence on the impacts of intermittent generation was published by the UK Energy Research Centre in 2006. Whilst this report does not review the most recent evidence, it concludes that the additional costs of systems with up to 20% of intermittent renewable generation are between £5 and £8/MWh (UKERC 2006). It also makes the point that more ‘conventional’ sources of generation are not 100% reliable – and therefore have associated system costs of their own.

6.6 Summary

This analysis of recent estimates of UK nuclear costs, and those of other large-scale low carbon technologies, leads to a number of conclusions:

- Nuclear power costs have risen substantially and continually in the past, including in some countries that have been relatively successful in the deployment of this technology (i.e. France). In common with many large-scale infrastructures, there is a history of ‘appraisal optimism’ in the

estimation of nuclear costs – but the level of optimism has been particularly high in the nuclear case.

- Costs are rising significantly for the latest generation of new reactors that are being built in Europe (in Finland and France). This suggests that the nuclear industry has not yet been able to break away from the historical pattern of cost escalations – at least in OECD countries. Some of the reasons for this are nuclear specific, but there have also been significant underlying cost increases for all power plant technologies in recent years
- Discussions of nuclear costs need to bear in mind the market and regulatory environment in a particular country where nuclear investment is planned. The UK energy market will have a significant effect on the cost of capital for nuclear investors, as will the planned reforms under the Energy Bill 2012. It is also important to pay attention to how nuclear costs compare to those of other low carbon technologies
- Nuclear plants have never been financed in a liberalised electricity market such as that currently in place in the UK. This explains why the government has proposed the negotiation of long term ‘contracts for difference’ with developers of nuclear and other capital-intensive low carbon technologies.
- The cost of capital has a very important influence on estimates of the cost of electricity. There is no economic rationale for using a social discount rate (such as the Treasury Green Book 3.5% rate) as the cost of capital for low carbon technology cost appraisals, including those focusing on nuclear power. Nuclear cost estimates are also heavily affected by other variables, particularly cost escalations and interest during construction and the load factors achieved in operation.
- Fuel and operations and maintenance costs are much smaller as a proportion of generating costs than capital costs. The costs of waste management and decommissioning also tend to be relatively low, but in the case of decommissioning costs this is because they will occur in the distant future – and are therefore discounted significantly from their nominal value. However, liabilities for possible accidents and for waste management - which can be both short and long term - represent a big financial risk for investors, and therefore need to be shared with the government for nuclear investments to be realised. This effective subsidy for nuclear power (which is particularly large with respect to the cap on accident liabilities) has been seen as justified by successive UK governments, the European Commission and other governments.

Overall, the lower estimates of nuclear generation costs reviewed in this chapter are more optimistic in their estimates of capital costs. Whilst some of the assumptions behind these estimates have not been published, it is likely that they do not take full account of interest during construction or of the historic experience with cost escalations. Of the three studies reviewed, the more pessimistic ICEPT study is more comprehensive with respect to the coverage of these escalation risks, and therefore suggests a more plausible range of potential costs. Given this view, we conclude that claims that nuclear power is cheaper than other low carbon options (including CCS and wind) are unlikely to be borne out in reality. This conclusion remains valid when costs that are not normally included in such calculations are considered - including any electricity system costs of integrating intermittent renewables and the costs of liabilities for CCS and nuclear that are co-funded by taxpayers. It is more plausible to assume that onshore wind would be cheaper than nuclear power under present UK

investment conditions. Estimates of generation costs for other large scale low carbon options reviewed here (i.e. CCS and offshore wind) have uncertainty ranges that overlap significantly with the higher cost estimates for nuclear power. Given the amount of uncertainty in these estimates, particularly for CCS technologies, it is not possible to provide a definitive view of which of these options will be cheaper or more expensive than the others.

7 Siting and planning of low carbon generation

The ability to achieve consent and the time taken during the planning process is significant for the development of new electricity generating and supply infrastructure. A supportive planning regime has been identified as a key determinant of delivery of a new generation of nuclear power stations in the UK, both in terms of time taken for approval to proceed and the impact of planning risk on financing (Ion 2007). The experience of obtaining planning consent for Sizewell B, which took six years and included a two year public enquiry, is seen as a 'lesson learned' by the nuclear industry and Government (IMechE 2010). We consider two significant aspects of planning for nuclear power; the first being the planning regime that is in place for different forms of energy generation, the second being the selection of sites to host new infrastructure. Brief comparison is made with the planning process wind power.

7.1 The planning regime

Under the Planning Act (2008) provision was made for 'nationally significant infrastructure projects' (NSIPs) to be referred to the Infrastructure Planning Commission (IPC), an appointed body "to examine applications and make decisions" (Department of Energy and Climate Change 2011a, 3). In terms of electricity generation, NSIPs were defined as projects over 50MW onshore and over 100MW offshore. For smaller scale projects, the planning process would be through the local planning authority where the project was sited. However, the Localism Act (2011) revised this structure from April 2012. For the electricity NSIPs considered here, the examination of applications is now performed by the Major Infrastructure Planning Unit (MIPU) within the Planning Inspectorate, whilst ultimate decision-making responsibility rests with the Secretary of State for Energy and Climate Change. Guiding the assessment of the MIPU are a series of National Policy Statements (NPS), with one covering energy policy more broadly (EN1) and others focusing on specific technologies (e.g. renewable technologies, EN3; nuclear, EN6). EN1 sets out policy objectives around climate change, the need for low carbon electricity generation and the general principles of assessment for applications. Each technology specific NPS then elaborates on these.

The process of reform that has led to the current NSIPs planning approach has, in part, been driven by consideration of the requirements for new energy infrastructure (Marshall 2011). Significant pressure for reform, particularly with respect to large infrastructure projects in general, came from the Confederation for British Industry (CBI). In its Manifesto in 2000 the CBI stated, "The government should ... urgently and radically improve the speed and transparency of the planning process. For major infrastructure projects, the time taken to hold enquiries must be radically shortened" (CBI, 2000, 22–3, cited in Marshall 2011, 448). Alongside this pressure, the move by the UK Government to advocate a return for nuclear power in 2007 is cited as a key motivation for the development of the 2007 Planning White Paper, which led to the Planning Act (2008) (Greenhalgh and Azapagic 2009; Marshall 2011; Blowers 2010).

Energy projects that are not considered to be NSIPs proceed through the traditional planning process. This could impair the development of low carbon developments that are not at a scale covered by the NSIPs. Historically, small scale renewables projects have received significant opposition from local communities, with the cultural value placed on natural landscapes and the commercial value of land and property often cited (Brennand, 2004). Abolition of the Regional Spatial Strategies (RSS) as part of planning reforms has effectively removed a layer of regional

planning for energy generation projects. With democratically elected authorities, accountable to their local communities, encouraged to take a more active role in the planning process via the National Planning Policy Framework (Department for Communities and Local Government, 2012), it is plausible that local preferences may displace national priorities and long term objectives. Barclay (2012) suggests that it is likely that if local neighbourhood plans¹⁵ do not conform with national and local policy, it would not pass independent examination. However it does mean there is potential for smaller onshore wind farms and other renewables such as anaerobic digesters to face greater planning barriers than large scale nuclear and offshore wind developments.

7.2 Site selection

For nuclear power a number of sites have been preselected through the Strategic Siting Assessment (SSA). This was “designed to identify sites in England and Wales that are potentially suitable for the deployment of new nuclear power stations by the end of 2025” (Department of Energy and Climate Change 2011c, 8). Initially ten sites were examined, although Kirkstanton and Braystones – which do not already have a nuclear facility - were later dropped. The remaining eight sites (Bradwell, Hartlepool, Heysham, Hinkley, Oldbury, Sellafield, Sizewell and Wylfa), all have existing reactors. In comparison, for onshore wind, NPIS EN3 outlines the main factors influencing the choice of sites, including predicted wind speed, proximity to dwellings, capacity of site, electricity grid connections and vehicular access (Department of Energy and Climate Change 2011b), but it does not specify sites.

The ownership of land in these areas by former nuclear operators (e.g. British Energy) bought by new build developers is likely to have been a key determining factor for site selection. Similarly, there is existing grid infrastructure available that at existing sites that offers connection benefits, although some upgrade work may be required. Blowers (2010) discusses the siting of nuclear power in detail and offers three reasons why the eight sites identified were chosen; i) supportive ownership, ii) existing infrastructure, and iii) that local popular acceptance. He expands on the latter point, arguing that “they are situated in communities where public support allegedly derives from familiarity with the nuclear industry and the jobs and investment it will bring” (p.160) and goes on to suggest that existing nuclear sites “may be called “peripheral” communities, places on the edge of the mainstream” (p.162) characterised by their remoteness, economic marginality, political powerlessness, cultural defensiveness, and environmental degradation. He suggests that, given the selection of existing nuclear sites, the SSA was an exercise to provide legitimation for a predetermined policy (p.162).

A technical issue that has been raised with selected sites concerns flood risk. All listed potential nuclear sites are located close to the sea, for access to cooling water, and NPS EN-6 recognises that this brings risks associated with climate change related sea level rise. A number of the chosen sites

¹⁵ In comparison to nuclear power, the Localism Act has potentially significant implications for smaller scale wind projects as “Local planning authorities will no longer have to adopt targets for wind farms set at regional level” (Barclay, C 2012, 3). It also gives parish councils the power to develop neighbourhood plans, which, if passed by independent examination and approved by 50% support in a local referendum, would have to be adopted by the local planning authority. Integration of wind power is not included in this process, raising the prospect that neighbourhood plans could exclude onshore wind farm development.

are within high-risk flood zones (zone 3) (DECC 2011). For other technologies, NPS EN1 sets out the 'sequential test' which means that development in a flood zone 3 should only occur after possibilities in zones 1 and 2 have been eliminated, with part of the planning process to assess this is the case. For nuclear, however, this test is seen as having been applied during the SSA so is not part of the planning process. Applicants are expected to submit a flood risk assessment and need to "demonstrate suitable flood risk mitigation measures" (p.22). However, what is deemed suitable is open to interpretation. NPS EN6 states that all the sites have, "the potential to be adequately protected from flood risk (including the potential effects of climate change, taking into account the UK Climate Impacts Programme 2009)" (p.22). However, given that current emission trends are beyond those seen in the highest emissions scenario used in UKCIP 09, there is a real possibility that the climate change impacts envisioned in that work could occur earlier and be more severe over the course of the century. These issues have led some to call into question the safety of the proposed sites e.g. (Greenpeace 2007; Blowers 2010). Modelling carried out by Wilby, Nicholls et al. (2011) on UK reactor sites suggests this issue can be effectively managed even in scenarios with high climate impacts.

Site selection based on existing nuclear sites is also sub-optimal in terms of possible improvements the power station efficiency through combined heat and power (CHP). Given the potential for emissions savings through heat networks NPS EN1 states that, in proposing new thermal generation, opportunities for CHP should be considered at the "earliest point and it should be adopted as a criterion when considering locations for a project" (Department of Energy and Climate Change 2011a, 52). However, only three of the eight selected sites (Hartlepool, Heysham and Oldbury) have dense heating demand centres near enough for CHP district heating. NPS EN6 recognises "the economic viability of CHP opportunities may be more limited for new nuclear power stations" (Department of Energy and Climate Change 2011c, 14). Blowers (2010) highlights the contradictory nature of the SSA on this issue; whilst the SSA argues that there is no longer a need for remote siting it also sets criteria that rule out more urban areas. He poses the question, "If it is not necessary, on safety grounds, to site a plant at a remote location then it should follow that it is safe to locate it close to urban areas" (p.161).

It is often also asserted that the sites selected by the SSA will meet fewer objections in the planning process due to the local people's familiarity with proximity to a nuclear plant. This point is discussed by Venables et al (2012), whose study examines the relationship between how people perceive nuclear power, proximity, and sense of place. It is argued that the idea that existing 'nuclear communities' will be more accepting of new build is simplistic. Within communities, people's perceptions will differ: "For some, the power station and its operations are an integral and reassuring presence. For others, it is not generally noticed, but it may cue anxiety, possibly because of what it represents or symbolises, when one is reminded of its presence. Finally, for some segments of the community it is visually salient as an ugly eyesore that has been imposed upon the local area" (p.380). They conclude that the way that the current nuclear power station is incorporated into people's sense of the place they live "appears to be most important in determining attitudes towards new build" (p.380).

Sense of place also has an important role to play when thinking about renewable energy, and in particular wind. The term NIMBY (not in my backyard) is often used to characterise opponents of wind developments, reflecting that they do not want the development to happen in their area.

However, it is term that has been critiqued by academics as it is derogatory, simplistic and lacking empirical support (Devine-Wright 2011). It is important to recognise that people have emotional bonds with places and, when planning renewable energy projects that involve land use change, developers should take into these bonds into account (McLachlan 2010). There are other issues involved in support or opposition to wind farm developments, and indeed Toke (2005) suggests that although ‘landscape impacts’ is commonly cited as the reason for refusing planning applications, this often hides the real factors behind such decisions. He highlights the national political environment regarding wind power and local perception of economic impacts as crucial variables. Whatever the reasons, expansion of onshore wind power is presently limited by the number of planning applications that are refused; in both 2011 and 2010 although approximately even, the number of approved applications was outweighed by refusals.¹⁶

7.3 Summary

The planning process is a key issue in the development of new electricity generation projects. This process has undergone reform since 2007, driven by the concerns of business and energy industry, including nuclear power developers, that the previous process led to excessive delays and associated costs.

Decision making authority for large scale renewable and nuclear power projects now resides with the Secretary of State for Energy and Climate Change following the abolition of the Infrastructure Planning Commission. This structure provides strategic guidance through national policy statements on particular technologies and democratic accountability at the national scale. Given the recent changes in planning policy, there is little academic literature which explores the impact of the reforms on planning applications for nuclear or renewable, be they major infrastructure projects or local projects. It is apparent, however, that nuclear new build is a clear beneficiary of these changes.

The generic design assessment (GDA) and the Major Infrastructure Planning Unit are intended to reduce delays in decision making on nuclear developments and direct decision making towards central authorities. The current timeline for new nuclear build suggests an expectation that planning will take at most one and half years¹⁷ although this is yet to be demonstrated. Nuclear siting is already ‘locked in’ to existing sites in England and Wales, for a range of ownership, infrastructure and social reasons. Whether these sites are good candidates in future contexts, in relation to increasing CHP and change climate impacts is unclear.

¹⁶ For 2010, approvals – 83; refusals – 84; for 2011, approvals 87; refusals 88. Information from <http://www.bwea.com/ukwed/>.

¹⁷ From http://www.decc.gov.uk/en/content/cms/meeting_energy/nuclear/new/new.aspx

8 Employment

Employment benefits for local residents and the UK as a whole are a significant criteria for energy infrastructure decision making (Glasson 2005). The economic benefits, both from direct and indirect employment (e.g. jobs created to provide services to power plant workers) feature heavily in announcements of new energy infrastructure projects.¹⁸

This section outlines the potential employment issues associated with a new build reactor programme in the UK. In particular it highlights studies that attempt to compare the employment benefits of different energy technologies and the uncertainties in doing this. Illustrative employment figures for different parts of the nuclear cycle are given to show how they are distributed through life time of the reactor and decommissioning. It concludes with a discussion of whether the jobs created by new nuclear will be within the UK or whether labour would be imported and to what extent.

8.1 Issues with employment models

There have been several studies carried out that attempt to forecast employment benefits from different energy technology development pathways. Some compare the employment opportunities between renewables and established fossil fuel technologies that show an increase in employment from increased renewables uptake. Similarly there have been employment studies of job creation from nuclear power although predominantly in a US context (Kenley, Klingler et al. 2009) or specific to Scotland and not the wider UK, e.g. Allan, McGregor et al.(2007).

Different studies use their own assumption and assessment boundaries that make comparison difficult (Wei, Patadia et al. 2010). An attempt to do this is presented in Wei, Patadia et al. (2010) which reviews a number of employment studies for different energy technologies and energy efficiency programmes. They found, by taking averages and adjusting various high and low cases of employment benefits that solar PV and energy efficiency performed best in terms of average job years per GWh of energy supplied/saved (although there was significant disparity between the high and low cases). Nuclear power performed on a similar level as wind and other non-PV renewables, although the authors point out that decommissioning was not considered in the studies they reviewed (Wei, Patadia et al. 2010).

As with Wei, Patadia et al. (2010), Bannister and Berechman (2001), Allan, McGregor et al. (2007), and Fankhauser, Sehleier et al. (2008) note the limitations of modelling future infrastructure related employment. Problems include the potential for double counting for construction, system boundaries (for example, which parts of component assembly are considered and whether decommissioning is included), local versus migrant employment and assumptions used to extrapolate indirect job creation. In addition, most studies provide data as job years/GWh of generated electricity, meaning assumptions about capacity factors have to be made that will vary the results (Esteban, Leary et al. 2011). These studies suggest that while employment estimates can be

¹⁸ Pertinent examples include; DECC, (2012), *Ministers Welcome Hitachi New Nuclear Investment Programme*, Available at http://www.decc.gov.uk/en/content/cms/news/pn12_135/pn12_135.aspx (Accessed 10/11/2012). Similarly; BBC, (2012), *Wylfa Nuclear Plant: Political leaders welcome Hitachi deal*, Available at: <http://www.bbc.co.uk/news/uk-wales-north-west-wales-20128356> (Accessed 10/11/2012).

useful in making assessments on economic benefits, further research is required to improve accuracy and comparability (Fankhauser, Sehlleier et al. 2008).

8.2 Employment in nuclear power

Two dimensions of employment benefits from nuclear new build were examined; the employment needed to construct, operate and decommission a nuclear reactor and whether these jobs are likely to be taken by UK residents. The following provides an illustration of the employment required by nuclear reactors:

- Construction: The Birmingham Policy Commission (2012) estimate 3,000 construction jobs per reactor over a five year period. Areva claim 4,000 workers are involved with the construction of the two Olkiluoto-3 reactors in Finland¹⁹, while Hitachi state that 5,000 to 6,000 workers will be employed during the construction of each of their twin reactor projects.²⁰ Peak employment during the construction of the Sizewell B reactor was 5,000 (Glasson 2005).
- Operation and Maintenance: Kenley, Klingler et al. (2009) found that on average a 1.1GW nuclear power station (accounting for variation in design) requires 677 staff members. The Birmingham Policy Commission (2012) however put this figure at 330 per power plant for new build reactors.
- Decommissioning: There are currently 797 workers involved with 'care and maintenance preparations' at the Trawsfynydd nuclear power station.²¹ This is for a twin Magnox reactor site and it is not necessarily the case that new reactor designs would require the same staff levels.²² While the decommissioning process can take almost 100years (although more rapid timetables are available, notably for light water reactors) following defueling for a reactor, there are different stages, with the initial 22years providing the majority of employment opportunities.²³

In the future, on the current pathway outlined in DECC (2011), new build reactors will not include fuel reprocessing. Therefore UK jobs associated with reprocessing may not be carried forward though some jobs may arise from the processing of UK (and possibly overseas) plutonium into MOX

¹⁹ Areva, (2012), *Finland-Olkiluoto 3*, Available at: <http://www.areva.com/EN/operations-2389/finland-olkiluoto-3.html> (Accessed 10/11/2012).

²⁰ Henning Gloystein and Karolin Schaps, (2012), *Update 3-Hitachi Wins Bid to Build up to 6 UK Nuclear Plants*, Reuters, Available at: <http://www.reuters.com/article/2012/10/30/energy-britain-nuclear-idUSL5E8LU25P20121030> (Accessed 10/11/2012).

²¹ Magnox, (2012), *Facts and Figures*, Available at: <http://www.magnoxsites.co.uk/our-sites/trawsfynydd/facts-and-figures> (Accessed 10/11/2012).

²² The Magnox reactor's graphite core provides challenges light water reactor decommissioners do not. See World Nuclear Association, (2012), *Decommissioning Nuclear Facilities*, Available at <http://www.world-nuclear.org/info/inf19.html> (Accessed 10/11/2012).

²³ See NDA, (2012), *Trawsfynydd*, Available at: <http://www.nda.gov.uk/sites/trawsfynydd/> (Accessed 10/11/2012).

fuel (Birmingham Policy Commission 2012). In the long term waste management will be an area of further development, although the employment issues relating to building a geological disposal facility or other storage solution are not yet known. UK jobs created by the wider supply chain – for example by component manufacture - are considered in the following subsection.

8.3 UK Employment

From a national policy perspective job creation may be assessed on the basis of whether jobs are created/retained within the UK or if skilled workers are brought in. Glasson (2005) highlights the significance of providing local and UK jobs in relation to migrant jobs in determining economic benefits.

The extent to which the jobs created by a new build nuclear programme will be taken by UK nationals will depend upon whether a perceived skills shortage is addressed. The UK has an aging nuclear workforce with the necessary experience reaching retirement age (Sacchetti 2008). As the Birmingham Policy Commission (2011) state, there is a need to establish and attract sufficient numbers of new entrants into nuclear sector to provide a UK workforce for a new build reactor programme. A large proportion of jobs with the nuclear power sector require specialist science and engineering training, of which there is a potential global shortage (Wogman, Bond et al. 2005). The UK will have to compete with workers brought in from countries with more developed nuclear sectors. Areva for example state that nationals from 55 different countries are involved in the construction of the EPR at Olkiluoto in Finland.²⁴ There are, however, potentially several years in which to build up capacity in the workforce before reactor construction would begin fully (Birmingham Policy Commission 2012). In response to the skills shortage in the UK, the National Skills Academy was established to work with employers to provide nuclear power related apprenticeships and further education programmes (Birmingham Policy Commission 2012).

In addition to provided a skilled workforce, the UK also has to develop its contribution to the nuclear supply chain if it is to increase its benefit from employment opportunities related to nuclear new build programmes. Kenley, Klingler et al. (2009) show that associated domestic employment can be significantly increased if component manufacture and other services are included. Overall, the expertise in building reactors will come from outside of the UK (France and Japan in particular with Areva and Hitachi-GE). The UK already has a number of firms providing services for the global nuclear supply chain, as highlighted by the Department for Business Innovation and Skills (BIS) Nuclear Suppliers Group, however they currently only provide niche components (e.g. high energy capacitors and fuel cladding materials).²⁵ Hitachi-GE are reported to have signed a memorandum of understanding to work with UK based companies Rolls Royce and Babcock International, which could

²⁴ Areva, (2012), *Finland-Olkiluoto 3*, Available at: <http://www.areva.com/EN/operations-2389/finland-olkiluoto-3.html> (Accessed 10/11/2012).

²⁵ BIS, (2012), *Nuclear Suppliers Group*, Available at: <http://www.bis.gov.uk/policies/export-control-organisation/eco-policy-consultations/international-proliferation-arms-control-regimes/nuclear-suppliers-group> (Accessed 10/11/2012).

increase the UK share of the value chain for new reactors although investment in facilities is yet to be secured.²⁶

8.4 Summary

Employment is a widely cited criterion for selecting low carbon energy options. Defining the number and type of jobs created, and whether these jobs would be available for UK residents is a key debate. Models for predicting the employment implications of all technology pathways can be misleading owing to their variation according to the assumptions that are used.

Nuclear power can be seen to provide a number of highly skilled jobs throughout the lifecycle of a reactor site. As with other energy technologies the peak level of employment is highest during construction. Comparisons with other technologies will depend upon a number of factors, but domestic contribution to the supply chain is of particular importance. However, the proportion of components manufactured in the UK and numbers of skilled workers brought in from outside of the UK are not currently known. As with other technologies where the UK provides a market but does not have established domestic companies providing the majority of services, such as offshore wind,²⁷ a great deal will depend upon expanding the UK supply chain and building a skills base.

²⁶ World Nuclear News, (2012), *Britain to Have Boiling Water Reactors*, Available at http://www.world-nuclear-news.org/NN_Britain_to_have_boiling_water_reactors_3010121.html (Accessed 10/11/2012).

²⁷ Currently the UK imports many of the components and relies upon European companies for installation services. See Technology Strategy Board, (2012), *Developing the Offshore Wind Supply Chain*, Available at: <http://www.innovateuk.org/content/competition/developing-the-offshore-wind-supply-chain.ashx> (Accessed 10/11/2012).

9 Issues in managing a low carbon grid

This section reviews the implications for the UK's future electricity grid of decarbonisation with and without new nuclear capacity. It considers the relationship between different electricity supply options and the technical properties of the grid itself. The review draws substantially from the Pöyry (2011) report for the Committee on Climate Change (CCC) and its portfolios of alternative supply options, with supplementary references and analysis included where necessary.

The UK's electricity grid faces a number of challenges over the coming decades and there are different approaches to meeting them. The grid has to be able to provide the requisite security of supply, which conventionally has been premised on an understanding that electricity generation should match demand. To comply with the Climate Change Act the carbon intensity of the grid has to fall from 486gCO₂/kWh (in 2011) to almost zero before 2050 (with a target of 50gCO₂/kWh by 2030)(Committee on Climate Change 2011). It is also preferable if the grid can do this at the lowest cost per unit of energy for end users (DECC 2011). Consequently the electricity grid in the next two decades is likely to be distinct from the current network in five key ways:

- Increased grid capacity, specifically transmission: Although energy efficiency measures are expected to reduce overall energy demand, increased electrification of heating and transport (both in terms of electric vehicles and hydrogen electrolysis for hydrogen vehicles) would increase total electricity demand. In CCC 2030 scenarios overall energy demand falls but electricity is assumed to increase from ~350TWh to 407TWh, reaching ~600TWh by 2050 (Speirs, Gross et al. 2010; Committee on Climate Change 2011; Pöyry 2011).
- Demand side management: If smart grid technology proves successful it could enable greater demand side flexibility. This would assist with load balancing and reducing peak demand (Pöyry 2011).
- Storage: In a future with electric vehicles, and assuming batteries remain the dominant technology, the storage capacity of individual car batteries could assist with load balancing (Pöyry 2011). Hydrogen produced through electrolysis can be stored in bulk and used to fuel vehicles, or combusted in gas turbines to act as backup capacity when other generating output cannot meet demand (Korpas and Greiner 2008). Pumped hydro storage, could be increased but is limited by suitable sites. Individually or collectively, these measures would facilitate greater supply flexibility.
- Interconnectors: A new electricity interconnector with Ireland and future interconnectors with Norway and North West Europe could give the UK access to around 12TWh of electricity imports annually by 2030 (Pöyry 2011). They would also give the UK the option to export electricity during periods of surplus supply to mitigate load shedding (excess electricity generation). Political risks to supply vary according to trading partner in a similar way to gas imports and exports.
- Two way electricity flows: An increase in micro-generation would mean electricity supply networks have to have increased capacity and flexibility to accommodate grid inputs from more household and business scale electricity generators (EA Technology 2010; DECC 2011).

Three supply side technology types are currently available for decarbonising electricity; renewables, nuclear and coal/gas with carbon capture and storage (CCS). The Committee on Climate Change

recommends that all three technology types should be deployed to achieve a grid that ensures security of supply, is low carbon and affordable for users (Committee on Climate Change 2011).

9.1 Issues associated with an entirely renewable grid

An electricity grid with a very high renewables component in the UK is likely to include a very large wind component, adding a significant amount of variable generation to the power system. Wind output variability at hourly, daily, seasonal and annual durations presents challenges for system balancing, while sharp variations over seconds and minutes can cause frequency stability issues for network operators (Soder, Hofmann et al. 2007). There are existing examples of regional grids where wind is a significant contributor to annual generation, for instance Northern Germany (33%) and West Denmark (24%) (Holtinen, Meibom et al. 2009). In the current context these are very high levels of penetration; going beyond this level to over 50% wind penetration (of annual supply) raises research questions about how to achieve this effectively within a power system (Holtinen, Meibom et al. 2009; Lannoye, Flynn et al. 2012).

The CCC commissioned Pöyry to assess the feasibility of an electricity grid with very high levels of renewables penetration. The report considered three scenarios; High (with 60% renewables), Very High (with 80% renewables) and Max (with 94% renewables) all by 2050. The report found that the Max scenario, based almost entirely on renewable generation technologies, could be technically feasible and able to achieve security of supply (Pöyry 2011), but did so at the highest cost/kWh. Perhaps counter intuitively, the Max scenario also had the highest grid carbon intensity – an outcome of Pöyry's assumption of back-up supply being met by open-cycle gas turbines combusting natural gas and not a potential low carbon substitute such as bio-methane²⁸.

The Max scenario takes all renewable technologies to very high development rates and supplements this with a very large expansion of offshore wind to 156GW (52% of installed generating capacity). This includes a substantial roll-out of anchored 'floating' offshore wind generation (93GW) and an increase in the expansion of fixed platform offshore wind through new site allocations. In this scenario floating offshore wind generation becomes the largest supply technology of electricity to the grid; the scenario also assumes large interconnector capacity and successful application of demand-side management (including smart grids) to balance loads.

The Max scenario implies the highest per unit cost for energy. This is because of the high offshore wind component (related to an aggressive increase in build rate that requires new installation ships and other supporting investment) and the need to construct grid infrastructure in new and in some cases remote locations (Pöyry 2011). The levelised costs in this scenario are also increased by load shedding that is three times greater (19% of electricity output) than in the Very High scenario, despite interconnectors, storage and demand-side flexibility (Pöyry 2011). There is uncertainty about how power systems will accommodate such high levels of variable generation even with improved

²⁸ Although there are methodological difficulties in calculating emissions savings in ecological systems, bio-methane from anaerobic digestion is anticipated to offer electricity generation with emissions in the order of 15-65 gCO₂e/kWh Cherubini, F., N. D. Bird, et al. (2009). "Energy- and greenhouse gas-based LCA of biofuel and bioenergy systems: Key issues, ranges and recommendations." *Resources, Conservation and Recycling* **53**(8): 434-447.

storage and demand side flexibility, particularly when wind generation is over 50% of annual generation (Holttinen, Meibom et al. 2009; Pöyry 2011; Lannoye, Flynn et al. 2012).

The High and Very High scenarios proposed by Pöyry also include high levels of renewables. The High scenario alone would involve a significant increase in renewable energy capacity from 12.3GW (DECC 2012) to 113GW installed capacity (Pöyry 2011) by 2050. The remainder of the low carbon electricity generation in these scenarios is met by CCS and nuclear output.

Although not discussed in these scenarios as a constraint, it is worth bearing in mind that international replication of such a shift to “Max” renewable generation may lead to temporary or permanent increases in raw material costs or ultimately resource exhaustion. Concerns around the availability of “energy critical elements” (ECEs), such as the lithium in batteries, tellurium in solar cells and rare earth metals in wind turbine magnets, have led to investigation by the American Physical Society and Materials Research Society and action from a number of national authorities (Hurd, Kelley et al. 2012). Copper, cobalt and tellurium have recently been identified as elements with particular geochemical concerns due to their rate of consumption (Bradshaw and Hamacher 2012). Research is limited and clear conclusions hampered by the uncertainties in resource availability, confusion between geochemical and geopolitical scarcity, the possibility of substitution and the unknown economic interactions of these phenomena. However, consideration of mining practices, resource efficiency and recycling will be crucial to the persistence of their availability, even if a strong interpretation of sustainability is not achieved.

9.2 CCS as an alternative to nuclear power

Another option for providing low carbon electricity generating capacity is coal or gas CCS. Under the Pöyry High renewables penetration scenario, if the technology proves successful after large scale demonstration, around 13GW would be constructed by 2050.

Whilst the economics of CCS technology are likely to favour baseload output, they technically could be developed for output flexibility (Chalmers, Lucquiaud et al. 2009; Davison 2011). This form of more easily dispatchable generation can have an important role in balancing an electricity network with high levels of variable generation (Pöyry 2011) but is yet to be demonstrated at commercial scale. Geological storage capacity for CO₂ is not given as a constraint on CCS deployment by Markusson, Kern et al. (2012), Stigson, Hansson et al. (2012) or by Pöyry (2011). Moreover, access to affordable coal and natural gas reserves are both predicted to last for over a century (Tester, Drake et al. 2005).

Pöyry assume there is a higher proportion of nuclear as opposed to CCS capacity by 2050 and give two reasons for this. The first is based on DECC cost models in which nuclear appears to be the most cost effective supply option (Pöyry 2011). However, given uncertainties around both sets of costs, this rationale is certainly open to question, with economic conclusions sensitive to a wide range of parameters that are both highly uncertain and open to different interpretation. The second reason relates to previous delays in commissioning CCS demonstration plants and uncertainties about the how fast the technology can be scaled up (Pöyry 2011). This view is supported by (Stigson, Hansson et al. 2012) and (Markusson, Kern et al. 2012) who outline the uncertainties and potential barriers to CCS deployment and the planning, construction and commissioning of CO₂ pipeline infrastructures. It may however be possible to rapidly deploy gas CCS; the UK has experience of significant expansion of natural gas power stations during the 1990s (Wright 2005) although CCGT’s were certainly a more

established technology than is CCS. Against this backdrop of uncertainty, Pöyry (2011) assume that the earliest date at which CCS may become commercially available for a large increase in capacity is 2024 (in line with the DECC CCS Roadmap). This would make significant installed capacity of the technology before 2030 very challenging. As CCS is still at an early stage of development, uncertainties about how successfully it will perform carbon capture (therefore its effect on grid carbon intensity), the energy 'penalty' from capture and storage systems, and associated upstream GHG emissions remain to be addressed.

Overall, large CCS capacity could be possible, although whether it is economically appropriate or compatible with existing climate change commitments is unclear at this stage.

9.3 A mixed nuclear and renewables grid

With the constraint of grid decarbonisation, the proportion of grid capacity not met by renewables requires either CCS or nuclear capacity. For example, in Pöyry's Very High renewables scenario 11GW of nuclear (12GW by 2050) and 4GW of CCS (16GW by 2050) is required to meet grid capacity by 2030 (2011). These figures change to 19GW of nuclear (with 30GW by 2050) and 4GW of CCS by 2050 (13GW by 2050) in the High scenario (Pöyry 2011).

Nuclear output is usually classed as baseload and relatively inflexible supply. Under normal operating parameters it is available at high output whenever reactors are not shutdown for refuelling (in the case of light water reactors) or routine maintenance. AP-1000 and EPR reactors, for example are designed for 92-94% availability, though reduced refuelling time and anticipated lower maintenance requirements (Sutharshan, Mutyala et al. 2010; Areva 2012). This means the reactors should provide constant electricity output throughout most of the year and planned outages can be scheduled for periods of typically low demand. Historically however only one quarter of reactors worldwide operate at above 90% capacity, and there is significant variation by type and age of reactor from (~50%-91%).²⁹ In the UK reactor availability has been low owing to technical problems with the AGR and Magnox reactor design. Light water reactors, such as the AP-1000, the EPR and ABWR have historically achieved availability rates at the higher end of this range (Tester, Drake et al. 2005). However, as demonstrated in 2010 and 2011 at Sizewell B (also a light water reactor) unplanned outages do happen and reactor output can be reduced considerably taken offline for months at a time (DECC 2012).

System costs as a whole are expected to increase as variable renewables increase, both in terms of short term balancing and long term provision of sufficient capacity. This will have consequences for other generators including nuclear reactors (NEA 2012). Nuclear power output is typically inflexible because of a range of economic and engineering factors, and consequently nuclear operators aim to constantly maximise output throughout the year and achieve consistently high availability during operational life of a reactor. The operational costs of nuclear energy are relatively low due to proportionately lower fuel costs than other thermal power station types. By contrast, construction and decommissioning costs are considerably higher (Mott MacDonald 2010). The incentive therefore is for an operator to maximise electricity output even when the market price for electricity is low.

²⁹ World Nuclear Association, (2011), *Nuclear Power in the World Today*, Available at: <http://www.world-nuclear.org/info/inf01.html> (Accessed 16 November 2012).

For natural gas power stations, with proportionately higher fuel costs but with lower construction and decommissioning costs, there is an economic incentive to vary output based on electricity price (Mott MacDonald 2010; Denholm, King et al. 2012). The other important driver of nuclear power's baseload preference arises from aspects of reactor physics and thermal inertia in large steam turbines (an issue that also affects large coal power stations); individually and collectively these mean that varying output is more difficult to manage than in the case of CCGTs (Diamant and Kut 1981; Denholm, King et al. 2012). However, it should be noted that the French grid has demonstrated the long term capability of running light water reactors flexibly (Pouret et al, 2009).

Denholm and King et al. (2012) note; "as variable generation sources such as wind and solar are added to the grid, they will reduce the opportunities for continuous (baseload) operation.". Higher renewable generating capacity, with near-zero marginal generation cost, therefore creates the potential for nuclear load shedding when renewable output is high and electricity demand is low (Denholm, King et al. 2012; Grave, Paulus et al. 2012). Pöyry show that the annual load factor for nuclear reduces as the proportion of renewables capacity in the grid increases. This is because of an increase in load shedding during periods where electricity demand is low but wind output is high. Pöyry suggest that nuclear annual load could be reduced to as low as 60% in their Very High (80%) renewables penetration scenario. The implications of this amount of load shedding would be increased levelised costs for nuclear power providers as the operating output of the reactors against fixed costs is reduced. This situation is, however, subject to a contractual regime that favours spot prices over guaranteed delivery.

This issue may be mitigated by the flexible output provided by CCGT and OCGT generating capacity up until 2030, with reduced penalties in terms of efficiency and the release of non-CO₂ air pollutants compared to older coal plant. Ultimately, it is assumed that CCGT capacity will decline in line with decarbonisation pathways. It may also be possible, and economically competitive, to operate post-combustion capture CCS power stations as flexible capacity but this has not been demonstrated commercially (Chalmers, Lucquiaud et al. 2009; Davison 2011; Chalmers, Gibbins et al. 2012). To avoid load shedding, excess generation from nuclear plant, as with renewables, could potentially be stored for periods of peak demand in grid connected storage although this is not at present available at large scale (see Section 12.1 for further discussion).

9.4 Connection to the grid

New electricity generating capacity has to be connected to the national transmission network by relevant the National Electricity System (NETS) operators (National Grid in England and Wales, Scottish Power Transmission and Scottish Hydro Electric Transmission Ltd in Scotland), a process overseen by National Grid in Great Britain (Northern Ireland has different operator). NETS provide connections to existing transmission networks nearby and reinforce sections of the network if necessary to accommodate a higher voltage when a new generator is added. The costs of doing this vary by the location of new generating capacity and the capacity of the existing network in that area. For example, in West Cumbria both nuclear power and offshore wind generating capacity (installed in the Irish Sea) will require transmission line connections and reinforcement of the West Cumbrian

transmission system before new capacity can be added.³⁰ The cost of new infrastructure is dependent upon the distance to be covered, the voltage requirement and whether the cables are over ground (pylons), underground or subsea (Parsons Brinckerhoff 2012). Costs and the timescale for enabling a connection depend upon planning issues, which are particularly acute for areas without previous transmission infrastructure (Parsons Brinckerhoff 2012).

Increased renewables generation will require transmission line expansion into areas with suitable for wind, wave and tidal resources. The nuclear reactors under consideration are to be located adjacent to existing sites, meaning connection lines have a short distance to cover to national transmission infrastructure. However, this does not mean that grid reinforcement would not be required at all, particularly in scenarios where nuclear output is significantly increased.

In terms of the low voltage distribution network, averaged over the year the system usage is typically around 20% of capacity, rising significantly during periods of peak use. Whether the distribution network would require significant upgrading depends on three principal factors; i) what is the increase in the overall carrying capacity (i.e. a move to 470TWh), ii) how can this be distributed over time to ensure that peaks are kept within acceptable ranges (influenced significantly by the levels of demand management/active demand), and iii) what level of resilience to loss of load is acceptable. Currently the system has a significant level of redundancy that helps maintain security of supply. This could be weakened permitting greater demand and peaks without network upgrade – but at the cost of a reduction in the ability of the network to cope with periods of high demand and other network faults.

Low voltage distribution issues are equivalent for nuclear and centralised renewable electricity generating capacity. However, distributed generating capacity presents a distinct set of engineering difficulties in ensuring power quality (i.e. the stability of voltage, frequency, extent and restoration of interruptions to electrical supply). The delivery of “smart grids” and/or micro-grids to accommodate diverse and variable sources of electrical supply and demand is an area of substantial ongoing research (Blaabjerg et al 2006; Barnes et al 2007; Calderaro et al 2009). Such a transformation is a much greater investment and technical challenge than the addition of new passive transmission and distribution assets.

9.5 Summary

Decarbonisation of grid electricity is seen as a key component of delivering on the UK’s climate change commitments. Three supply side technology types are currently available for decarbonising electricity; renewables, nuclear and coal or gas with carbon capture and storage (CCS). Each has different properties and implications for the transmission, distribution and consumption of electricity through the grid. Furthermore, the grid itself is expected to change substantially through adding new and different loads (such as heating), the incorporation of demand side response, the

³⁰ See National Grid, (2012), *North West Coast Connections*, Available at: <http://www.nationalgrid.com/uk/Electricity/MajorProjects/NorthWestCoastConnections/> (Accessed 1/11/2012)

presence of storage, interconnection to other national grids, and the addition of distributed generation.

Given the absence of contemporary grids with many or all of these features it is difficult to establish robust conclusions on the constraints and feasibility of such grids from empirical research (Lannoye, Flynn et al. 2012). Pöyry, commissioned by the Committee on Climate Change, have modelled the feasibility of an electricity grid with very high levels of renewables penetration (up to 94%), but there are uncertainties to resolve about how a grid of this sort would function. A 74% renewables component of the UK electricity grid by 2030 specified in the FoE pathways may therefore be feasible, providing balancing and grid stability issues are resolved. With regard to CCS, the literature suggests that there may be barriers to upscaling gas CCS capacity even if the demonstration plants prove successful and are delivered on time.

In terms of compatibility, very high levels of variable renewable generation may reduce the load factor of baseload generators, such as nuclear power and CCS. This has consequences for the economics of these power sources, increasing the levelised cost of their electricity and potentially the overall cost of the grid supply. This would most likely effect nuclear power to a greater extent, as gas CCS appears to have greater potential to successfully operate as flexible generation (as CCGTs do in the current electricity mix).

Grid connection of the nuclear stations presently proposed for the UK will require some reinforcement in transmission capacity. Costs and time for delivery of grid connections for offshore renewables will be greater than for nuclear. Integration of distributed generation, directly on the low voltage network, presents a very different set of engineering challenges that have not been considered in detail in this report.

10 Interactions between nuclear power and other low carbon technologies

In much of the policy discourse around achieving low carbon electricity generation there is an assumption that this will be delivered by a mix of renewables, nuclear and fossil fuels with CCS; for instance in the UK Low Carbon Transition Plan (H.M. Government 2009). However, the idea that one technology can be easily substituted for another is open to question. For example, Willis and Eyre (2012) have argued that switching low carbon generation technologies for high carbon ones is likely to be more problematic than is often assumed due to the substantial differences in the physical properties of the supply technologies.

This section considers the issue of whether construction of new nuclear power plants is likely to promote or hinder the development of alternative forms of low-carbon electricity generation, either technically or socio-economically. It will consider why there may be issues with the relationships between different electricity generation technologies, focusing on nuclear and renewable, and what implications this may have for the compatibility of the two approaches to electricity to develop together.

10.1 Electricity generation as more than just technology

When considering electricity generation technologies it is all too easy to conceive of them as simple substitutes, where one technology delivering a given quantity of electricity can in essence be exchanged for an alternative design with the same annual output of electricity. As public and policy debates illustrate, there is clearly much more to technology than its presence as a discrete object delivering, in this case, identical electrons along very similar cables. Renewable energy and nuclear power are surrounded by a suite of social, economic and political factors. Echoing research from the field of sociology of technology, all technology “comprises a combination of technical, social, organisational, economic and political elements” (Bijker 2009) – in practice they are not discrete technologies but part of a complex and dynamic socio-technical system. Moreover, certain kinds of technology are, so it is often claimed, “strongly, perhaps unavoidably, linked to particular institutionalised patterns of power and authority” (Winner 1986, p.38). However, this can be a spatial-scale as much as a technical issue. Large wind farms may be owned and operated by the same energy firms as are coal and gas fired power stations, whilst smaller stand alone turbines and micro-renewables may be individually or communally owned – and as such be part of a very different pattern of authority and with very different sets of motivations.

Seeing nuclear power and renewable energy as socio-technical systems opens the debate about their compatibility and the need to go beyond the technical to consider political factors, economic issues and the society that they are part of. This does not suggest they are necessary incompatible, but that structures and policies for each individually may not only be different from each other, but also be very different from those that support a mixed portfolio of supply options.

10.2 Aspects of compatibility

The point that the relationship between nuclear power and renewable energy is chiefly antagonistic, has been made for many years, e.g. (Lovins 1977). Watson *et al* (2012) have recently assessed evidence for the proposition that institutional and economic support for nuclear will undermine

support for other options. Reviewing the levels of nuclear power and renewable energy across different countries, they find that for some countries there is evidence for a dominance of one path or the other being pursued, e.g. France for nuclear, Denmark for renewables.³¹ However, there are other examples where nuclear and renewable energy do appear to coexist, e.g. Sweden and, until the post-Fukushima acceleration of the *Energiewende* programme, Germany.³² Of particular interest is the suggestion that, even where nuclear and renewable energy have coexisted, their different paths did not always develop at the same times. However, the evidence base is limited and the area warrants further empirical research.

The nature of the technologies and how they generate electricity has the potential for them to be viewed as conflicting but a different interpretation of the electricity system, or alternative regulatory environment, could see them as naturally compatible. With nuclear power operating most effectively as a base load and renewable generation (particularly wind) providing much more variable levels of electricity, they offer very different supply characteristics. Watson *et al* (2012), suggest this does not imply they cannot ‘technically’ coexist. Verbruggen (2008) and to a degree Mitchell (2008), however argue that they are unlikely to coexist, as renewable energy’s affinity with demand reduction and demand side response contrasts with reduced incentives to do the same if nuclear power is pursued.³³ Such a conclusion is more a product of the political, regulatory and financial structures and intentions as it is an immutable facet of the different technologies. There may be real opportunities for developing synergies between nuclear and renewables but this will require a complete appreciation of the social-technical energy system comprised of technical, financial, material and habitual structures.

It is a considerable simplification to talk of renewable energy and nuclear power as homogeneous technologies themselves. Renewable energy generation especially is a diverse set of technologies with different technical and spatial characteristics. Some technologies such as off-shore wind ‘fit’ a centralised generation system (e.g. offshore wind) whilst others such as solar PV are being currently deployed in the UK in a more decentralised way with smaller scale generation closer to the electricity consumer. Different conceptions of the users of energy are also identified in the literature, from uninterested consumers in the centralised system to ‘energy citizens’ in a decentralised system (Devine-Wright 2007). The differences between the decentralised renewables and nuclear power are likely to be more significant than they are between nuclear and centralised large-scale renewables (Foxon, Hammond et al. 2008; Watson, Scott et al. 2012). It is, of course, possible that technically decentralised and centralised generation can coexist, indeed, Bouffard & Kirschen (2008) are clear that new approaches to network design can allow both systems to work in symbiosis.

³¹ The relative proportions vary; France produces approximately 75% of its electricity from nuclear power whilst in Denmark renewable sources and coal each provide about 40% of electricity at present ([Danish Energy Agency](#), 2012)

³² Germany is phasing out its existing nuclear power stations, a process which could conclude as soon as 2017; See Umwelt Bundes Amt (2011). Restructuring Electricity Supply in Germany. www.umweltbundesamt.de

³³ Whilst the ability to reduce peak load enables less responsive generators, e.g. nuclear, to provide a greater share of total energy supplied, demand side response is arguably more significant for grid stability when combined with non-dispatchable renewable technologies which vary over shorter time periods such as wind.

10.3 Summary

Seeing nuclear power and renewable energy as components of broader socio-technical systems opens the debate about their compatibility and the need to go beyond the technical to consider political factors, economic issues and the society that they are part of. This does not suggest they are necessary incompatible, but that structures and policies for each individually may not only be different from each other, but also be very different from those that support a mixed portfolio of supply options. It also opens up consideration of centralised and decentralised systems of provision and consumption, and the innovations required to integrate them.

This is an area of limited direct research. A review of the levels of nuclear power and renewable energy across different countries has identified both dominance and coexistence of nuclear and renewable electricity generation. However, the evidence base is limited and the area warrants further empirical research.

In the UK, recent years have witnessed concerns from business, NGOs, politicians, economists and academics about diverse aspects of electricity supply, be it lock-in, costs, intermittency, and (de)centralisation. However, whilst the fear of many stems from the perception that their favoured technology is not being considered fairly, since 2006 several GW of sizeable and centralised wind farms have been commissioned by multinational energy companies, decentralised photo-voltaic panels have undergone a *relative* explosion in their installation rates, triggered primarily by an explicit government policy of subsidisation through feed in tariffs, nuclear power has been evidently the subject of widespread discussion and increasing attempts to adjust market and planning rules in its favour, and gas CCGTs have increased their contribution to grid capacity by over 7GW. Whilst there is some academic legitimacy to concerns of one socio-technical system locking-out another, the UK reality appears much more muddled. It is perhaps from this that there is a real opportunity to rethink how a low-carbon and resilient energy system can be fostered, one in which traditionally competing generating technologies can be develop synergistically. What is evident is that the old ways of thinking are unlikely to resolve simultaneous contemporary climate change, sustainability, social and economic concerns around access to affordable and reliable energy.

11 CO₂ Implications of substituting gas for nuclear power generation

New build nuclear power stations are regarded by some as a key component of a decarbonised UK grid. Given the uncertainties in financing, technology, construction and planning, it is reasonable to explore the carbon emissions implications were nuclear plants not constructed on the eight sites identified in the UK before 2030. In this section we explore the emissions implications if nuclear generation capacity was replaced by gas, both with and without carbon capture and storage (CCS). The build program in the DECC Central Projections is compared to an ambitious but technically plausible roll out of new nuclear power capacity, the CCC “Illustrative scenario” for low cost decarbonisation of the power sector. Assumptions are also made about the availability of CCS that may mitigate emissions from additional gas capacity. Three possibilities for CCS are described; i) no additional capacity available other than that present in the base scenario, ii) additional availability, and iii) a scenario without any CCS present.

An alternative case of renewable energy generation, electricity demand reduction, or some degree of existing nuclear plant life extension, is of course conceivable. Feasibility would be dependent upon capacity requirements and grid characteristics as discussed below. However, these options would result in no major difference in emissions to a case with nuclear power and emissions calculations are not performed. It is likely that a struggling UK nuclear power programme would be replaced with a combination of gas and renewables capacity and so the figures calculated represent the upper and lower bounds of a range.

These scenarios are indicative and do not, for instance, include any direct modelling of the dispatch of different generators over a given load profile; electricity generated is assumed to substitute directly when averaged over a year. Interpretation of the significance of the emissions differences is dependent upon the context of nuclear and gas generation, for instance on the UK emissions budget being followed and the penetration of electricity into the energy system. The discussion chapter that follows considers these issues more fully.

11.1 DECC Central scenario

The DECC Central scenario is directly taken from the DECC Updated Energy & Emissions Projections (October 2012).³⁴ It envisages that the first new nuclear power station becomes operational in 2020 and five further stations are completed by 2030. The pace of roll out is much slower than in the CCC Illustrative scenario and results in 9.9GW of new capacity being added over this period.

It is assumed that the load factor³⁵ for new nuclear capacity is 86%. This compares with an average load factor for nuclear in the UK over the last five years of 60%.³⁶ Although it is towards the upper

³⁴ http://www.decc.gov.uk/en/content/cms/about/ec_social_res/analytic_projs/en_emis_projs/en_emis_projs.aspx

³⁵ Load factor is the ratio of the electrical energy produced by a power plant for the period of time considered, to the electrical energy that could have been produced at continuous full power operation during the same period.

³⁶ Calculated from DUKES (Department of Energy and Climate Change 2012)

end of expected load (see Chapter 6, p28), the DECC assumption is not unreasonable given that new build reactors are anticipated to have lower scheduled service requirements and frequency of unexpected outages compared to the UK's present fleet. The World Nuclear Association estimates "that one quarter of all reactors globally have load factors of more than 90% and nearly two-thirds have load factors of more than 75%" (National Audit Office 2012). Reactors are taken to be 1.65GW capacity.

11.2 CCC Illustrative scenario

The CCC Illustrative power sector scenario is described in the CCC Renewable Energy Review (May 2011) and is based around a 40% penetration of renewables into grid electricity. Full numerical details of the trajectory are not provided in the CCC document, however, the text refers to "investment on all eight currently approved sites, with around 18 GW new nuclear added to the system through the 2020s, resulting in around a 40% share (175 TWh) in 2030" (CCC 2011, p25). On this basis, the grid is taken to be 460TWh.

The Pöyry technical constraints report (2011) that supports the CCC Renewable Energy Review sets out the UK timeline for proposed nuclear power stations (p71). The numerical scenario presented here assumes that all proposals in the 2010 National Policy Statement (EN-6) are realized promptly. The construction programme to 2025 would involve:

- EDF building 3.2GW at both Hinkley Point and Sizewell, 1.6GW at Bradwell, Heysham and Hartlepool; and
- Hitachi's successor to Horizon Nuclear Power building at least 5GW split between sites at Wylfa and Oldbury; and
- NuGen³⁷ building up to 3.6GW at Moorside near Sellafield.

For a range of reasons this program is at the more optimistic end of the new-build futures:

- Horizon Nuclear Power was a joint venture between RWE and E.ON. However, in March 2012, after a strategic review, both companies pulled out of a potential deal (e.g. see National Audit Office 2012) and announced that they would be selling Horizon and the two proposed sites. Hitachi have recently purchased Horizon, after Areva and its partner, the China Guangdong Nuclear Power Group (CGNPC), withdrew their bid.³⁸
- Approval for only one of the three potential reactor designs is complete. Areva's UK EPR reactor completed the Generic Design Assessment (GDA) process in December 2012 having been originally scheduled to conclude by June 2011³⁹. The AP-1000 reactor has received interim approval but 51 technical issues remain outstanding⁴⁰. Without a customer confirmed for this reactor Westinghouse have put their response on hold. The Hitachi-GE Advanced Boiling Water Reactor (ABWR) was submitted for GDA in January 2013. Reactors

³⁷ A consortium of GDF SUEZ SA and Iberdrola SA

³⁸ <http://www.guardian.co.uk/business/2012/oct/03/british-nuclear-china-investors-pull-out>

³⁹ <http://news.hse.gov.uk/onr/2012/12/uk-regulators-confirm-acceptance-of-new-nuclear-reactor-design/>

⁴⁰ <http://www.hse.gov.uk/newreactors/2011-gda-issues-epr.htm>

of this type have been approved and completed in Japan, with others under construction in Japan and Taiwan, however, no timescale for the UK process has yet been released.

- There is uncertainty over construction times for new nuclear stations. The two current projects in Europe that are underway and use the EPR design, which would be used for at least some stations in the UK, are well behind schedule. For Flamanville in France, the original completion date was scheduled for 2012 and now has a likely completion date of 2016, giving a construction time of nine years. For Okiluoto in Finland, the likely completion date is also 2016 compared to the planned date of 2009, giving a construction time of eleven years (National Audit Office 2012). The use of the GDA in the UK may alleviate some barriers, as could the learning from the problems on these two projects (e.g. EDF is building the reactor at Flamanville). In Japan, the four most recent ABWRs were constructed in less than four years.⁴¹ It is suggested that construction projects in China are on schedule but acknowledged that they are being constructed under different workforce and governance regimes to those seen in Europe (e.g. see evidence from EDF in Energy and Climate Change Select Committee 2012).

A detailed build programme or generation trajectory is not provided by the CCC so reactors are assumed to be added at an even rate over the period 2019-2030, realising 20GW new capacity by the end of the period. Taking equivalent assumptions of load factor and reactor size as per the DECC Central scenario suggests the generation of 149TWh electricity in 2030.

11.3 Nuclear capacity and generation in each scenario

The growth in cumulative generation capacity and expected electricity output is presented in the figures below.

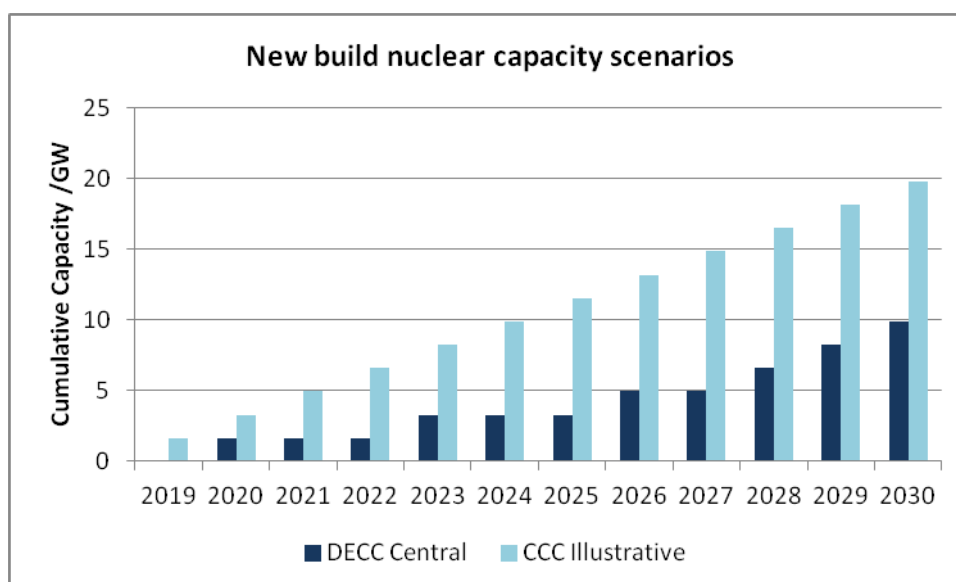


Figure 5 Total new nuclear capacity in the two alternative scenarios

⁴¹ <http://www.world-nuclear.org/info/inf08.html>

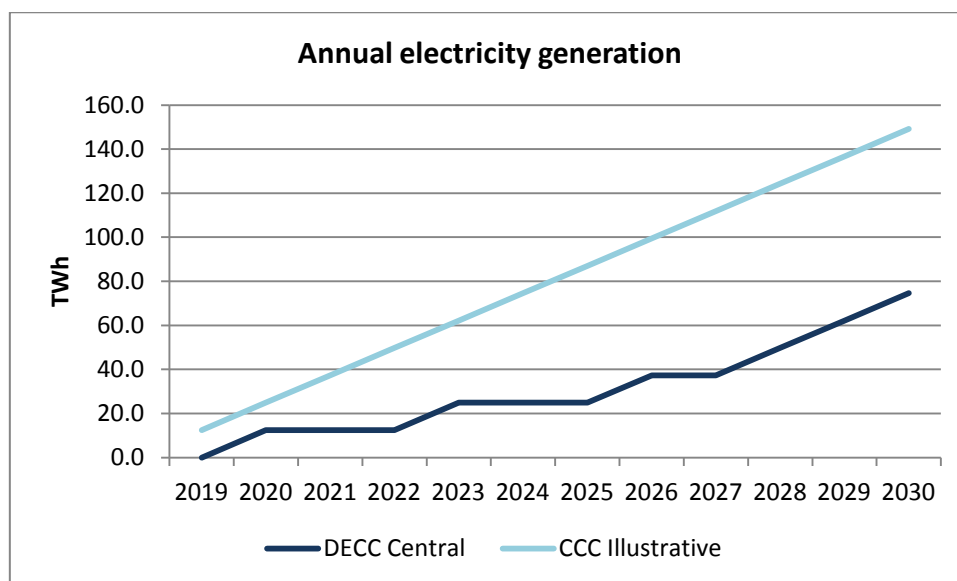


Figure 6 Annual electricity generation in the two alternative scenarios

11.4 Carbon Capture and Storage (CCS) deployment

CCS has the potential to substantially reduce the emissions from fossil fuel combustion in the power sector although it will not entirely eliminate them. The technology is complex, comprising both the capture process on the site of the power generator and wider facilities for the compression, transport and geological injection of the captured CO₂. It is also novel and has not yet been constructed at the utility scale. In order to look at the carbon implications of the different scenarios, it is necessary to understand how CCS might be deployed through time.

Given the uncertainty around the technology and its delivery, three different scenarios for CCS have been used to give a range of possible outcomes and timescales for deployment. “UKERC On Track” is taken directly from recent work by the UK Energy Research Centre (Heptonstall, Markusson et al. 2012), “Zero CCS” is self evident, and the third scenario is internally consistent with either the DECC or CCC nuclear scenario in each case. The details of the scenarios are:

- UKERC On Track – This is described as a “high but plausible level of CCS deployment by 2030 based on policy ambitions” (Heptonstall, Markusson et al. 2012). For the purposes of our study the distribution of early to mid 2020s deployment is modified slightly so as not to be arbitrarily exclude availability in the nuclear scenarios above because of timing mis-alignments by one or two years. However, the cumulative quantity and overall timing of the UKERC On Track CCS scenario is preserved: between 2019 and 2025 3GW is available, and by 2030 12GW of CCGT with CCS generation capacity is installed.
- No additional CCS – trajectories for CCS are taken for the DECC Central and CCC Illustrative scenarios respectively. It is assumed therefore that CCS proceeds but that no additional CCS capacity is available to mitigate emissions from gas replacing nuclear capacity.

- Zero CCS – No CCS deployment beyond demonstration facilities prior to 2020 (Heptonstall, Markusson et al. 2012). In effect, all unbuilt nuclear capacity *and* planned CCS capacity in each scenario is substituted with unabated CCGT power stations.

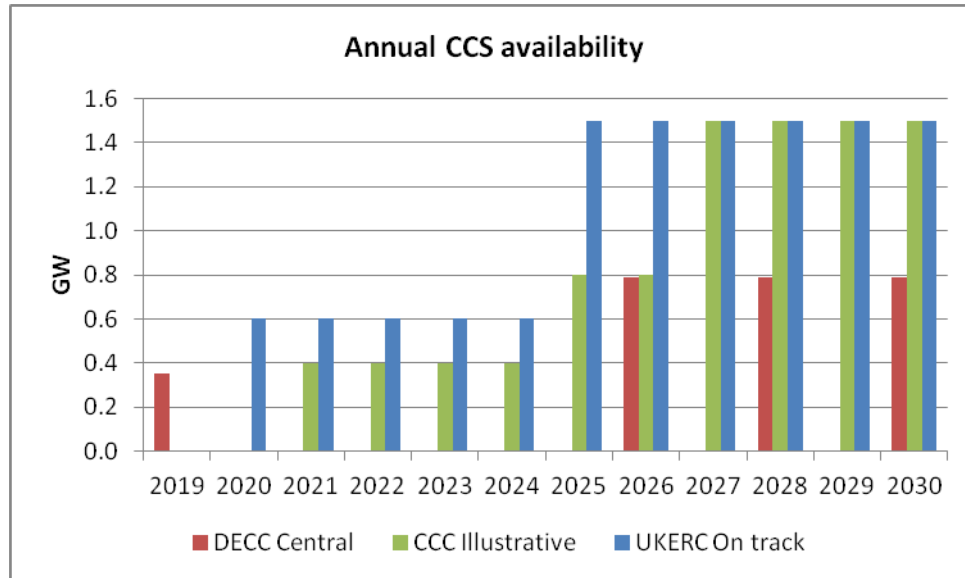


Figure 7 Annual CCS availability (2019-2030)

The CCS scenarios are combined with the nuclear scenarios to give a range of outcomes. For Zero CCS and No Additional CCS cases, all proposed nuclear capacity is replaced with unabated CCGT. In the UKERC On Track scenario it is assumed that CCS capacity that is available *over and above* that already included in the nuclear scenarios can be used to mitigate emissions. Figure 8 shows, for 2030, the total amounts of unabated and CCS gas capacity for each of the scenario combinations.

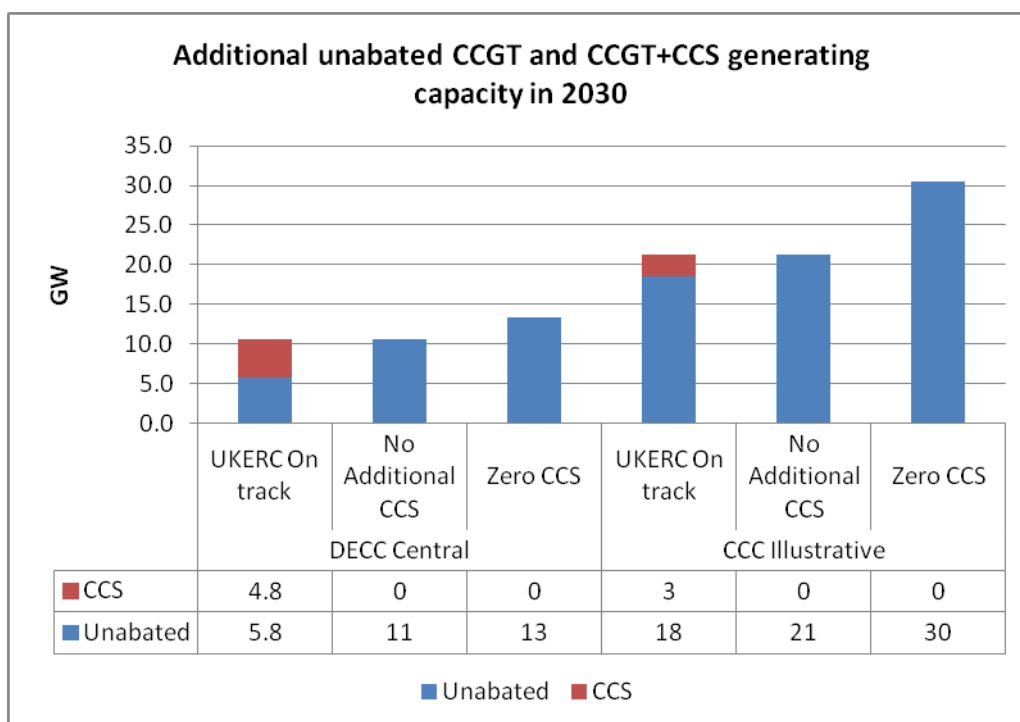


Figure 8 Additional unabated gas and gas CCS generating capacity in 2030

11.5 General assumptions

To assess the amounts of CO₂ emissions associated with the different nuclear/non nuclear scenarios, a number of further parameters need to be specified. An assumption on the thermal efficiency of new electricity generating gas plants is necessary to assess their future emissions output.⁴² The five year average thermal efficiency of gas generation in the UK is 47.3%.⁴³ Given that the gas stations being considered are new combined cycle (CCGT) units, a thermal efficiency of 55% has been assumed. This is in line with assumptions in Mott MacDonald (2010) and ‘top of the line’ efficiency for current CCGT plants.⁴⁴

For CCS plants both the efficiency penalty and capture rate need to be assumed from theoretical values as there are no CCS plants of comparative scale presently in operation. The efficiency penalty relates to the effect that CCS has on thermal efficiency of the plant and the additional energy needed for the capture process, compression, transport and injection of CO₂. Following the work of the International Energy Agency, Florin and Fennell (2010) suggest that current ‘state of the art’ post consumption carbon capture gives an efficiency penalty of 10%. However, a series of estimates from the USA suggest a penalty nearer 15% (Rubin and Zhai 2012). Combining this penalty with thermal

⁴² This is the efficiency with which the generation plant converts fuel to electricity. If the efficiency was 50% then producing 1GWh of electricity would require 2GWh of fuel.

⁴³ Calculated from Department of Energy and Climate Change (2012). Digest of United Kingdom Energy Statistics 2012, The Stationary Office.

⁴⁴ See for example <http://www.timera-energy.com/uk-power/ccgt-investment-in-the-uk-and-germany/>

efficiency estimates results in a net efficiency of 47%. This is in line with the DECC 2050 Pathways calculator 2025 assumption (Worksheet I.b:J55) and a number of thermodynamic model estimates (Kvamsdal, Jordal et al. 2007; Popa, Edwards et al. 2011). Unfortunately, analysis of thermal efficiency in load following mode for CCGT+CCS was not identified as is the case for coal+CCS (see Chalmers, Gibbins et al. 2012 Fig.2).

The capture rate reflects the proportion of CO₂ from combustion that is retained by the CCS process. Looking at CCS with different approaches to coal generation, Hammond et al (2011) suggest that capture rates could range from 85% to 93%, while Florin and Fennell (2010) cite capture rates of 90%. Capture rates beyond this level are reported to influence investment cost greatly but not affect energetic efficiency substantially (Kvamsdal, Jordal et al. 2007). A capture rate of 90% has been assumed for this work.

Key assumptions		
Nuclear	Load factor	86%
Gas	Load factor	80%
	Thermal efficiency	55%
CCS	Capture rate	90%
	Net efficiency	47%

Considering the absence of commercial utility or gigawatt scale CCS at present, this choice of parameters may be regarded as somewhat optimistic. Combining them suggests a direct emissions intensity of 43 gCO₂/kWh of electricity (Kvamsdal, Jordal et al. 2007). The parameters are taken to be constant over this time period with no major technical change; it is assumed that early demonstration plants in the UKERC On Track, DECC and CCC scenarios are sufficiently effective to be deployed at scale. However, no allowance is made for reduction in load factor due to integration with large quantities of variable renewable capacity, nor any reduction in thermal efficiency arising due to this sub-optimal operation.

With these assumptions it is possible to estimate the CO₂ emissions associated with both unabated and CCS gas electricity generation equivalent to amount of nuclear generating capacity outlined in the above scenarios (Figure 7). These figures represent direct combustion emissions (Scope 1) and do not account for upstream emissions in gas production, nor emissions embodied in the infrastructure itself. Upstream emissions may add a not insignificant penalty, up to 20% dependent upon the source and transport of the gas (AEA 2012; Hammond, Howard et al. 2013). This has implications for CCS where typical theoretical assumptions of 90% reductions in emissions output are not achieved in practice. Hammond et al (2013) estimate that the final emissions intensity of electricity from coal CCS to be 310 gCO₂e/kWh and for gas CCS 80 gCO₂e/kWh. Depending upon future grid composition, scale and level of decarbonisation required these levels are still likely to be problematic. Nuclear power also has indirect emissions from for instance, the production of fuel and the construction and decommissioning of plants, however, these are typically found to be much lower. Warner and Heath (2012) provide a comprehensive systematic review of life cycle assessments (LCA) and discussion of the field. They harmonise 99 independent estimates for

comparison, finding the median emissions intensity from their sample to be 12 gCO₂e/kWh, with median future expectations between 9 and 110 gCO₂e/kWh by 2050.⁴⁵ Given the difficulties of comparing LCAs the figures presented here are direct CO₂ emissions, which are negligible for nuclear and renewable power sources.

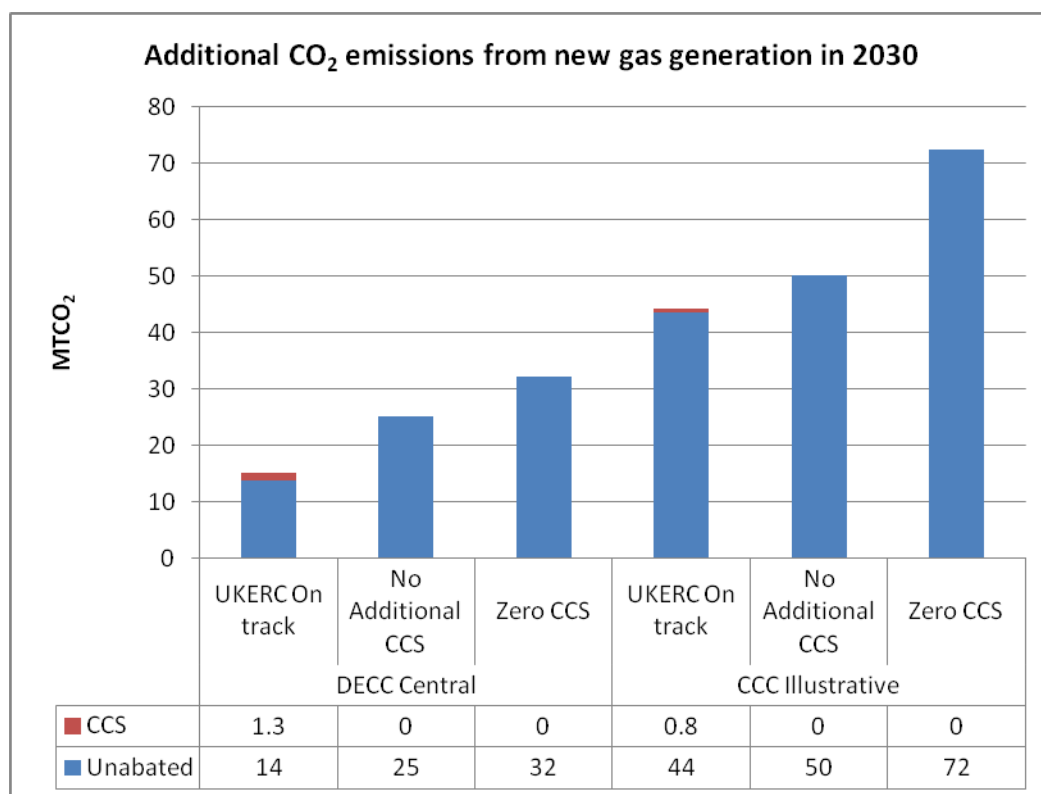


Figure 9 Additional CO₂ emissions from new gas generation in 2030

⁴⁵ Primary energy source for extraction, uranium ore grade and the LCA methodology were found to be the major factors contributing to a wide variation in estimates. The inter-quartile range, covering the central 50% of estimates, was 17 gCO₂e/kWh and the full range of the pool 110 gCO₂e/kWh. Warner and Heath (2012) is one of a number of papers in a special issue of the Journal of Industrial Ecology dedicated to meta-analysis of life cycle assessments and including discussion of multiple energy sources <http://onlinelibrary.wiley.com/doi/10.1111/jiec.2012.16.issue-s1/issuetoc>.

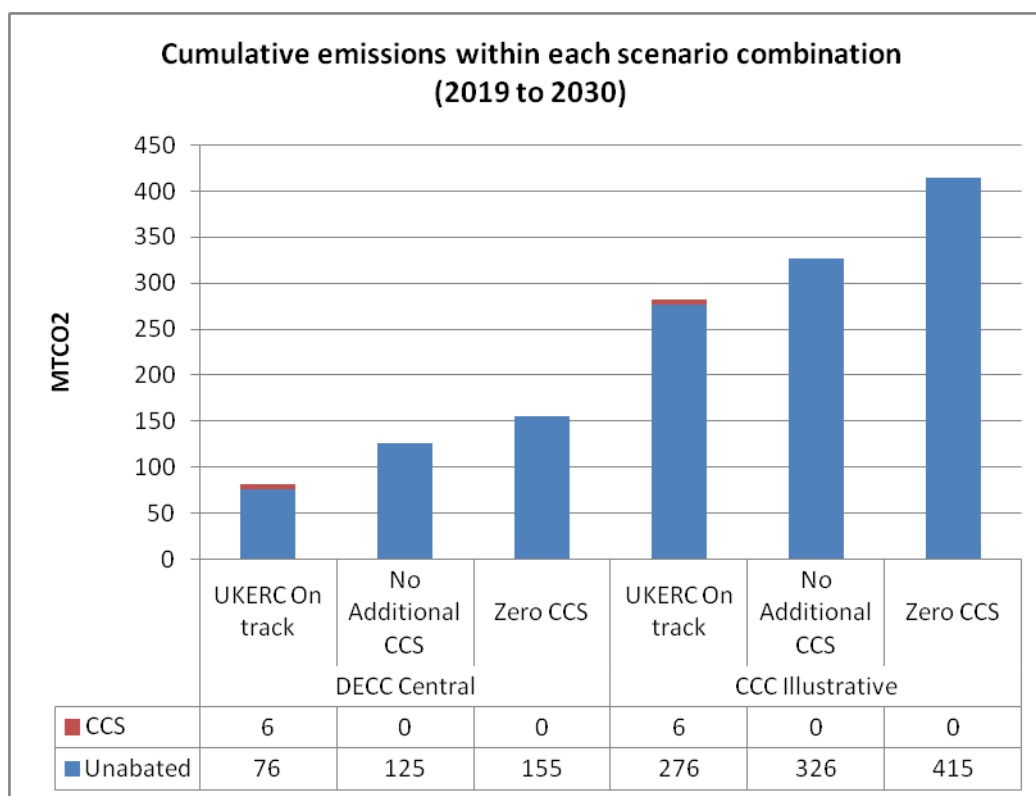


Figure 10 Cumulative CO₂ emissions within each scenario combination (2019 to 2030)

11.6 Contextualising CO₂ implications

Three comparisons are particularly useful in helping to understand the implications of this possible substitution and are presented in the table below. They concern i) the grid decarbonisation target for beyond 2030, ii) the cumulative emission budget on the way to 2030 and iii) the final proportion of the grid that must be met by renewable sources (all other parameters remaining constant). Table 5 describes the quantitative outcomes of the combination of the nuclear build plans and CCS availability scenarios. The three highlighted bands draw attention to key results.

Considering CCS, UKERC On Track will be challenging to deliver technically and politically and its authors cite 15GW as the upper bound of multiple policy appraisals (Heptonstall, Markusson et al. 2012). “Zero CCS” clearly represents the lower bound of possibilities for CCS.

Table 5 Contextualising CO2 implications of combinations of nuclear build plans and CCS availability

Nuclear scenario	DECC Central			CCC Illustrative		
	UKERC On Track	No Additional CCS	Zero CCS	UKERC On Track	No Additional CCS	Zero CCS
Grid impact in 2030						
Total electricity generation (TWh)		370		458		
Baseline grid emissions intensity (g/kWh)		102		50		
Emission from additional gas plant (MTCO2)	15	25	32	44	50	72
Resulting grid emissions intensity (g/kWh)	142	170	189	147	160	208
Total emissions, CCC 4th Budget (MTCO2)		310		310		
% of total budget from new gas	5%	8%	10%	14%	16%	23%
Cumulative impacts 2023-2027						
Additional emissions (MTCO2)	35	50	59	125	146	177
% Domestic Action budget	2%	3%	3%	6%	8%	9%
% Domestic Action Traded sector budget	5%	7%	9%	18%	21%	26%
% of reduction from Third to Fourth period	12%	17%	20%	42%	50%	60%
Renewable Alternative						
Alternative generation required (TWh)	41	75	96	130	149	214
Final Grid % Renewable	49%	58%	64%	68%	73%	87%

11.6.1 Grid emissions intensity in 2030; an indicator of progress to long term decarbonisation

The CCC's Fourth Carbon Budget report (Committee on Climate Change 2010) outlines the importance of reducing the emissions intensity of power generation to 50gCO₂/kWh by 2030 to, amongst other reasons, enable the decarbonisation of mobile and dispersed sources of emissions that would otherwise be very difficult to mitigate, namely heating and transport. This measure is an indication of progress towards meeting overall decarbonisation objectives from 2030 to 2050. It should be noted that the baseline grid, including nuclear, anticipated in the DECC Central projections does not meet this recommendation, it is also somewhat smaller than the CCC's scenario. In all cases, replacing nuclear capacity with gas would substantially exceed the 50g/kWh objective, even if CCS were available to the greatest extent suggested at present (UKERC On Track). If CCS is not available at all then the issue is compounded.

11.6.2 Quantities of emissions to 2030; an indicator of pressure to decarbonise other sources of emissions

Considering the absolute quantities of emissions in terms of the total UK emissions budget in 2030 gives a sense of the additional reductions that would be required from other sectors of the economy. The CCC's Fourth Budget Report outlined a Domestic Action emissions budget in line with the UK achieving its endpoint 2050 emissions reductions target. Emissions in 2030 should be no more than 310 MtCO_{2e}, a 50% reduction on 1990 levels (Committee on Climate Change 2010). Replacing nuclear capacity with gas in the DECC Central projections occupies 5-10% of the annual budget, but this rises to 14-23% in the CCC Illustrative scenario. Non-power sector emissions reductions may be achieved, for instance, through energy demand reduction in heating and transport, and increases in biofuel or biomass imports, but reductions will have to be beyond those already included in the respective scenarios and likely at greater marginal cost than in the power sector. Emissions from substituting gas capacity are larger for the CCC scenario given the much greater quantity of nuclear power it otherwise includes.

The consequences of replacing nuclear capacity with gas are also relevant in the period prior to 2030. The Committee on Climate Change outline two possible Fourth Carbon Budgets for the period 2023-2027; Domestic Action totals 1950MtCO_{2e} and is presented as a medium abatement pathway to be achieved within the UK whilst Global Offer is slightly stricter at 1800MtCO_{2e} but has provision for the import of emissions reductions credits from outside Europe. It is worth noting that such offset credits from the Clean Development Mechanism have been substantially criticised from conceptual, ethical and pragmatic perspectives in the academic literature (Lohmann 2005; Bumpus and Liverman 2008; Anderson 2012).

Within each of these budgets a distinction is made between the "traded" and "non-traded" aspects of the economy i.e. those sectors that are regulated under the EU Emissions Trading Scheme (EU ETS) including power generation, and those that are not, such as road transport. Were nuclear stations to be relied upon to meet electricity demand but fail to achieve the expansion outlined in the scenarios above, gas would add emissions to the traded sector budget. In the DECC Central case this may be between 5% and 9%, but were a larger programme to be relied upon over this period, as outlined by the CCC, gas replacement would exceed the traded sector budget by up to 26%.

The global net quantity of emissions resulting from the UK power sector is also complicated by the operation of the EU ETS prior to 2020. As this is a cap and trade system, any UK changes should not affect the final volume of emissions from the EU as the same quantity of permits persists and will be imported or exported by UK generators. It is for this reason that Germany has argued that the shutdown of nuclear power stations will not necessarily increase net emissions even if their generating capacity is replaced by fossil fuel stations. It is unclear in practice whether or not emissions have increased as a result of the nuclear phase out as the counterfactual case, of how the alternative power sector would have performed otherwise, cannot be observed directly. Direct assumptions and economic models with implicit assumptions have presented alternative cases (Bruninx, Madzharov et al. 2012; Lechtenböhmer and Samadi 2013).

One might therefore expect the emissions consequences from these scenarios to be equivalent prior to 2020. However, in practice the EU ETS is substantially over supplied with emissions permits. Although this policy instrument was intended to drive decarbonisation of the power sector, the price

of EUAs has been persistently low and is expected to remain so throughout the third phase (2013 to 2020) as the excess from the second phase will be carried over. Presently there appears to be little or no abatement occurring in Europe as a result of the ETS (Morris 2012). It is not clear what the political response to these chronic problems will be before and after 2020. Therefore, as well as being a useful exercise in comparing the emissions performance of different technical systems, it seems likely that the infrastructure path taken by the UK will have material implications for climate change.

11.6.3 Renewables requirement to substitute for nuclear and CCS in each case

Finally, it is important to note that gas is not the only possible alternative to nuclear generation for emissions reductions in the power sector. Renewable technologies of various sorts would maintain the emissions budgets and decarbonisation targets. Of course other factors could change; energy demand could be reduced, fuel switching may take place in the power sector or elsewhere in the economy, or the emissions budgets themselves may be breached.

The electricity required to replace the nuclear and/or CCS requirement in the DECC and CCC scenarios in 2030 is presented in the final section of the table above. These figures are within the realms of technical feasibility as presented within the DECC 2050 Pathways Tool Level 4 trajectory for renewables but would require very high levels of deployment of offshore wind and solar PV. In the case of the CCC Illustrative scenario, 68-87% renewable penetration by 2030 is similar to the FoE contribution to the DECC 2050 Pathway (74% renewable grid) but beyond the Pöyry Very High scenario (64% renewable grid), all with similar grid energy supply (430-470 TWh).⁴⁶ Whilst the Pöyry Max scenario also indicates that a greater penetration of renewables is possible (94%) no date is specified for the realisation of such a grid; the technical issues this may introduce are discussed in Chapter 9.

11.7 Summary

The purpose of this short analysis has been to explore the potential carbon implications of replacing different amounts of nuclear electricity generation with gas in the UK for the period up to 2030. A judgement is not made on the political likelihood or economic implications of any particular combination. The policy framework of legally binding emissions budgets arising from the EU ETS and the UK's Climate Change Act mean that the net environmental consequences of the alternatives are unclear. In theory net emissions should remain constant regardless of the physical infrastructure as reductions should be displaced to other parts of the economy. In practice this is likely to generate significant political resistance and may cause budgets to be relaxed or breached.

Comparison programmes of nuclear new build were taken from DECC projections and CCC scenarios, suggesting 9.9GW and 20W of new capacity anticipated by 2030. The nuclear scenarios were combined with three scenarios for CCS deployment; UKERC On Track representing current industrial ambitions, No Additional CCS and Zero CCS to develop beyond demonstration sites. Substituting

⁴⁶ The FoE pathway includes expansion of the electricity grid, to 470TWh in 2030, due in part to substantial electrification of industry, heating and transport. It meets the CCC Domestic Action budget whilst also including 50MTCO₂e from international aviation and shipping. Full details are available on the DECC site <http://goo.gl/r96zh>

nuclear capacity for renewable generation or electricity demand reduction would have negligibly different emissions consequences. The additional renewable generation and possible grid penetration was calculated for each scenario, and shown to be within the scale of technical resource availability.

The implications of the gas scenarios are significant, primarily in the long term. It is the grid decarbonisation target for 2030 and beyond that is threatened most by the presence of increased gas fired generation, more so than the carbon budgets on the way to this goal. If CCC Illustrative proposals for new nuclear were relied upon but not achieved, for whatever reason, and replaced with new gas electricity generation then the target for emissions intensity of generation would be pushed out of reach even with additional CCS capacity. Furthermore, the emissions calculations presented here are for direct emissions from combustion, not including upstream emissions in fuel processing for either nuclear or fossil fuels. They are therefore most likely an underestimate.

In the DECC Central scenario, more modest build rates suggest that there would be less of an impact were they to be abandoned, although in this case, the scenario's original grid emissions factor is double the 50gCO₂/kWh decarbonisation objective. The emissions difference between nuclear and gas capacity in the fourth carbon budget period would not substantially exceed the traded sector budget, which is 35% of the total budget. However, the presence and persistence of this higher carbon infrastructure will increase pressure on non-power sector emissions reductions in the years that follow, even if retrofit CCS were available.

If at a future date it seems likely that both nuclear and CCS deployment are unlikely to be built at utility scale then substantially increased ambition in the renewable sector will be vital to maintain progress in decarbonisation. As noted in the introduction, the context and parameters for the scenarios in this chapter have been drawn predominantly from CCC recommendations and budgets. They have not been compared to emissions budgets that would give good probabilities of meeting 2°C commitments equitably, as enshrined in the Copenhagen Accord (2009). Such budgets would be expected to necessitate more stringent and urgent reductions in emissions, the consequences of which are discussed in the following chapter.

12 Nuclear power and climate change mitigation pathways

12.1 Comparison of CCC and FoE Pathways to 2030

As part of the DECC 2050 Pathways exercise Friends of the Earth (FoE) have presented a 2050 energy and emissions pathway (Bullock, Childs et al. 2010), that meets stricter emission budgets than the Committee on Climate Change (CCC) and does so without new nuclear capacity. FoE and the CCC choose different global budgets with differing expected consequences; FoE use a global budget with a less than ~33% chance of exceeding a 2°C global mean temperature increase, as opposed to a global budget with a ~63% chance of exceeding a 2°C presented by the CCC (Bullock, Childs et al. 2010; Anderson and Bows 2011). FoE also give the UK a reduced share (in comparison with the CCC) of the global emissions budget, by using an apportionment methodology reflecting the UK’s diminishing proportion of global population. This means that the FoE emissions pathway requires a greater level of decarbonisation than that of the CCC by 2030.

The FoE low carbon energy pathway is achieved without new nuclear capacity. It includes greater reductions in total energy demand than assumed in the CCC pathways but with similar steps towards electrifying transport and heating. Although overall energy demand is reduced by ~27% between 2010 and 2030 in the FoE pathway, electricity demand increases from the 330TWh baseline⁴⁷ to 466TWh over the same period. Both FoE and the CCC adhere to a target of reducing the carbon intensity of electricity supply (gCO₂/kWh) from around 540 gCO₂/kWh (2008 level (Committee on Climate Change 2010)) to 50gCO₂/kWh in 2030. While the CCC include for 175TWh of nuclear output by 2030 in their 40% renewables illustrative scenario, FoE have presented a pathway with 74% renewable electricity alongside carbon capture and storage technology, and some remaining nuclear and unabated gas generation.

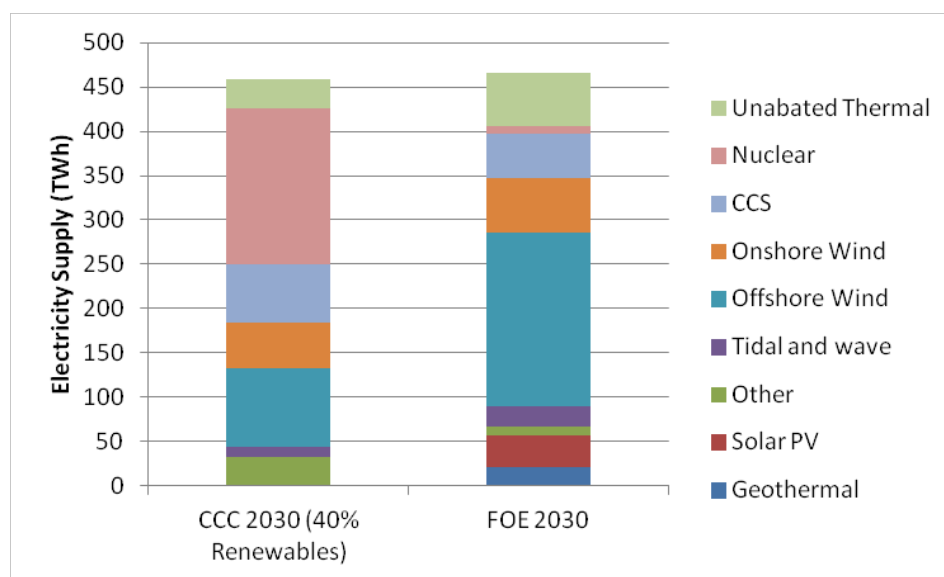


Figure 11: Comparison of FoE and CCC (40% Renewables) 2030 electricity mix (TWh)

⁴⁷ The 2010 baseline in the DECC 2050 Pathway Calculator.

Given the availability of different renewable electricity resources in the UK, it seems likely that a high renewables future will be dominated by wind generation, but with a significant contribution from solar PV. An electricity grid with this configuration differs significantly from the current grid and presents a number of challenges. The intermittency associated with wind energy causes periods of excess generation, relative to demand, and periods of low wind output (again) relative to demand – such as when low wind speeds coincide with demand peaks. Wind output variability at hourly, daily, seasonal and annual durations present challenges for system balancing, whilst rapid variations over seconds and minutes can cause frequency stability issues for network operators (Lannoye, Flynn et al. 2012). Northern Germany (33%) and West Denmark (24%) are examples of regional electricity grids where a significant proportion of annual electricity supply is from wind generation. Going beyond this level to over 50% wind penetration (of annual supply) raises research questions about how to achieve this effectively within a power system (Holtinen, Meibom et al. 2009; Lannoye, Flynn et al. 2012). In particular there is an identified need to develop voltage management strategies that reduce faults and improving wind output forecasting techniques (Holtinen, Meibom et al. 2009; Lannoye, Flynn et al. 2012). In addition to technical issues around power system stability from higher proportions of variable generation there is a need to have strategies and assets in place to assist with balancing supply and demand. Pöyry (2011), Lannoye, Flynn et al. (2012) and Holtinen, Meibom et al. (2009) identify a number of ways to balance power systems with high levels of wind capacity:

- **Bulk Storage:** Large scale electricity storage offers the potential to reduce load shedding when renewables output exceeds demand, and supplement supply when demand exceeds available renewables output. Holtinen, Meibom et al. (2009) suggest that as the proportion of variable generation increases, so will the value and relative investment in storage systems. With higher wind capacities, inter-month and inter season storage (with lower wind output in summer months and load shedding in winter from offshore wind in particular) storage will become more important (Pöyry 2011). This requires methods of storing more energy than likely to be possible through pumped storage and pressurised air. Hydrogen produced through electrolysis and then stored for use in CCGTs or in fuel cells has been proposed as one means of achieving this (Korpas and Greiner 2008; Pöyry 2011), although there are a number of inefficiencies in this process that reduce effective storage capacity.
- **Interconnectors:** Wind energy intermittency can be reduced by expanding ‘balancing areas’. This mitigates the impact of lulls in wind speed in specific geographic areas, by having a greater area over which to aggregate output (Holtinen, Meibom et al. 2009). The national grid in Great Britain is itself a large balancing area, but interconnection with electricity generation in Ireland, Norway and Northern European regions expands this further. The UK could then export surplus electricity if there is demand in neighbouring electricity grids and import it to help meet demand when neighbouring grids have surplus to export. The role of interconnection is limited by connection capacity (up to 12GW capacity is identified by Pöyry) and the alignment of UK demand for imports with excess generation in connected grids for export (Pöyry 2011). If neighbouring grids include similarly high proportions of variable generation, particularly wind, the ability of interconnection to balance UK supply and demand may be reduced (Pöyry 2011).

- Demand Flexibility. Smart grids, time variable energy tariffs and operating reserve contracts (a payment for a user reducing demand at short notice) can provide demand-side balancing of the power system. Flexible demand, energy requirements that can be shifted to different time, could help to align demand with supply in a more variable grid. For example, electric vehicle and appliance charging could be designated to activate when electricity generation is high. Important questions about how much demand can be shifted and over what period (i.e. within a day or week etc) is a matter of ongoing research.

In their ‘Very High’ renewables scenario Pöyry (2011) suggest that 64% renewable electricity generation could be possible in the UK by 2030. Their analysis shows that in this scenario, unabated and CCS gas could provide sufficient flexibility in the power system to balance intermittency issues (Pöyry 2011). This scenario has the similar grid emissions intensity (51gCO₂/kWh) as the FoE pathway in 2030, but includes new build nuclear providing capacity. Although the FoE pathway includes more intermittent renewables, it also includes a much greater geothermal, CCS and unabated (CCGT) gas, which add greater flexibility than nuclear (Pöyry 2011).

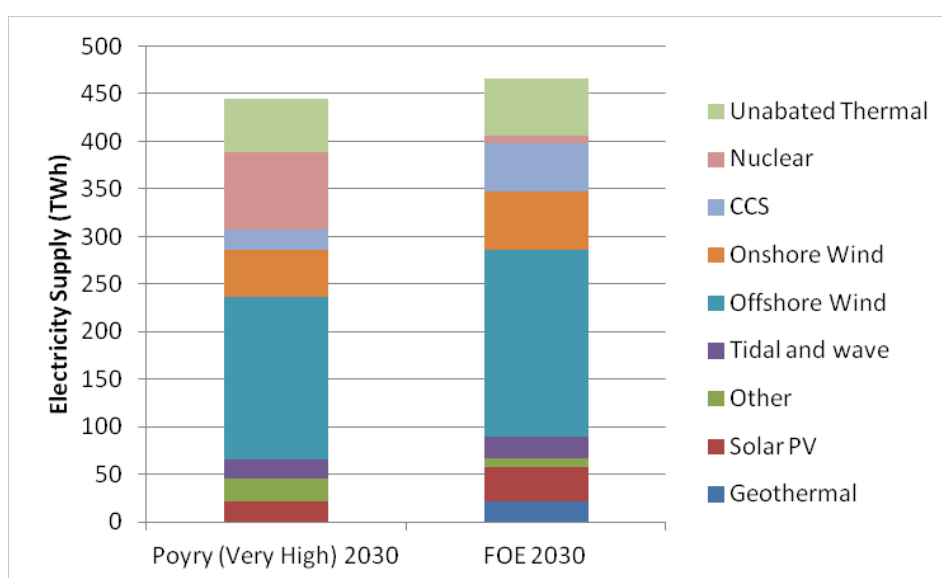


Figure 12 Comparison Pöyry (Very High) and FoE 2030 electricity mix (TWh)

The FoE pathway to 2030 represents a technically credible alternative to new build nuclear scenarios. Further research is needed on integrating higher proportions of variable generation, particularly wind, but it is anticipated that future electricity grids will likely be able to accommodate 74% renewable penetration, subject to deployment of flexible demand and delivery of advanced power electronics.⁴⁸ The high proportion of gas CCS (more than double the capacity estimated in Pöyry scenarios) by 2030 may be more challenging given the potential for delays in establishing

⁴⁸ Personal communication with Professor Peter Crossley, University of Manchester (November 2012).

demonstration programmes and subsequent deployment (Heptonstall, Markusson et al. 2012). The potential for hydrogen generation and other bulk storage options may mitigate this risk.

12.2 Post 2030

The energy system challenges post-2030 requires further research. To fulfil FoE emissions budgets decarbonisation of the whole energy system is required. Without significant use of bio-energy this implies an increase in electrification of transport and heating (electrification of 76% of total energy demand), thereby increasing overall annual electricity demand. Expanded power sector CCS capacity compensates for a phasing out of unabated natural gas, meaning the overall proportion of renewables on the grid only increases to 77%. Given the increased prominence of CCS (23%) in this pathway, by 2050 the carbon intensity of the grid will depend upon the gCO₂/kWh performance realised by CCS at this time.⁴⁹

In the FoE pathway there is also a large (100TWh) annual demand for electricity to power air capture carbon sequestration of around 110MtCO₂ by 2050, which adds a large load to the future grid. The FoE pathway achieves greater electricity supply requirements (up to 815TWh in 2050) by increasing renewables and CCS capacity. Should air capture not prove viable at such a scale all energy services not supplied by low carbon sources may have to be transferred on to the electricity grid. This grid would then itself have to be as close to zero carbon as possible, which may have implications for the level of CCS appropriate within the FoE budget. It may be possible to achieve this through greater renewable energy generation, but this would require further research into grid stability and power quality to establish.

12.3 Discussion: How the Copenhagen Accord's "on the basis of equity" reduces emissions budgets for the UK

The analysis within this review is premised fundamentally on the framing of climate change specified by DECC, the Committee on Climate Change and Friends of the Earth (FoE); in particular the global and national-level assumptions underpinning their pathways for decarbonising the UK's electricity supply. Consequently, in using this review to inform decisions on the value or otherwise of nuclear power as a low-carbon energy source within the UK mix, it is essential to do so with a full understanding of the higher-level global context. If this context were to change, for instance, raising the probability of not exceeding 2°C (i.e. reducing the global emission budget) or allocating a greater proportion of the global budget to non-Annex 1 nations (i.e. reducing the UK budget) the relative merits of nuclear power would also change (but not necessarily the final judgement).

For example; if the probability of not exceeding 2°C was reduced in line with the language of the Copenhagen Accord (i.e. 1-10%), the available global carbon would be radically reduced. Assuming FoE's specified energy demand remains unchanged and with other things being equal, this would dramatically reduce the UK's pre-2030 budget and essentially eliminate any emissions space post 2030. In light of this and given that the only very-low/zero carbon energy supply options are

⁴⁹ Consideration should also be given to the upstream emissions associated with natural gas in light of the increased energy input for CCS, as highlighted by Hammond et al (2013).

renewables, some biomass sources and nuclear (a gas CCS emission factor of $\sim 80\text{gCO}_2/\text{kWh}$ would be too high) the relative merits of the different supply options would certainly change.

Similarly, if the global budget remains at the level proposed by FoE, but the apportionment of emissions between Annex 1 and non-Annex 1 nations was to be closer to the equity framing of the Accord, with later emissions peaks for non-Annex 1 nations, the budget for the UK (and other Annex 1 nations) would again be dramatically reduced, with the relative merits of the very-low/zero carbon supply options changed.

To put this simply, if the 2°C and equity commitments of the Copenhagen Accord and Cancun Agreements (reaffirmed at the 2012 G8 Camp David meeting) were to be adhered to, four alternative conclusions arise:

1. *A radical and sustained reduction in energy demand (probably an aggregate, across all sectors, of well over 70% within ten years)*
2. *A rapid and significant extension of renewable supply capacity, well beyond the level FoE consider possible in their DECC 2050 example pathway*
3. *A significant and rapid new build programme of nuclear powerstations commenced immediately and in complement with large-scale renewable supply*
4. *A combination of two or more of the above; one of which would need to be a reduction in energy demand (i.e. #1) to realise the significant and immediate reductions dictated by tighter 2°C and equity constraints.*

Whilst FoE have explicitly opted for a global carbon budget with a lower probability of exceeding 2°C than did the Committee on Climate Change, they nevertheless chose to maintain a similar division of global emissions between Annex 1 and non-Annex 1 nations (though using a different method). Both of these decisions are important issues for this analysis, with the subsequent conclusions substantially a function of this quantitative and qualitative framing.

FoE's choice of global carbon budget for a 33% chance of exceeding 2°C is readily defended in light of the science, but such a defence is much more challenging to evoke in terms of how this budget is apportioned to the UK. In this regard, two particular issues arise.

Firstly, the CCC and FoE budgets imply all responsibility for emissions from global deforestation accrue solely to those nations deforesting. Whilst, such a position may have merit in terms of increasing the available 'energy' budget to the Annex 1 nations such as the UK, it does so at the expense of major reductions in available 'energy' emissions space for the poorer, non-Annex 1, nations (where the deforestation is occurring). Climate change has arisen as an issue principally from the emissions of wealthier, and already deforested, Annex 1 nations. It is therefore difficult to reconcile the view that responsibility for current deforestation emissions resides solely with those nations' deforesting - and the explicit equity dimension of the Copenhagen Accord, amongst various international agreements. In response to this inequity, Anderson and Bows chose to consider deforestation as a global overhead, thereby allocating emissions from deforestation amongst all nations – not only those deforesting. As they note *"[t]he global overhead approach ... does not absolve non-Annex 1 nations of responsibility for deforestation emissions, as their available budget for energy-related emissions, along with the budget for Annex 1 nations' energy emissions, will be reduced as a consequence of the emissions from deforestation."* Anderson and Bows go on to

defend this position by noting how historical emissions (pre-2000) are essentially considered a global overhead that favours Annex 1 nations. Ultimately they conclude that “[g]etting an appropriate balance of responsibilities is a matter of judgment that inevitably will not satisfy all stakeholders and certainly will be open to challenge. As it stands, the approach adopted for this paper in which historical (and deforestation) emissions are taken to be global overheads, is a pragmatic decision that, if anything, errs in favour of the Annex 1 nations.”⁵⁰

Translating this principal into a quantitative constraint for the UK, Anderson and Bows assume a twenty-first century budget of 266GtCO₂ from deforestation, which, disaggregated to the national level equates to about a 20% reduction in the available energy-emission space in the UK’s budget. However, since Anderson and Bows first proposed the 266GtCO₂ budget, deforestation emissions have fallen sharply. Following a similar method, this is likely to halve the global overhead to around ~130GtCO₂. In light of this, it is probably wise that the FoE and CCC budget be reduced by approximately 10% to account for the UK’s ‘fair’ share of global deforestation.

The second and much more significant issue, is to ask what it is reasonable to expect for emissions paths for non-Annex 1 nations, and therefore what is a remaining budget for Annex 1 (UK-type) nations (with the sum of the two equating to the global budget for ~33% of exceeding 2°C). As it stands the FoE and CCC approaches, almost by necessity given the legacy of cumulative emissions, demand an inequitable division of emissions space with increasingly little distinction drawn between the two regions. In brief, the CCC base their apportionment on a global peak in emissions of around 2016, with non-Annex 1 nations peaking just two years later. As with the apportionment of deforestation emissions, such a division of the global budget between Annex 1 and non-Annex 1 emissions runs contrary to both the wording and spirit of the Copenhagen Accord.⁵¹ The FoE methodology allows for a diversity of peaking dates within non-Annex 1 countries, China for instance in 2013 and India in 2034. Peaking is determined by present day per capita rates of emissions, placing urgent demands on middle income countries such as China, Thailand, Mexico and South Africa. Neither approach includes allowance for historic responsibility within the 21st century allocation; a consistent sticking point in UNFCCC negotiations.

Anderson and Bows (2011) again took a different framing of equity beginning with the question “what reduction profiles could non-Annex 1 nations reasonably be expected to achieve if pushed extremely hard in terms of a rapid transition away from their growing emissions, and towards absolute mitigation”. They adopted a range of scenarios, but suffice to say the budget remaining for

⁵⁰ It is worth noting that a recent paper Jiankun, H., C. Wenying, et al. (2009). Long-term climate change mitigation target and carbon permit allocation. 1673-1710. Energy Environment and Economy (3E) Research Institute, Tsinghua University. **1673-1710**. based on analysis undertaken at Tsinghua University in Beijing makes the case that "reasonable rights and interests should be strived for, based on the equity principle, reflected through cumulative emissions per capita". Building on this *cumulative emissions per capita* approach, the authors demonstrate how China's historical cumulative emissions are only one-tenth of the average in industrial countries and one-twentieth that of the U.S.

⁵¹ In addition to the clear language around equity, the Accord makes specific reference to how “*time frame for peaking will be longer in developing (non-Annex 1) countries*”. It would be misleading to suggest that the CCC UK pathways, in which just a few years’ grace is afforded non-Annex 1 nations to peak their emissions (based on territorial emissions) was in keeping with this.

the Annex 1 nations for all of these was substantially smaller than that assumed by CCC and FoE; and this for a slightly higher chance of exceeding the 2°C target.

In brief, and to put some perspective on the change in the scale of the challenge, if non-Annex 1 nations can peak by 2025, and reduce emissions thereafter at approximately twice the level Stern et al suggest is possible with economic growth, then there is no discernible emission space remaining for Annex 1 nations. Only if the growth to a 2025 peak in non-Annex 1 emissions is radically curtailed to just 1% p.a., from around 2011, and subsequently reduced at over 7% from 2025, is there any space for Annex 1 emissions – but still only if the latter’s emission reduce at over 10% p.a. from around 2010 – if not earlier.

The implications of this for the analysis within this report are potentially profound with the inclusion of even weak levels of equity considerably reducing the available UK emission budget. In brief, if the Anderson and Bows type assumptions are considered reasonable, radical increases in both the penetration of much lower-carbon energy supply along with a further reduction in absolute energy demand become necessary. This puts a very different complexion on the issue of whether nuclear power is advantageous to the energy system or not. Certainly, as the budget for the UK reduces there is a reciprocal increase in the need for more lower carbon electricity supply. The scale of the reduction in budget suggests that what supply there is, likely needs to be much lower in aggregate emissions/kWh, as well as much more of the total energy consumption being transferred to the grid. Put bluntly, with a 33-37% chance of exceeding 2°C and assuming non-Annex 1 nations collectively peak in 2025 and then radically reduce emissions thereafter, the UK energy system as a whole will need to be fully decarbonised by 2030; i.e. ~zero emissions/kWh from the grid with electricity providing 70 to 90% of final energy demand, depending on the viability of sustainable and very low-carbon biomass supply. This is a substantially more challenging energy system than that accompanying DECC, CCC and FoE’s pathways and as such gives rise to issues of scale that are beyond the scope of this current review of nuclear power.

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14 Annex 1 – Terms of Reference

This research will consider the potential new fleet of nuclear-power stations in the UK. Life extensions to existing plants or the longer term development of new reactor designs may be included in other subsequent pieces of work but are not directly investigated in this report.

This Terms of Reference sets out the overall context for the research, and the research questions, methodology, timetable and outputs for part one of the project.

All of the reports (interim and final) shall be confidential to Friends of the Earth until published by Friends of the Earth at a time and method of its choosing. All final reports will be published as long as they meet appropriate quality standards (well referenced, peer reviewed, evidence-based). The intellectual content of the work may be used by the Tyndall Centre for academic purposes, including *inter alia* research papers, grant proposals and presentations, after a period of 3 months following completion of the project, or if necessary sooner in consultation with FoE.

Context

Friends of the Earth is opposed to the construction of new nuclear power plants. Although nuclear power is comparatively low-carbon, there are major environmental downsides, for example the unresolved problem of the need for long-term storage of nuclear waste. These and other problems, in our view, outweigh the carbon benefits of nuclear, particularly given that our analysis suggests that nuclear power is not an essential requirement in tackling the UK's contribution to climate change.

We have carried out research into UK carbon budgets, using the DECC 2050 Energy pathway model, which demonstrates that new nuclear power is not necessary to meet the 2030 electricity decarbonisation goal recommended by the Committee on Climate Change or to keep the lights on⁵².

David Mackay, Chief Scientist at DECC⁵³ and Edward Davey, Climate and Energy Secretary⁵⁴ have both said that nuclear power is not essential to delivering the carbon reductions specified in the present UK carbon budgets.

We do not believe that new nuclear is a “cheap” option, as some claim. It receives multiple, ongoing subsidies, and the industry has a history of escalating costs during construction and over-runs in building schedules. We believe that there is mounting evidence that the Government's claims on the cost of nuclear do not stand up to scrutiny. There is also mounting evidence that costs of renewable power are falling and will decline significantly in future years.

Research objective

Friends of the Earth regularly reviews the evidence for its positions to ensure they are up to date.

This research is to provide an independent assessment to Friends of the Earth on evidence as to the importance or otherwise of nuclear power in meeting climate change commitments specifically and sustainability concerns more generally.

⁵² http://www.foe.co.uk/resource/briefing_notes/electricity_mix_2030.pdf

⁵³ See 5.04 pm at <http://www.guardian.co.uk/global/blog/2012/feb/01/nuclear-power-carbon-emissions-target?INTCMP=SRCH>

⁵⁴ <http://www.ft.com/cms/s/0/70f2a90e-b89e-11e1-a2d6-00144feabdc0.html#axzz1yGpEwcjK>

Questions for researchers

1. Would the development of new nuclear power hinder the development of alternative forms of low-carbon electricity production, either technically or socio-economically? Is there evidence of this in the recent past? Has research to date examined the institutions, economic, legal and social, created by or for new nuclear stations and the extent to which they are inimical to, or supportive of, renewable generation?
2. What is the carbon implication of a failure to meet the Government's expectation that eight nuclear plants will be built in the UK, in the period 2017 to 2030, if this generation capacity was provided by gas (abated and unabated)? The availability, timescale and performance of CCS will be considered without extensive additional research.
3. What are credible estimates for the current and future overall economic costs of electricity generated through new nuclear power plants compared to the costs of other forms of low carbon electricity generation? What are the trends in these costs and future expectations? What are the reasons for discrepancies between cost estimates (e.g. Mott MacDonald, Areva, Stephen Thomas)? Financial issues pertaining to the construction of new low-carbon generation of all kinds are a secondary consideration.
4. What are the other undesirable and desirable attributes of new nuclear power plants? Can the desirable attributes be met through some other way (e.g. CCS/renewables)? Issues to investigate include intermittency, employment, safety, risks, planning and ease of deployment, proliferation, waste and risks of simultaneous outages.

Research methodology

The research should be desk based secondary research involving critical examination of published material, supplemented with personal communications with research authors where necessary, and fully referenced. The final report should be peer-reviewed by two external academic peer-reviewers. Peer reviewers to be agreed by Friends of the Earth and the Tyndall Centre.

Research timetable

- A final report of 50 pages or more covering all questions should be completed by end of October 2012 with a draft final report provided by 17th October.
- FoE will return comments on the draft by 22nd October. Peer review of the report will proceed in November. Reviewers will be identified in advance by the authors and FoE.

Audience

The audience for the research is Friends of the Earth and technical in character with a short summary in the style of a summary for policy makers.

Research sign-off

The research will be signed off for fully meeting the Terms of Reference by Friends of the Earth's Executive Director after consultation with Friends of the Earth staff (Mike Childs, Simon Bullock, appropriate campaign and programme staff).