British Pugwash

Pugwash conferences on science and world affairs

Pathways to 2050:

Three possible UK energy strategies

Report of a British Pugwash Working Group

About British Pugwash

British Pugwash is the UK arm of Pugwash Conferences on Science and World Affairs, an international network of scientists and experts on international affairs, which seeks to inform government and the public on matters relating to science and world affairs. Carrying on the work that Joseph Rotblat and his colleagues began, it aims to bring scientific insight and reasoning to bear on threats to human wellbeing arising from the application of science and technology, and above all from the threat posed to humanity by nuclear and other weapons of mass destruction. It is also concerned with questions relating to the social responsibility of scientists, and the quest for an end to war itself.

Activities range from regular public discussion meetings and public education events to working with policy makers and officials. Publications include in-depth scientific and policy research as well as letters and statements to the media.

British Pugwash believes that we are living in challenging times, in which many established patterns of domestic and international behaviour are being questioned, and that there is a very real opportunity to influence political developments by urging that decisions should be based on good science and rationality.

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Cover photos (clockwise):

EPR nuclear power plant under construction at Olkiluoto, Finland

Jackup installing a turbine in an offshore wind farm (Seajacks)

Sandia Labs PV array in New Mexico (Solar Tour Southwest - photographer Pamela Cargill)

Carbon capture and sequestration pilot plant, Latrobe Valley, Victoria, Australia (CSIRO)

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February 2013

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Contents

Table of abbreviations

ABWR	Advanced Boiling Water Reactor
AGR	Advanced Gas-Cooled Reactor
AP1000	Westinghouse PWR (3rd generation)
BERR	Department of Business, Enterprise and Regulatory Reform
BETTA	British Electricity Trading and Transmission Arrangements
bn	Billion
BNFL	British Nuclear Fuels Ltd
BWEA	British Wind Energy Association [now RenewableUK]
BWR	Boiling Water Reactor
CAT	Centre for Alternative Technology
CCC	Committee on Climate Change
CCGT	Combined cycle gas turbine
CCS	Carbon Capture and Storage
CHP	Combined Heat and Power
COP	Coefficient of Performance
CPV	Concentrated Photovoltaic
CSP	Concentrating Solar Power
DECC	Department of Energy and Climate Change
DEFRA	Department for Environment, Food and Rural Affairs
DFR	Dounreay Fast Breeder Reactor
DfT	Department for Transport
DH	District Heating
DUKES	Digest of United Kingdom Energy Statistics
E.ON	International energy company
EDF	International energy company
EPR	European PWR (3rd generation)
FBR	Fast Breeder Reactor
FIT	Feed-in tariff
FOAK	First of a Kind
GHG	Greenhouse Gas
GIF	Generation IV International Forum
GNP	Gross National Product
GW	Gigawatt
GWav	annual average Gigawatts
GWe	Gigawatts electric

GWn	Nameplate capacity in Gigawatts
GWth	Gigawatts thermal
HLW	High-level waste
IAEA	International Atomic Energy Agency
IEA	International Energy Agency
IGCC	Integrated gasification combined cycle
INPO	Institute of Nuclear Power Operations
IPCC	Intergovernmental Panel on Climate Change
ITPOES	Industry Task Force on Peak Oil and Energy Security
LCGE	Levelised cost of generated electricity
LCICG	Low Carbon Innovation Coordination Group
LWR	Light water reactor
Markal	MARKet Allocation computer model
MOX	Mixed oxide fuel
MtCO2e	million tons of CO_2 equivalent
NGC	National Grid Company
NPT	Nuclear Non-Proliferation Treaty
NRC	Nuclear Regulatory Commission (US)
NTS	National Transmission System
Ofgem	Office of the Gas and Electricity Markets
PFR	Prototype Fast Breeder Reactor
PRISM	Power Reactor Innovative Small Module
Pu	Plutonium
PV	Photovoltaic
PWR	Pressurised Water Reactor
TINA	Technology Innovation Needs Assessment
toe	Tons of oil equivalent
TWh	Terawatt-hours
TWh/y	Terawatt-hours per year
url	Uniform Resource Locator
V2G	Vehicle to grid
WANO	World Association of Nuclear Operators
μSv/y	Micro Sieverts per year

Foreword by the Chairman of British Pugwash

Professor David MacKay, the current Chief Scientific Advisor to the UK Department of Energy and Climate Change (DECC), is urging the British public to engage in "grown-up conversations" about UK energy policy. We in British Pugwash decided to get involved in this issue in October 2011, shortly after holding an open meeting to publicise and discuss the concept of Planetary Boundaries, one of which is climate change due to CO_2 emissions. At that meeting we were impressed by the strong scientific consensus that there was an urgent need for national and international action to achieve substantial reductions in greenhouse gas (GHG) emissions, if not on the precise figure to target. However there was much less consensus on the practical steps to be taken. We have been concerned about the quality of public and political discussions on this subject, which frequently lack reference to realistic numbers, or use numbers very selectively. So we decided to prepare a report which would try to embody the kind of informed and quantitative debate on this subject which MacKay is seeking. Our intention was to exhibit a debate on possible UK energy policies, which was based on agreed facts and figures, and was focused on feasible energy strategies.

We decided at the outset not to get involved in the debate over the level of GHG emission reductions that are needed, or the required timescale. That requires an expertise in long-term climate modelling which we do not possess. In any case, the British government has decided that it cannot wait for the outcome of that debate, and has made international commitments on the emissions targets that underlie current UK energy policy. For the purposes of this report, those commitments have been accepted.

We considered, but quickly abandoned, the idea that we should come up with a single 'British Pugwash' view – our membership is too diverse for that. Instead, we set up a small Working Party to produce a report in which we would map out three 'possible' energy strategies. We defined 'possible' as meaning that the proposed technology either existed or could be developed and deployed on the required industrial scale within the period up to 2050, and that the resulting energy supply system would comply with the UK's international and UK parliamentary commitments on GHG emissions.

Our Working Party is a team of experts, each with years of experience of working in one or other sector of the energy industry, who collectively represent a reasonably broad spectrum of opinion about the best way forward for the UK. Within this team, we identified a 'champion' for each of the three strategies, and asked them to draft a chapter of this report. In order to ensure a common approach to energy accounting and costing the champions were encouraged to make full use of a computer tool which DECC has made publicly available under the title 'Pathways to 2050 Calculator'. Using this software, each champion has developed a 'Pathway', and computed its key numbers. We have called these quantified strategies the 'High Nuclear', 'High Renewables' and 'Intermediate' Pathways. Although there are doubtless many other equally 'possible' Pathways, we believe that our three span the range of possibility reasonably well.

The outcome of our analysis is that all three Pathways are broadly 'possible', though in each case, some of the technology is not yet fully proven. According to current estimates, all three Pathways have a broadly similar total cost - about £2.8 trillion between now and 2050. The real challenge will be to achieve political consensus on the right way forward, and to put in place a management process which will deliver it.

Christopher Watson

Executive Summary

Cheap, reliable energy is the bedrock of modern industrial societies. Over the past two centuries, the world has largely relied on fossil fuels. However there is now almost universal recognition that this reliance is unsustainable, if only because it is predicted to change the climate of our planet in disastrous ways. So there is an urgent necessity to develop energy strategies in which fossil fuels are progressively replaced by sustainable, low-carbon energy sources. In recognition of this, successive governments have committed the UK to reducing its GHG emissions by 80% (against a 1990 benchmark) in the period leading up to 2050. The task facing energy planners is to devise a strategy capable of meeting this target.

In October 2011, British Pugwash set up a Working Group composed of experts in various sectors of the energy industry to explore 'possible' strategies. By this we meant that the strategies should be based on technologies which had already reached sufficient commercial maturity, or could reasonably be expected to have reached it in time for them to be rolled out to meet the likely UK energy demands in the year 2050, and to meet the emissions target by that date. Being aware of the very wide range of opinion on how the required emission reductions might be achieved, British Pugwash did not task the Working Group to produce a single preferred strategy. Instead, it asked them to come up with three 'possible' Pathways to 2050, representing a wide range of possible strategies, and to initiate a debate on their strengths and weaknesses.

To encourage a quantitative, informed debate on this subject, the Department of Energy and Climate Change (DECC) has developed, and made publicly available, a computer tool entitled the 'Pathways to 2050 Calculator' that allows a wide range of strategies to be developed and assessed quantitatively. The Working Group has made extensive use of this software in preparing this report. For each Pathway, it has appointed a 'champion', charged with defining its parameters, and making the case for that strategy. All three Pathways envisage significant cuts in energy usage, and extensive electrification of energy uses in the home, industry and transport. All three Pathways achieve the required 80% reduction in GHG emissions by 2050.

The 'High Nuclear' Pathway relies predominantly on nuclear energy, backed up by lesser amounts of wind power and biofuels combined with Carbon Capture and Storage (CCS). It assumes that the UK will initiate its planned 'new build' of nuclear power stations as quickly as possible, and then continue to build further stations at a rate of about one station per year until 2050, at which point about 74% of its electricity would be nuclear. The most significant risks with this Pathway are associated with the high rate of nuclear build, and the possibility that CCS may be much more difficult or expensive than anticipated.

The 'High Renewables' Pathway assumes that the UK will run down its nuclear power programme as quickly as feasible, reaching zero by 2040, and will build up a portfolio of renewable sources, dominated by offshore wind turbines delivering 76 GW of installed 'nameplate' capacity by 2050. It also includes a substantial amount of bioenergy, leading to the use of 10% of the UK land area for the production of energy crops. It is also the Pathway that invokes the greatest reductions in energy demand, proposing that domestic and commercial energy consumption should fall by 38% between 2010 and 2050.

The 'Intermediate' Pathway is intentionally cautious in its assumptions about the growth in both nuclear and renewable energy, and in what can be achieved by energy savings. It does, however, introduce another (and perhaps more adventurous) element in the form of a significant programme of Carbon Capture and Storage (CCS), the use of which by 2050 accounts for 37% of electricity production. Since this technology has not yet been demonstrated anywhere in the world on a full commercial scale, its feasibility and cost remain to some degree unproven, though some components of the system are well-established.

The outcome of our analysis is that all three Pathways are broadly ‘possible’, though each has challenges which might eventually prove to be ‘show-stoppers’. All three meet the UK‘s international commitment on GHG emissions in 2050, though other (more immediate but less binding) targets for 2020 and 2030 may not be wholly achievable. According to the DECC Calculator, all three Pathways have a broadly similar total cost (capital plus operation costs) between now and 2050, with a total bill of order £2.8 trillion. To put this figure in context, the UK spent ~£95bn in 2010 alone on its energy supply system. So the estimated 40-year cost is not unreasonable.

Our overall conclusions are:

- There is an urgent need for the UK to take a decision on which Pathway to select. Leaving this decision to ‘the market’ is not a credible policy, if we are to meet the 2050 emissions target. Substantial government leadership and funding will be required.
- A plan with named technologies needs to be drawn up urgently, with target dates for the construction of full-scale commercial plants of the chosen types, a management team capable of implementing that plan, and a set of government-funded incentives to induce the private sector to implement it, and to establish training schemes for the cadres of skilled staff required to make it all happen.
- There needs to be an informed public debate on this issue, including an assessment of the less quantifiable environmental, social and international implications that are outwith the DECC Calculator.
- There is a need for an improved version of the DECC Calculator, which is more user-friendly, better documented, and better able to represent the renewables options.
- Whichever Pathway is eventually chosen, there will be a need for a very substantial expansion of the UK industrial infrastructure to handle a very major programme.
- We would encourage a prompt public debate on the future of UK energy policy.

The report begins by providing background information on the development of UK government energy policy (including the various commitments made, both to Parliament and internationally, on GHG emissions). Chapter 2 gives a brief survey of the current UK energy industry, with a focus on the numbers. Chapter 3 presents information about all the technologies invoked by the champions in the development of their chosen strategies, and provides background information about the DECC Pathways to 2050 Calculator. In Chapters 4-6 the three champions present their chosen Pathways. Chapter 7 brings together the numbers generated by the Calculator for the three pathways, and highlights their similarities and differences. It also highlights a range of issues which are relevant to the choice of the preferred Pathway, but which are not susceptible to simple numerical analysis, including international issues and UK public opinion. Chapter 8 gives each of the three champions (plus a few invited external experts) an opportunity to play ‘devil’s advocate’, and voice their concerns about the other pathways. Chapter 9 provides an overall summary and conclusions.

1 Introduction

1.1 UK government energy policy planning 1998-2012

The current phase in UK government thinking on energy policy can be said to have begun with the work of the Cabinet Office Performance and Innovation Unit (PIU) which was set up by the then Prime Minister, Tony Blair, in 1998, and which reported its review of energy policy in 2002[1]. This review emphasised that, after a decade or more of energy self-sufficiency, the UK now needed to formulate its energy policy in a new, and less favourable, economic climate. It would in future be increasingly dependent on imported oil and gas.

The 2003 Energy White Paper[2] picked up the conclusions of the 2002 review, and proposed concrete steps towards the creation of a low-carbon economy. It defined an energy policy with five key goals:

- to put ourselves on a path to cut the UK's carbon dioxide emissions – the main contributor to global warming – by some 60% by about 2050, with real progress by 2020
- to maintain the reliability of energy supplies
- to promote competitive markets in the UK and beyond, helping to raise the rate of sustainable economic growth
- to improve our productivity
- to ensure that every home is heated adequately and affordably.

This White Paper did not specify the energy mix which would achieve these goals, preferring to rely largely on the market to determine this. However it did recognise a role for government actions to help achieve these goals (see paragraphs 1.27-1.33), including measures to stimulate the growth of renewable and energy efficiency technologies and, very possibly, new nuclear build and carbon capture technology, if the carbon-emission targets were to be met.

The 2006 Energy Review Report[3] confirmed the 2003 goals, and argued that by 2020, 20% of our electricity should come from renewable sources. It also indicated a certain shift in policy on the nuclear option, recommending that government should seek to remove the administrative barriers to the replacement of our existing nuclear fleet by new build, while insisting that the private sector should initiate, fund, construct and operate any new nuclear plants.

The Energy White Paper of May 2007[4] largely confirmed the government's support for the 2006 Energy Review. It also quoted with approval the conclusions of the Stern report on climate change[5], published in October 2006. Furthermore, it supported steps to improve energy efficiency in the home and in industry and transport, and to develop micro-generation, district heating (DH) schemes, combined heat and power (CHP) and biomass-fuelled heating at community and industry scale. It announced that the government was also issuing a public consultation document[6] on its proposals for new nuclear build in the UK.

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[1] http://webarchive.nationalarchives.gov.uk/+/http://www.cabinetoffice.gov.uk/media/cabinetoffice/strategy/assets/theenergyreview.pdf

[2] http://www.decc.gov.uk/assets/decc/publications/white_paper_03/file10719.pdf

[3] http://www.decc.gov.uk/en/content/cms/legislation/white_papers/energy_rev_06/energy_rev_06.aspx

[4] http://www.berr.gov.uk/files/file39387.pdf

[5] http://webarchive.nationalarchives.gov.uk/+/http://www.hm-treasury.gov.uk/independent_reviews/stern_review_economics_climate_change/stern_review_report.cfm

[6] http://webarchive.nationalarchives.gov.uk/+/http://www.berr.gov.uk/files/file39197.pdf

This consultation led to the publication in January 2008 of the White Paper on Nuclear Power[7]. This reported that the government had received over 4000 responses to its consultation. It confirmed its view that nuclear power was low-carbon, affordable, dependable, safe and capable of contributing to diversity in electricity supply. However it recognised that there were widespread concerns about nuclear power, which needed to be properly addressed. These included the familiar issues of safety, environmental protection, security and nuclear weapon proliferation. There were also concerns about the long-term management of radioactive waste, particularly as regards the appropriateness of relying on the private sector to take responsibility for facilities that could lead to permanent liabilities. There was also a perception that investment in nuclear energy might 'crowd out' investment in alternative technologies, particularly renewables, and a concern that there was a growing skills gap in the UK nuclear industry. Nevertheless, in his introduction to the White Paper, the Prime Minister, Gordon Brown made it clear that he was now personally committed to the inclusion of a nuclear contribution to the generation of electricity, alongside other low-carbon technologies.

The White Paper spelt out the government arguments in support of this conclusion. Not having nuclear as an option would increase the costs of delivering its carbon emission goals, and would increase the risk of failing to meet those targets. It expected that applications from energy companies to build new nuclear power stations would focus on areas in the vicinity of existing nuclear facilities, but did not consider it necessary to put in place additional restrictions or conditions before giving energy companies the option of investing in new nuclear power stations. It envisaged delivering a framework that would enable energy companies to begin construction of the first new nuclear power stations in the period 2013-2014.

This White Paper was followed by a statement to Parliament, on 9 November 2009[8], made by Ed Miliband, the Minister for the newly-formed Department of Energy and Climate Change (DECC), in which he informed the House that, in response to the lifting of the moratorium on the construction of new nuclear power stations, energy companies had announced intentions to build 16 GW of new nuclear power, and had nominated 11 sites for new nuclear power stations, all on or near existing nuclear sites. Of these, 10 sites had been judged by the government as potentially suitable, and these had been included in the draft Nuclear Policy statement being put before the House. The 11th site, Dungeness, was not included in this National Policy Statement, because it was liable to cause an adverse effect on the integrity of its internationally unique eco-system.

Along with this policy on nuclear power, the government was also supporting work on clean fossil fuels. The statement to Parliament noted that the EU was provisionally offering €180 million to assist Hatfield power station fit CCS, and it confirmed that E.ON and Scottish Power were bidding for the next stage of the current government-funded CCS competition for a post-combustion power station. The government's aim was for CCS to be ready to be deployed on 100% of all new coal-fired power stations by 2020. To support this aim, there would be no new coal-fired power stations built without CCS. Furthermore they were planning up to four projects between 2009 and 2020, including up to two post-combustion projects and up to two pre-combustion projects. To make CCS financially viable, the proposed Energy Bill would contain powers to introduce a 'Climate Change levy' on energy suppliers, as announced in the Budget by the Chancellor, to support demonstrations and retrofit of CCS.

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[7] http://webarchive.nationalarchives.gov.uk/+/http://www.berr.gov.uk/files/file43006.pdf
[8] http://www.clickgreen.org.uk/news/national-news/12852-ed-milibands-energy-statement-to-parliament-in-full.html

In parallel with this statement on nuclear power, DECC also published the Low Carbon Transition Plan of July 2009[9]. This reported that the government had set a series of five-year 'carbon budgets' to 2022 to keep the UK on track in meeting its commitments. Achieving these would involve reducing GHG emissions by 1.4% a year. In addition to new nuclear build, it envisaged that electricity from renewable sources would increase to around 30% by 2020, a five-fold increase in renewable capability. The document also announced that DECC was embarking on a detailed planning exercise to map out a National Strategy to achieve its energy targets by 2050.

In the event, this did not happen, but instead, DECC launched a major initiative to consult the British public on the subject, as described in Section 1.3 below. The key feature of this new initiative was that, unlike all the preceding White Papers and Reviews, it was highly quantitative. This was perhaps related to the appointment of Professor David MacKay as Chief Scientist to DECC. His publication in 2009 of *Sustainable Energy – Without the Hot Air*[10] set a new standard for a quantitative approach to energy policy.

1.2 National and international commitments on carbon emission reductions

The first international agreement to set carbon reduction targets was the 1997 United Nations Kyoto Protocol, which requires consenting developed countries to reduce their human-generated GHG emissions by an average of just over 5% on 1990 levels by 2008 to 2012. The original Protocol was scheduled to expire in 2013. Attempts have since been made to extend this period, first (and unsuccessfully) at Copenhagen in 2009, and then at Cancun in 2010, and more recently (and partially successfully) at Durban in 2011.

In response to Kyoto, the UK passed its Climate Change Bill (November 2008), which introduced the world's first long-term legally binding framework to tackle the dangers of climate change. The key provisions of the Act were[11]:

- A legally binding target of at least an 80% cut in GHG emissions by 2050, together with a reduction in emissions of at least 34% by 2020, both targets being set against a 1990 baseline.
- A carbon budgeting system that caps emissions over five-year periods, with three budgets set at a time. The first three carbon budgets were set in May 2009, running from 2008-12, 2013-17 and 2018-22. The government has to report its policies and proposals to meet these budgets on a regular basis (and first did so by publishing the UK Low Carbon Transition Plan).
- Creation of the Committee on Climate Change (CCC) – a new independent, expert body to advise the government on the level of carbon budgets. The committee has to submit annual reports to Parliament on the UK's progress towards targets and budgets. The CCC has a duty to advise on the appropriate balance between actions at the domestic, European and international level, for each carbon budget.
- Further measures to reduce emissions, including the Carbon Reduction Commitment Energy Efficiency Scheme and measures on biofuels.
- A requirement for the government to report at least every five years on the risks to the UK of climate change, and to publish a programme for addressing these.

The EU has since offered to increase its emissions reduction to 30% by 2020, on condition that other major emitting countries in the developed and developing worlds commit to do their fair share under a future

[9] http://www.decc.gov.uk/assets/decc/white%20papers/uk%20low%20carbon%20transition%20plan%20wp09/1_20090724153238_e_@@_lowcarbontransitionplan.pdf
[10] MacKay, D.J.C. (2009) *Sustainable Energy – Without the Hot Air* UIT, Cambridge
[11] http://www.decc.gov.uk/en/content/cms/legislation/cc_act_08/cc_act_08.aspx

global climate agreement. This agreement should take effect at the start of 2013 when the Kyoto Protocol's first commitment period will have expired[12].

In December 2011, DECC published the UK 2011 Carbon Plan[13]. This confirmed a UK baseline level of 783.1 Mt CO_2 e in 1990, and proposed a set of four quinquennial carbon emission budgets:

Carbon budgets	Budget (2008–12)	Budget (2013–17)	Budget (2018–22)	Budget (2023–27)
$MtCO_2e$	3,018	2,782	2,544	1,950
% below base year levels	23	29	35	50

(*The unit Mt CO_2e, short for 'million tons of CO_2 equivalent', is a weighted sum of all the GHG emissions)*

It also reported on progress to date in meeting its targets:

- Between 1990 and 2010 emissions from power stations had fallen by almost a quarter, as the 'dash for gas' in the 1990s saw large numbers of coal-fired power stations replaced. In the last decade, wind and other renewables had grown to the point that they now provide nearly a tenth of UK generating capacity. With nuclear power at 16%, about a quarter of electricity generating capacity was now low carbon.
- Buildings emissions had fallen by 18%, despite the growth in population and housing, due to such measures as the introduction of new, more efficient, condensing boilers, and injecting insulating foam into existing cavity walls.
- Transport emissions had remained roughly the same, with the growth in miles travelled balanced by improvements in new car efficiency and an increased uptake of biofuels.
- Industrial emissions had fallen by 46%, as industry had become more energy efficient and the UK's industrial base had shifted away from energy-intensive manufacturing.
- Agricultural emissions had fallen by almost a third, due in part to more efficient farming practices.
- Waste emissions have fallen by more than two-thirds, due to the diversion of waste from landfill, as a result of the landfill tax.

The report also enumerated the government's plans, by sector, to achieve each of the quinquennial targets. In relation to electricity generation, it now envisaged that 40-70 GW of new low-carbon generating capacity would need to be constructed during the 2020s. Because it wanted to see nuclear, renewables and CCS competing to deliver energy at the lowest possible cost, it was not setting targets for each technology, or a decarbonisation target, at this point. However scenarios which it has modelled showed that by 2030 new nuclear could contribute 10–15 GW, with up to 20 GW achievable if build rates were higher; fossil fuel generation with CCS could contribute as much as 10 GW; and renewable electricity could deliver anywhere between 35 and 50 GW – depending on assumptions about costs and build rates.

1.3 Energy modelling and the DECC 'Pathways to 2050' initiative

Building on previous efforts to model future energy supply and demand in July 2010, DECC published a report entitled '2050 Pathways analysis'[14]. This sought to identify what might be practically and physically deliverable in each primary energy supply and end-use sector over the next 40 years. It developed a Pathways to 2050 Calculator which would allow those interested to explore their own choices, and in

[12] http://ec.europa.eu/clima/policies/brief/eu/index_en.htm
[13] http://www.decc.gov.uk/assets/decc/11/tackling-climate-change/carbon-plan/3702-the-carbon-plan-delivering-our-low-carbon-future.pdf
[14] http://www.decc.gov.uk/assets/decc/What%20we%20do/A%20low%20carbon%20UK/2050/216-2050-pathways-analysis-report.pdf

particular to confirm whether any selected pathway in fact met the UK's legally binding commitment to reduce its GHG emissions by 80% by 2050, compared to 1990 levels[15] while, at the same time, providing enough energy to meet the country's needs.

An initial version of this Calculator, which did not give any indication of the cost of the option selected by the user, was published on the web in July 2010. However in January 2012, DECC released version 2.1 of the Calculator, now based on an Excel spreadsheet[16], which gives a range of costs (low, 'point' and high) for each supply and demand option selected by the user. The sources of the cost data, and the related methodology, are summarised in two separate publications[17, 18]. To assist users of this software, DECC has provided six illustrative pathways, with the intention of inspiring users to develop their own ideas on possible pathways. David MacKay has published a brief blog[19], encouraging users to engage in "grown-up conversations about our possible energy futures" with the help of this tool.

In its simplest form the Calculator works by offering the user a series of choices in relation to 43 energy-related issues, which we shall here call 'Headings', that collectively determine energy supply and demand and GHG emissions. Nearly half of the 43 DECC decision 'headings' relate to energy demand. These cover such things as energy-saving measures (for example, the number of buildings that have been fitted with thermal insulation) and the extent to which activities such as transport and domestic heating have been 'electrified'. In relation to energy supply, they dictate things such as the amount of energy to be generated by each specific technology. Each of the 43 Headings presents the user with a set of choices that indicates the extent to which this particular measure or energy source is to be deployed. Each set of 43 choices then represents a user-defined 'pathway', and the Calculator then shows the implications of those choices – e.g. whether or not the choices have defined a pathway in which supply equals demand, and whether the UK commitments on GHG emissions have been respected. In most cases there are four possible choices or '**Levels**' for each heading, which (usually) deliver progressively more benefit in terms of energy saved or produced, but with escalating difficulty and expense. The report [ref. 14 p.10] describes the Levels thus:

- **Level 1:** assumes **little or no attempt is made to decarbonise or change** or only short run efforts; and that unproven low-carbon technologies are not developed or deployed.
- **Level 2:** describes what might be achieved by applying a level of effort that is likely to be viewed as **ambitious but reasonable** by most or all experts. For some sectors this would be similar to the build rate expected with the successful implementation of the programmes or projects currently in progress.
- **Level 3:** describes what might be achieved by applying a **very ambitious level of effort that is unlikely to happen without significant change from the current system**; it assumes significant technological breakthroughs.
- **Level 4**: describes a level of change that could be achieved with effort at the **extreme upper end of what is thought to be physically plausible** by the most optimistic observer. This level pushes towards the physical or technical limits of what can be achieved.

[15] DECC's understanding of this term is explained in the Foreword to ref 14, and a (slightly revised) estimate of the baseline '1990 value is given in ref 13 (p.22) as 783.1 $MtCO_2e$. This appears to be the figure used in the DECC Calculator.
[16] www.decc.gov.uk/2050 follow link to Excel 2050 Calculator.
[17] http://www.decc.gov.uk/assets/decc/11/tackling-climate-change/2050/3705-2050-calculator-costs-inclusion-results-and-metho.doc
[18] http://2050-calculator-tool-wiki.decc.gov.uk/pages/28
[19] http://withouthotair.blogspot.com/2012/01/version-3-of-2050-pathways-calculator.html

For more advanced users, the option is given to define an intermediate level (for example, 2.3). For 10 of the 43 Headings, the choices are not presented in terms of the **Levels** defined above, but as '**Trajectories**', usually labelled A to D. In this case, the sequence does not necessarily correspond to increasing benefit or expense but rather, to alternative pathways whose benefits and costs differ.

Once the user has set the relevant parameters of the model, the Calculator then calculates the implications of the choices made, including the carbon emissions resulting. The user can then 'fine-tune' the chosen pathway.

Instructions on how to use the Excel spreadsheet Version 2.1 Pathways Calculator are available on DECC's website[20], and some further information on this subject is given in Annex 1. There are already numerous published examples of the use of the Calculator to explore possible scenarios, and DECC has used it in its planning of the 4th Carbon Budget Evidence Base, using AEA Technology as its contractor[21].

1.4 The Working Group's commentary on the DECC Calculator

The British Pugwash Working Group has found the DECC Calculator to be a very valuable tool in developing its approach to UK energy policy. Nevertheless, it has become aware of some weaknesses and limitations in the DECC Pathways model. There are a number of software errors, which we discuss in Annex 1, but which we judge to be non-critical. There are also some assumptions built into the model, which limit the freedom of users to specify the Pathway of their choice – for example the assumption that any excess electricity production is exported rather than, say, stored in the form of hydrogen or syngas. These assumptions are discussed in later chapters of our report, and could in principle be modified by those with expertise in advanced Excel programming. However there are other more fundamental limitations relating to gaps in the range of issues which the Calculator is seeking to address. These are discussed later in this report.

1.5 British Pugwash contribution to public debate

British Pugwash strongly endorses Professor David MacKay's request that the public should engage in grown-up conversations on the vitally important matter of UK energy policy. In the Working Group's view, these should be based on:

- Objective and agreed quantitative information about the current situation, both as regards the amounts and nature of energy supply and usage, and the mechanisms which are currently used to keep these two in balance
- Information about the history of changes in the pattern of energy supply and demand, which can provide some indication of the timescales on which changes can be effected
- Guidance from experts on the possible developments in energy technology over the next 40 years, including estimates of likely trends in efficiency and cost
- Scenarios for possible pathways between the current situation and 2050 which meet the UK's commitments on emissions
- An assessment of the many issues which go beyond the scope of the DECC Calculator, and are perhaps not readily quantifiable, but which nevertheless need to be taken into account when selecting an optimum Pathway. These include public acceptability, land use, environmental impact, practical deliverability, technological risk, international implications, business investment behaviour, and fiscal,

[20] http://2050-wiki.greenonblack.com/pages/72
[21] http://www.decc.gov.uk/assets/decc/11/cutting-emissions/carbon-budgets/2290-pathways-to-2050-key-results.pdf

competitive, socio-economic and welfare considerations. We would emphasise that some of these issues lie outside the scope of this report, yet need to be brought into the overall discussion.

We hope that this report will provide some useful background to this debate, by providing numerical data where appropriate, and by drawing attention to points of view on the less quantifiable issues. We hope that this debate will now proceed rapidly, because a coherent UK policy on energy has, until recently, been markedly absent and decisions on the overall pathway, and on the roles of government and the private sector in planning, funding and implementation need to be taken urgently.

1.5.1 Units of energy and power

There is one further issue which should be mentioned at the outset. We have had considerable debate within the Working Group on whether we should standardise on a single unit of energy or power. The problem in doing so is that each sector of the energy industry has adopted a different standard usage for reporting energy measurements. The coal industry uses tons of coal, the oil industry either barrels or tons of oil equivalent (toe), the gas industry m^3, the nuclear industry GWth and GWe and the renewables industry, typically TWh. This is perfectly understandable, but can be confusing in a report which is trying to discuss all sources of energy on an equal footing.

This problem is further complicated by the fact that some of the units in standard use are units of energy and some are units of power. These can be inter-converted if the time interval over which the energy was delivered is specified. In most discussions of energy policy, this is implicitly a year, though it may sometimes be a quarter or even a month. To avoid this ambiguity, many authors, when quoting figures originally published as TWh, transcribe them as TWh/y, making it explicit that they refer to a year's supply. Transcribed in this way, the unit is formally a unit of power, and it can trivially be converted to GW by dividing the figure in TWh/y by 8.76. The resulting figure is clearly an average power supplied over the course of the year. To make this clear, it is appropriate to add the suffix 'av' to the GW designation.

A second problem is that in the energy policy literature, a distinction is made between this annual average power (in whatever unit) and the 'nameplate' power of an energy source – i.e. the maximum power that the source has been designed to deliver. The ratio of these two powers is the 'load factor' for that power source, and this factor takes account of the consequences of breakdowns, maintenance outages and (in the case of some renewables) the non-availability of wind or sun. It is clearly helpful to the reader if the nameplate power and the annual average power are expressed in the same unit.

Given these two problems, we have decided to standardise on the GW, so far as possible, as the single unit of power throughout this report, and to add a suffix to specify whether it is a nameplate or annual average figure, using the notation GWn for nameplate capacity and GWav for the annual average power delivered.

However, since much of our numerical information comes from the DECC *Digest of United Kingdom Energy Statistics* (DUKES), which uses both GW and TWh in different tables, we have in places added a parallel column showing TWh/y, to assist the reader in comparing our report's figures with those in DUKES. One advantage of taking the GW as our standard unit is that our numbers are typically in the range 1-100, which makes them easy to remember and quote. In all our tables, where we show the power in both TWh/y and GWav, the conversion has been undertaken simply by dividing by 8.76. No assumptions have been made about the load factor, except in the case of some future scenarios, in which case the assumed load factors are also specified. In a few places, DUKES chooses to present energy use figures in millions of tons of oil equivalent/year (Mtoe). To convert these to GWav, we have used the standard conversion factors quoted by DUKES:1 toe = 41.868 GJ = 11630 kWh. So 1 Mtoe/y = 11630/8760 = 1.328 GWav.

2 Energy supply and demand in the UK in 2010

The official source of information on the UK's supply and use of energy is the DECC *Digest of United Kingdom Energy Statistics 2011* (DUKES)[22], and all the figures quoted in this chapter come from that source. The most recent edition gives final figures for 2010.

In Section 2.1 we present highly summarised information on the overall energy supply and demand. This is followed in Section 2.2 by more detailed information on electricity supply and demand over the UK as a whole, and the significance of these figures is discussed. In Sections 2.3-2.5 we describe the diurnal and annual variations in supply and demand, and how these are accommodated. Section 2.6 discusses relevant regional and local variations.

2.1 Overall energy production and use

Statistics on the overall production and use of energy in all its forms are not readily summarised, if only because there is no one obvious measure for the output to the end user. The DECC solution to this problem is to convert all overall energy supply and use figures to tonnes of oil equivalent (toe). In this report, we convert the DUKES toe data into GWav (see Section 1.5.1 above). It will be seen from Table 2.1 that the UK supplies energy in all its forms at an average rate of about 300 GW, of which about 90 GW get lost in the process by which raw 'primary' energy gets converted into the forms required by the end users. These losses are dominated by the process of converting thermal primary energy ('heat') into electricity, though distribution losses are also significant. End use is dominated by the transport and domestic consumption sectors (74 and 64 GWav respectively), with industry coming third (37 GWav).

Table 2.2 shows the present distribution between the various primary energy sources, with gas leading at 40%, closely followed by coal at 32% and nuclear at 18%. All other sources together only contribute 10%. The picture changes somewhat if one looks at the distribution of end-use power by source: the fraction contributed by nuclear and hydrocarbon sources decreases because of the low energy efficiency of the required transformation processes, but renewables sources still only make a contribution of about 1%.

Tables 2.3 and 2.4 show that the overall electricity production figures have remained relatively flat during the past decade, with reductions in nuclear and coal output replaced by increases in gas and renewables.

As regards electricity end use, there has been a 10% decrease in the use by industry (due largely to increases in energy efficiency and the recession which began in 2008), together with an increase in the 'domestic' and 'commercial' sectors, in which energy efficiency savings have been more than offset by increases in demand due to social factors, such as more one-person households and increased use of energy-consuming electronic devices. There is room for much debate over how these trends should be extrapolated into the future, and these arguments form the basis of the choices made in Chapters 4-6.

[22] http://www.decc.gov.uk/assets/decc/11/stats/publications/dukes/2312-dukes-2011--full-document-excluding-cover-pages.pdf

Table 2.1 Aggregate UK energy balance in 2010 (*DUKES Table 1.1 p29*) Gross calorific values in MToe converted to GWav

Supply	Coal	Manufactured fuel(1)	Primary oils	Petroleum products	Natural gas(2)	Renewable & waste(3)	Primary electricity	Electricity	Heat sold	Total GWav
Indigenous production	15.2	0.0	91.6		75.9	7.1	20.1			210.0
Imports	23.1	0.1	79.2	35.1	67.3	2.3		0.8		207.9
Exports	-0.7	-0.5	-61.3	-37.7	-20.1	-0.1		-0.5	0.0	-121.0
Marine bunkers	0.0	0.0	0.0	-3.0	0.0	0.0	0.0	0.0	0.0	-3.0
Stock changes at collieries etc	6.1	-0.2	-0.1	0.9	1.7	0.0	0.0	0.0	0.0	8.5
Total (excl st errors)	**43.4**	**-0.5**	**109.4**	**-4.6**	**124.8**	**9.3**	**20.1**	**0.3**		**302.2**
Transformation										
Energy transformations	-41.1	3.0	-106.1	104.0	-45.2	-5.9	-18.5	41.6	1.8	-66.4
Energy industry use	0.0	-0.9	0.0	-7.0	-7.9	0.0	0.0	-2.9	-0.1	-18.9
Losses	0.0	-0.2	0.0	0.0	-2.1	0.0	0.0	-3.1	0.0	-5.5
Transformation total (incl other)	**-41.1**	**1.8**	**-106.1**	**97.0**	**-55.2**	**-5.9**	**-18.5**	**35.6**	**1.7**	**-90.7**
Consumption										
Industry	**1.5**	**0.8**		**6.6**	**13.9**	**0.6**		**11.9**	**1.1**	**36.6**
Transport:										
Air	0.0	0.0	0.0	16.3	0.0	0.0	0.0	0.0	0.0	16.3
Road	0.0	0.0	0.0	52.8	0.0	1.6	0.0	0.0	0.0	54.4
Total Transport (incl rail etc)	**0.0**	**0.0**		**71.9**	**0.0**	**1.6**	**0.0**	**0.4**	**0.0**	**74.0**
Other :										
Domestic	0.7	0.3		4.5	44.5	0.7		13.6	0.1	64.4
Public administration	0.0	0.0	0.0	0.4	4.4	0.2		2.1	0.5	7.6
Commercial	0.0	0.0	0.0	0.5	3.6	0.1	0.0	9.0	0.0	13.2
Total Other (incl agriculture)	**0.7**	**0.3**		**6.2**	**54.6**	**1.1**		**25.1**	**0.6**	**88.7**
Non energy use	**0.0**	**0.0**	**0.0**	**11.0**	**1.0**	**0.0**	**0.0**	**0.0**	**0.0**	**12.0**
Total final consumption	**2.3**	**1.2**	**0.0**	**95.7**	**69.5**	**3.4**	**0.0**	**37.5**	**1.7**	**211.3**

Table 2.2 UK Energy flows from source to end use in 2010

Type of energy	Input to Electricity production *table 5.4 p140*		Losses during transformation		Electrical output to end user *table 5.1 p137 & flowchart p118*		Efficiency	Non-electrical Output to end user	
	TWh in	GWav in	TWh lost	GWav lost	TWh out	GWav out		TWh out	GWav out
Nuclear	162	18.5	100	11.4	62	7.1	38%	0	0.0
Hydro	4	0.4	0	0.0	4	0.4	100%	0	0.0
Wind	10	1.2	0	0.0	10	1.2	100%	0	0.0
Coal	297	33.9	190	21.6	108	12.3	36%	80	9.2
Oil	14	1.6	9	1.0	5	0.6	36%	1196	136.5
Gas	372	42.4	197	22.5	175	20.0	47%	699	79.8
Other renewables	51	5.9	39	4.4	13	1.5	25%	0	0.0
Net Imports	3	0.3	0	0.0	3	0.3	100%	0	0.0
Manufactured fuels	9	1.1	9	1.1	0	0.0	0%	0	0.0
Total production	**922**	**105.3**	**544**	**62.1**	**378**	**43.1**	**41%**	**1975**	**225.4**

Notes:

Nuclear input is the energy content of the steam: the efficiency is that of the turbines

All other efficiencies are either measured or notional

There are minor discrepancies between figures in different tables in ref. 22, leading to some minor internal inconsistencies in this summary table

Non-electrical outputs are largely petroleum products for transport (63.3 GWav) and gas for domestic heating and cooking (44.5 GWav)

2.2 UK Electricity production and use 2000 and 2010

In summary, the DUKES figures for electricity production and use are:

Table 2.3 UK Electricity production

DUKES Table 5.1 p137	**2000**		**2010**		*DUKES Table 5.7 p144(1)*
Electricity production	**TWh/y**	**GWav**	**TWh/y**	**GWav**	**Capacity in GWn at end 2010**
Nuclear	85.1	9.7	62.1	7.1	10.9
Hydro(excl. pumped storage)	5.1	0.6	3.6	0.4	1.5 (1.6)
Wind	0.9	0.1	10.2	1.2	2.3 (5.3)
Coal	120.0	13.7	107.7	12.3	31.4
Oil	6.5	0.7	4.9	0.6	3.8
Gas	148.1	16.9	175.0	20.0	35.7
Other renewables	4.3	0.5	12.8	1.5	2.0
Other	4.4	0.5	1.6	0.2	
Total production	**374.3**	**42.7**	**378.0**	**43.1**	**87.5 (91)**
Pumped storage production	2.7	0.3	3.1	0.4	2.7
Imports	14.3	1.6	7.1	0.8	
Exports	-0.1	0.0	-4.5	-0.5	
Total supply	**391.2**	**44.7**	**383.8**	**43.8**	**90.2**

Note: The capacity figures quoted here from DUKES Table 5.7 p144 are different from those given in its Table 7.4 (p214), because Table 5.7 'corrects' the bare nameplate figures for Small-scale hydro and Wind given in Table 7.4 to put them onto a 'declared net capability' basis, with correction factors of 0.365 and 0.43 respectively. (Un-corrected figures in brackets)

Table 2.4 UK Electricity end use

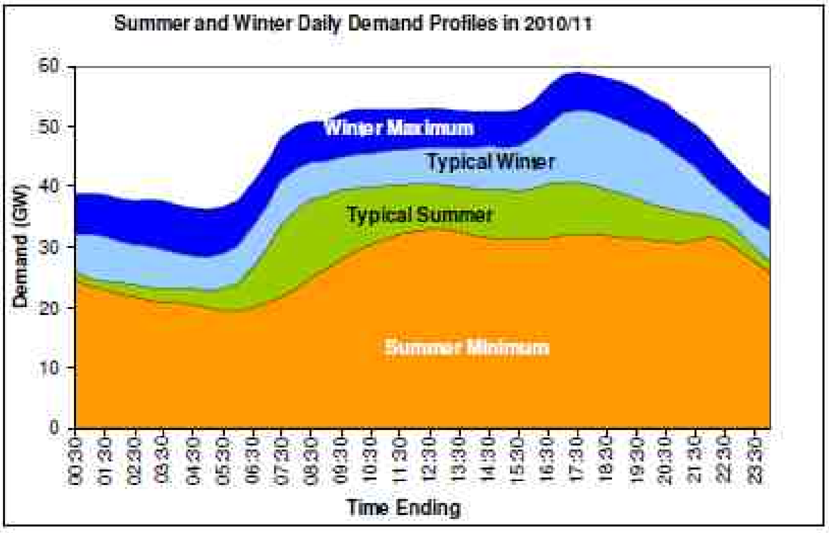
DUKES Table 5.1 p136,	**2000**		**2010**	
Electricity use	**TWh/y**	**GWav**	**TWh/y**	**GWav**
Industry:				
Iron and steel	6.3	0.7	3.5	0.4
Non-ferrous metals	6.2	0.7	6.7	0.8
Mineral products	8.1	0.9	7.3	0.8
Chemicals	23.7	2.7	18.2	2.1
Mechanical engineering. etc	9.4	1.1	7.7	0.9
Electrical engineering, etc	6.2	0.7	6.7	0.8
Vehicles	6.3	0.7	5.2	0.6
Food, beverages, etc	11.7	1.3	11.5	1.3
Textiles, leather, etc	3.6	0.4	3.1	0.3
Paper, printing, etc	11.4	1.3	11.4	1.3
Other industries, incl construction	21,1	2.4	23,2	2.7
Industry total	**114.1**	**13.0**	**104.5**	**11.9**
Transport (air, road, rail etc)	**8.6**	**1.0**	**3.9**	**0.4**
Domestic consumption	111.8	12.8	118.7	13.5
Public administration	20.9	2.4	18.8	2.1
Commercial	69.6	7.9	78.4	9.0
Agriculture	4.4	0.5	4.0	0.5
Other total	**206.7**	**23.6**	**219.9**	**25.1**
Total final consumption	**329.4**	**37.6**	**328.3**	**37.5**
Electrical production industry use & losses	**60.3**	**6.9**	**55.7**	**6.4**
Total electricity use	**389.7**	**44.5**	**384.0**	**43.8**

2.3 Demand variation – diurnal, seasonal and exceptional

Sections 2.3-2.6 drafted by David Finney

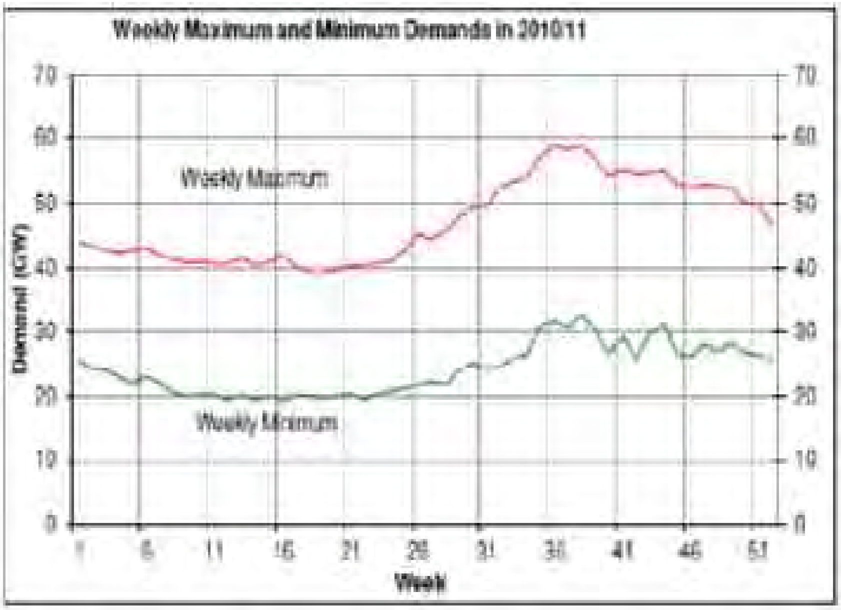
Demand for energy varies from moment to moment, as well as hourly, and seasonally. Figure 2.1 illustrates the diurnal variation in the demand on the UK electricity system, showing how this varied during the summer and winter of 2010/11, and Figure 2.2 compares weekly maximum and minimum demand. Week1 in Figure 2.2 refers to the first week in April 2010. It is clear from these data that diurnal demand varies by a factor of 1.6 -1.7 and weekly demand by a factor of about 2 throughout the year.

Figure 2.1



Source: National Grid Seven Year Statement 2011[23]

Figure 2.2



Source: National Grid Seven Year Statement 2011

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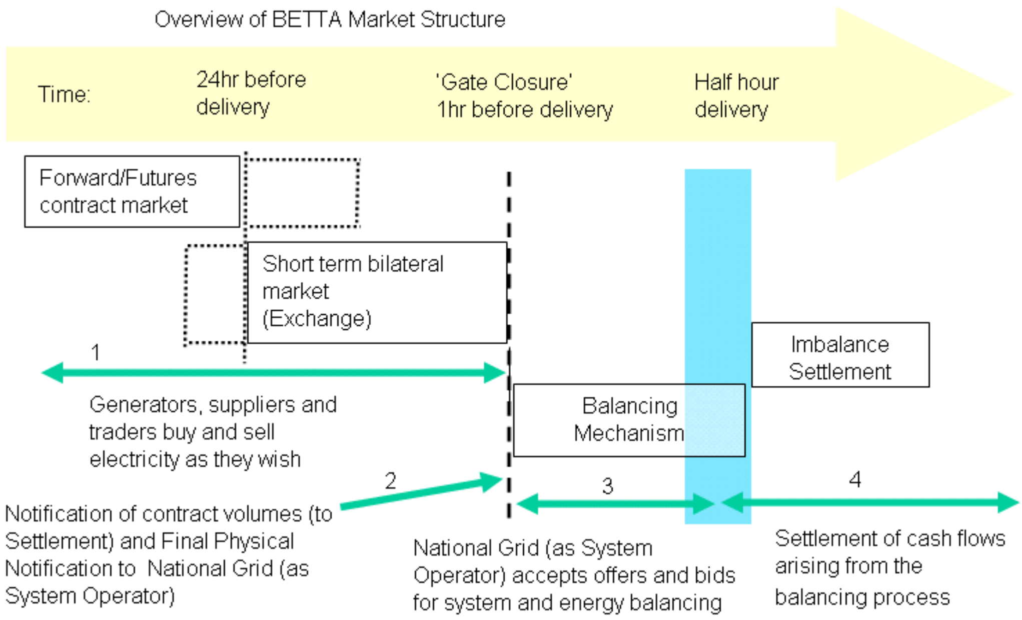
[23] National Grid, *National Electricity Transmission System Seven Year Statement 2011* http://www.nationalgrid.com/NR/rdonlyres/4AB92B80-499A-4D3A-84E4-BBE884CBBA55/49900/NETSSYS2011.pdf For information about the corresponding gas transmission system, see: http://www.nationalgrid.com/uk/Gas/About/How+Gas+is+Delivered/

In addition to these normal diurnal and seasonal variations, exceptional electricity (and/or gas) demand can arise for many reasons. The arrival of unusually severe winter weather is an event which can be forecast and prepared for, as can changes in behaviour by a large number of people, as happens when the nation's attention is focused on a special event, such as a World Cup final or an eclipse of the Sun, causing one or more steep reductions followed by steep rises in demand as the event proceeds.

Since the privatisation of the UK electricity supply industry in 2001, the responsibility for managing both electricity and gas supply and demand in such a way that the two are kept equal, and within the constraints of the available generating capacity, is now vested in the UK competitive market system. This is now known as the British Electricity Trading and Transmission Arrangements (BETTA), and is operated by the National Grid Company (NGC). The structure is conveniently summarised in Figure 2.3, taken from the NGC *National Electricity Transmission System Seven Year Statement 2009*.

Figure 2.3



Source: National Grid Seven Year Statement 2009, Chapter 10

It can be seen that BETTA is a system which enables exchanges and brokers to create forward, futures and short-term bilateral markets. Overall, it successfully facilitates trade in bulk electricity. BETTA requires each contracting generator and supplier to inform the NGC of the quantity of electricity traded and the duration of the contract, and to notify NGC of their forecasts of demand and operating levels for the following day by the time of 'gate closure'. In return, NGC informs each generator of its planned plant operation schedules and plant to be held in reserve. However the actual demand for electricity is often different to that predicted by the supply companies, so NGC has to bring on line, or take off line, at short notice, additional generating plant in order to match supply to demand. This incurs additional expense for the generating companies. These 'imbalance costs' are calculated by NGC through a series of counter-bids and offers, made by the generating companies and suppliers.

Natural gas is delivered to nine reception terminals by gas-producing companies, whence it is distributed by NGC through its 7,600 km network of high-pressure pipes, known as the National Transmission System (NTS) [for details see ref. 23]. A further 278,000 km of pipework is connected at 175 off-take points where large industrial consumers and power stations receive high-pressure gas directly. Eight distribution zones, owned and managed partly by NGC and partly by many competing distribution companies, distribute gas at low pressure to small end users including domestic premises. As gas flows through the distribution networks its ownership may be transferred several times. As with electricity, the industry is regulated by Ofgem.

Unlike electricity, natural gas is a primary fuel which can be stored in large quantities. Demand for natural gas is very seasonal and weather dependent, whereas electricity has to meet a significant base load throughout the year. Consequently facilitating a competitive market in gas is much simpler than in the case of electricity.

It is the responsibility of NGC to balance supply and demand on the NTS. If too much gas enters the network it must be stored. Conversely, if too little enters, gas from storage vessels will have to be utilised. Therefore gas supply companies have to ensure that the gas they inject into the network roughly balances the gas consumed. If they miscalculate either way by too great a margin the NGC will levy a penalty charge.

For both electricity and gas, the NGC has to ensure that throughout the year the system has a sufficient margin of supply in hand above the annual peak demand to cope with any sudden loss of supply, should one or more generators trip out or some other fault develop in the grid. Generating plant removed for routine maintenance also has to be covered, but this is done on a planned basis and is scheduled during the summer when demands on the system are low. From Figure 2.1 it can be seen the annual peak demand for 2010/11 was just under 60 GW which is well below the total UK-based generation capacity of 90 GWn. Furthermore, additional power was available via the 3.2 GW interconnector cables linking UK with France (2.0 GW) and Netherlands (1.2 GW), though the average use of these was much lower.

2.4 Supply variation

From the earliest days of the electricity supply industry, intermittency was an accepted fact of life, as equipment frequently broke down. In recent years, the technology has improved substantially and such failures have become much less frequent, but the size of generators has increased, so the consequences of failures have become potentially more serious. Currently, a thermal electricity generator is likely to be out of action for around 170 hours per year due to unforeseen circumstances, and for a further 600 hours for routine maintenance[24]. At the current level of intermittency, the UK electricity grid system has managed to avoid any disastrous failure by arranging for routine maintenance outages to occur well away from predicted peak demand times, and by ensuring that a large reserve generating capacity is available at all times.

The apparently generous reserve capacity within the UK grid (90 GW capacity as compared with a peak demand of 60 GW), is in fact less generous than it might appear. This is because much of the reserve capacity is in the form of elderly coal- or gas-fired thermal plant with high operating costs and poor carbon-emission characteristics. In addition, some of the 'baseload' capacity is in the form of nuclear stations which are approaching the end of their design life, and are currently scheduled for decommissioning within the next 10 years. A further problem, which is not serious at present, but threatens to become significant within the next 20 years, is the growing proportion of the planned generating plant which is intrinsically intermittent (for example, wind or solar generating plant). Research by the NGC suggests that as long as the contribution from wind and other variable renewable sources remains below 20%, this intermittency can be

[24] Danish Energy Authority, 2008 www.ens.dk

accommodated without adding to the already available mechanisms. The most challenging circumstance is thought to be the arrival of a large high-pressure weather system in midwinter when wind generation could be minimal at precisely the time when it is needed most. This is the basis of the 'stress test'" in the DECC Calculator, which is discussed in detail in Section 3.6.2 below.

2.5 Load following – supply and demand management, storage, reserve capacity

UK electricity customers have a high expectation of the supply system. They expect the voltage and frequency of grid electricity to remain within tightly defined limits, and for the system to be kept going 24/7, notwithstanding the supply and demand variations described above, and to be robust enough to be restarted quickly in the event of a partial or complete grid failure. Since the establishment of a complete National Grid in 1935, these expectations have in large measure been satisfied, and grid voltage and frequency have been controlled within increasingly narrow limits. This implies a close matching of supply and demand, and since there is currently little scope for managing the latter, 'load following' becomes necessary. This is achieved by increasing or decreasing generator outputs, and/or by closing down or opening additional plant. To achieve this, NGC now requires a ramping capability of 10% of capacity in 10 seconds for all generating plant operating above the base-load region of the demand curve (see Figure 2.1). In addition, NGC places 'fast reserve' and 'fast start' contracts that require plant to increase or reduce power at short notice. Additional flexibility is obtained through agreements for 'energy readiness' and 'hot start'[25].

Electricity generators capable of fast response include the 2.7 GWn capacity of pumped storage generators, which the NGC estimates will provide 48.9 TWh during 2011/12[26]. Within this total, the Dinorwig pumped storage facility, with a capacity of 1.8 GWn, can generate full power from a standing start in 100 seconds (or from standby, with turbines rotated by compressed air, in 10 seconds). It aims to keep sufficient water in its upper reservoir to generate 1.68 GW continuously for up to 5 hours. An attractive feature of this facility is that water can be pumped up from the lower to the upper reservoir by driving the turbines in reverse when there is a surplus of electricity on the grid. It is foreseen that this situation will arise in the near future, when the wind generators now under construction are in operation: there will be times when they produce more electricity than the grid can accommodate. This facility will therefore be able to exploit the price differential between peak and off-peak periods, using cheap off-peak electricity to pump water into the upper reservoir and then using this to 'peak lop' when the price is at its highest – recognising that, at the present time, maximum price usually coincides with maximum demand. We can expect increased complexity in the pricing of electricity in future, because wind conditions as well as ambient temperature will affect the balance of supply and demand.

Other relatively rapid contributions to system balancing are provided by DC interconnectors (currently at 3.2 GWn, with a further 2.5 GWn planned), together with the few remaining oil-fired plants and some gas turbine generators (based on turbojets). Generators that are not operating at base load are generally required to load follow, and some types of plant are more capable of this than others. The variation in demand for electricity during the day is generally met by the older combined cycle gas turbine (CCGT) and coal-fired steam plants. More modern CCGT generators are mostly designed so that the turbine and alternator are located on a single shaft and these are less easily used for load following. Multi-shaft designs, which have independent alternators for the gas and steam turbines, avoid this problem but they are more expensive to build.

[25] National Grid (2011a), Operating the Electricity Transmission Networks in 2020. June
[26] National Grid (2011b), Winter Outlook Report. October

Both renewables and nuclear plant have in common low operating costs and high fixed costs, so economic pressures dictate that they should run so as to maximise output. Load following is a deviation from this business model, so both nuclear and renewables plant operators seek to avoid it. Furthermore there are performance, operational and safety considerations which limit the use of nuclear plant in load following, and which can increase costs if they do so[27]. Nevertheless, the French Pressurised Water Reactors (PWRs) do load-follow to match daily demand cycles, by selecting reactors within the fleet that are at an appropriate part of the fuel cycle[28]. Further, PWRs and Boiling Water Reactors (BWRs) are also used for load following in Germany and have even been used to balance wind generation[29]. There is no doubt, however, that the ability of nuclear reactors to do this on a regular and frequent basis is limited. The UK gas reactors are especially inflexible, as they were designed specifically for base load generation. New reactor technology may be able to improve on this, but even here there will be constraints[30,31] although Germany and France have shown that nuclear reactors can be designed for load following[32,33].

At the present time it is clear that the UK has enough flexibility in the system to keep grid voltage and frequency within their prescribed limits, albeit with some loss of thermal efficiency, and despite the limitations of specific kinds of plant. With increasing numbers of wind generators it is inevitable that additional flexibility will be required and it seems unlikely that nuclear plant will be particularly helpful in meeting this new challenge. Furthermore, similarities in the economics of renewables and nuclear will put them in direct mutual competition, since both seek to maximise revenue by generating whenever it is possible for them to do so.

Possible future measures for the management of intermittency, if there are high levels of renewable generating capacity on the grid, are discussed further in Chapters 3 and 5.

2.6 Regional and local variations – national networks, CHP, micro-generation

Historically, thermal power stations were built in or near areas where electricity demand was highest. The coal was transported long distances by rail or water, and the electricity distribution system was relatively local. Following the nationalisation of the electricity supply industry, a national grid was established, and it became possible to transmit electricity over long distances at 275kV and 400kV. It then became more economical to build power stations close to the mines and oil ports and to transport electricity at high voltages throughout the UK, a process dubbed ‘coal by wire’.

A similar historical process has occurred in the distribution of gas. In Victorian times, all major communities had their own local gas works, which generated coal gas, and this was distributed by a local pipe network.

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[27] Bruynooghe, C., Eriksson, A., and Fulli, G. (2010) ‘Load-following operating mode at Nuclear Power Plants (NPPs) and incidence on Operation and Maintenance (O&M) costs. Compatibility with wind power variability’, European Commission, Joint Research Centre, Institute for Energy, EUR 24583 EN http://tinyurl.com/6n7grs9

[28] World Nuclear Association, Nuclear power in France (updated 2012) http://www.world-nuclear.org/info/inf40.html

[29] Pouret, l., Buttery, N., and Nuttall, W. (2009) ‘Is nuclear power inflexible?’ *Nuclear Future* Vol.5, No.6, pp. 333-341, Nov/Dec

[30] EDF (2008) EDF’s submission to the UK government’s renewable energy strategy consultation: ‘UK Renewable Energy Strategy: Analysis of Consultation Responses’. Prepared for: Department of Energy and Climate Change, File Log Number 00439e p.3 www.berr.gov.uk/files/file50119.pdf

[31] BERR (2008) ‘Growth Scenarios for the UK Renewables Generation and Implications for Future Developments and Operation of Electricity Networks’. Sinclair, Knight Merz SKM Consultants, report for BERR, BERR Publication URN 08/1021, June http://www.berr.gov.uk/files/file46772.pdf

[32] Ward, D. (2011) Is nuclear power flexible? http://www.claverton-energy.com/is-nuclear-power-flexible-does-it-have-load-following-capability.html

[33] Ludwig et al (2010) Load cycling capabilities of German Nuclear Power Plants http://www.vgb.org/en/load_cycling_capabilities_npp.html

When North Sea natural gas replaced coal gas in the early sixties, these local pipe networks became linked into a national pipeline grid, with pumping stations at the gas field terminals. This created the opportunity to establish gas-fired power stations driven by gas turbines, which proved relatively quick and cheap to build, resulting in the 'dash for gas' seen in the 1990s. These have also provided a new tool for balancing the electricity grid, as explained in the previous section.

All thermal power stations – coal, gas and nuclear – suffer from relatively low efficiencies in converting the source fuel into electric energy, in the region of 35% for most stations, although combined cycle gas turbine systems can achieve around 50%. Such low efficiencies result in enormous amounts of low-grade heat being ejected into the environment and, if the power station is located sufficiently close to a centre of population, there is an argument in favour of taking off the unutilised heat at a reasonable temperature, and piping it to the local community for heating purposes. This has the effect of further reducing the efficiency of electricity generation, but can lead to a greater overall utilisation of the energy in the source fuel. Such Combined Heat and Power (CHP) facilities have never been very popular in the UK, but Denmark, Finland, Sweden and Iceland already provide between 50% and 90% of their heating for buildings in this way. By not going down this route, the UK is currently rejecting heat into the environment at a rate of about 62 GWav (see Table 2.2 above). Added to this are energy losses in transmission, which amounted to 3.1 GWav in 2010 (Table 2.1).

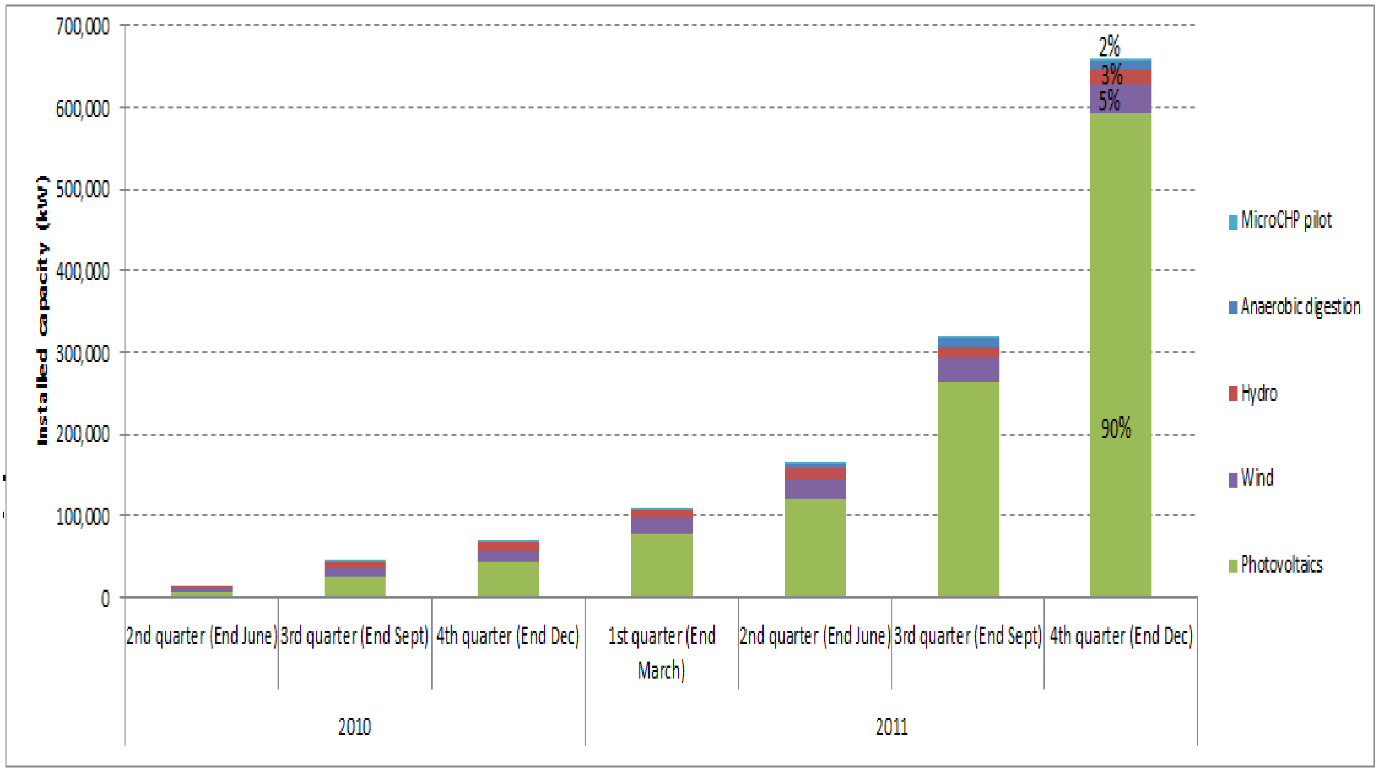
A radical solution to this problem is to generate electricity precisely where it is wanted – i.e. at the individual household, commercial premises or factory. In this way transmission losses are reduced and heat that might otherwise be wasted can be utilised. During the twenty-first century, the UK government has encouraged the development of such 'micro-generation' through grants and feed-in tariffs (FITs) that allow local generators to sell their excess electricity to the grid. Table 2.5 shows the take-up of this scheme, and the amounts of power fed back into the grid during the first year of its operation. It will be seen that solar photovoltaic (PV) panels dominated the outcome. For a short period, wind turbines fitted to house roofs were also popular, but it emerged that in an urban environment, with low wind speeds and high turbulence, they were often not cost effective. Figure 2.4 shows the spectacular growth in this scheme during its first 18 months. Indeed, so successful was it that the government feared the allocated budget would be overspent and, accordingly, the FIT was reduced by 50% from April 2012. Nevertheless, the average rate of energy export by all UK 'micro-generators' in 2010/11 was only 0.009 GWav.

Table 2.5: Feed-in Tariffs (FITs) Generation 2010/11

Technology aggregated tariff bands	Actual generation reported by Ofgem in 2010/11 MWh	Number of sites
Anaerobic Digestion	2,671	3
Hydro	19,699	203
Micro CHP	43	100
Solar Photovoltaics	22,949	28,556
Wind	21,493	1,339
Ex-Renewables Obligation	16,646	
Total	83,501	30,201

Source: *http://www.ofgem.gov.uk/Sustainability/Environment/fits/Documents1/FITs%20Annual%20Report%202010%202011.pdf figures 1 and 5*

Figure 2.4 Micro-generation Installations by technology – cumulative installed capacity (kW)



Source DECC Energy Trends Tables ET 5.6 Chart 6.5
http://www.decc.gov.uk/assets/decc/11/stats/publications/energy-trends/5627-energy-trends-june-2012.pdf

3 Background to the selection of three possible pathways

3.1 Introduction

The intention of this report is to promote an informed public debate on UK energy policy by presenting three representative energy pathways to 2050, each of which is broadly ‘possible’ and meets the UK international commitments on the reduction in emissions. Accordingly we have asked three ‘champions’ to develop and defend their preferred pathways, and these are described in Chapters 4-6. Unsurprisingly, their three approaches exhibited some overlap: for example, all three chose to include some wind power, reflecting the commitments that UK has already made in this direction. To avoid having to repeatedly cover the same ground, this chapter presents information on the main technologies that may be reasonably considered as ‘common ground’. We also indicate the way in which all three champions have made use of the DECC Pathways to 2050 software to obtain quantitative information on the implications of their chosen pathways, both as regards energy mix, compatibility with UK commitments on GHG emissions, and possible costs.

3.2 Nuclear power – the common ground

The history of civil nuclear power in the UK is a long and complicated story, with a number of very real successes, interspersed with a number of seriously bad decisions which have marred an otherwise creditable record. It begins with the undoubted success in building the world’s first commercial nuclear power station, Calder Hall, which began operation in 1956, and ran for 47 years. This gas-cooled Magnox design was the prototype for a series of 11 power stations containing 26 Magnox reactors built in the UK, plus a further three in Japan, Italy and North Korea.

In 1962 the UK embarked on its ‘second-generation’ reactor, building its prototype Advanced Gas-Cooled Reactor (AGR) at Windscale. It subsequently rolled out this design concept, building seven 1 GW stations. These two designs, taken together, reached a peak capacity of 12.9 GWn in 1996, which at that stage represented 17.5% of UK generating capacity, and produced 25% of its electrical consumption.

Because of its early success with gas-cooled Magnox reactors, the UK continued to follow the gas-cooled route, while the rest of the world pursued Light Water Reactor (LWR) systems – PWRs) and BWRs – and quickly amassed invaluable operating experience with those designs. Only in 1980 did the UK conclude that it was unwise to remain so far outside the mainstream of the world nuclear industry, and in consequence decided to construct a PWR at Sizewell. Although this was intended to be the first of a series, because of the rapid growth of the UK North Sea oil and gas industry, no further nuclear power plant has been built in the UK since Sizewell B. and the UK nuclear industry has until recently been in a state of decline, with most of its activities related to decommissioning redundant nuclear facilities in the UK, and providing nuclear services for overseas customers.

Meanwhile, the international nuclear industry has continued to develop, though with a number of setbacks, particularly following the major incidents at Chernobyl and Fukushima. A number of countries still have flourishing nuclear industries – notably the US, France, Russia and (until very recently) Japan – and others are well on the way to establishing their own industries, such as India, China, and Korea. There are 435 power reactors currently in operation worldwide, of which 242 are PWRs and 83 are BWRs.

3.2.1 The current situation in the UK

It has been clear for some years that the existing fleet of UK reactors is coming to the end of its useful life, and 14 reactors have already been shut down, and are at various stages of decommissioning. As regards the remainder, the current situation is as shown in Table 3.1 below. The one remaining Magnox reactor is scheduled to close in September 2014, and the oldest of the fourteen AGRs will probably close around 2022. Thereafter, there will be a fairly rapid run down of capacity so that by 2035 only Sizewell B will remain. This could however, with a life extension, continue in operation until 2055.[34]

Table 3.1 Operating nuclear generation plant in the UK

Plant	Type	Power MWe	Commissioned	Likely closure date [2]
Wylfa 1	Magnox	490	1971	Sep 2014
Dungeness B 1&2	AGR	2 x 545	1983 & 1985	2025
Hartlepool 1&2	AGR	2 x 595	1983 & 1984	2022
Heysham I-1 & I-2	AGR	2 x 580	1983 & 1984	2022
Heysham II-1 & II-2	AGR	2 x 615	1988	2030
Hinkley Point B 1&2	AGR	2 x 430 [1]	1976	2023
Hunterston B 1&2	AGR	2 x 430 [1]	1976 & 1977	2023
Torness 1&2	AGR	2 x 625	1988 & 1989	2030
Sizewell B	PWR	1188	1995	2055
Total: 16 units		10,038		

Source: World Nuclear Association

Notes:

[1] Designed as 2 x 610 MWe but currently running at 70%

[2] EDF has announced that life extensions across the AGR fleet will average at seven years[35].
AGR dates given here assume exactly seven years and may be over- or under-estimates.
None of the above dates is immutable, but the cost of further life extensions would be significant.

3.2.2 Current planning for a 'new build' to replace the existing UK reactors

It is clear from the preceding section that the UK nuclear industry is at a turning point. It either needs to follow the example of Germany (and possibly Japan) and cease its activities as soon as legacy issues permit, or to engage in a major new build programme, to replace its superannuated fleets. As noted in Section 1.1, the UK government has taken a decision of principle that a new build programme should be undertaken by the private sector to replace the entire fleet of Magnox and AGR reactors, using 'third-generation' light water reactor technology. Hitherto, DECC has carefully avoided expressing a preference for any specific reactor design, though it has encouraged the UK Nuclear Regulator to review two specific designs – the European PWR (EPR) and the Westinghouse AP1000 reactor – and these have now received preliminary Regulatory approval.

A number of public sector consortia have taken up the UK challenge, and have begun to plan major construction projects. As of March 2012, there were three companies/consortia, EDF, NuGen and Horizon which between them had provisional plans to build 16 GWe of new capacity. The EDF proposal was for two new EPRs at Hinckley Point. NuGen (owned by IBERDROLA and GDF SUEZ) aimed to build two EPRs or three AP1000 reactors in West Cumbria to create 3.6 GWe of additional capacity. Horizon, owned by E.ON

[34] http://www.world-nuclear.org/info/inf84.html
[35] http://www.edfenergy.com/about-us/shareholder-information/documents/AGR_Life_Extension_Expectations_-_16.02.12.pdf

and RWE, had similar plans for Wylfa and Oldbury. In March 2012, however, Horizon announced that it was withdrawing.

An important reason for this was a fall in revenues and an increase in liabilities brought about by the German government's decision, in response to the Fukushima accident, to bring forward the closure dates for all German reactors, effectively abandoning nuclear technology in that country[36]. However, according to current news reports, the Japanese firm Hitachi has bought out Horizon's option[37], and Rolls Royce is bidding to join the consortium. According to the *Financial Times*[38], this was an unusual venture for Hitachi, which normally avoids the complexities of a complete generation site, preferring to restrict itself to less complex reactor build contracts. The reason, it seems, is the cancellation of orders in Japan (another consequence of Fukushima). They would envisage building Hitachi-GE Advanced Boiling Water Reactors (ABWRs) in the UK. If the purchase by Hitachi is confirmed, the UK could have three reactor types in its new fleet: EPR, AP1000 and the Hitachi-GE ABWR. So far, none of the companies has committed unequivocally to building new reactors because they need to finalise the electricity trading arrangements with the UK government.

Of the three third-generation reactors now under consideration, the two best known are the EPR (the European PWR developed by Areva) and the Westinghouse AP1000. The EPR is a large reactor (1750 MWe), which was confirmed in mid-1995 as the new standard design for France, and received French design approval in 2004. Four EPR units are currently under construction: one at Olkiluoto in Finland, another at Flamanville in France, and two at Taishan in China. The Olkiluoto and Flamanville projects are reported to be running over budget and behind schedule[39]. There is as yet little information available on the two reactors being constructed at Taishan.

The AP1000 is a 1200 MWe (or in China 1250 MWe) reactor, which was certified by the US Nuclear Regulatory Commission (NRC) in 2005. Twelve AP1000 units are being built in China, where construction appears to be running on schedule, and applications for licenses to construct another 14 units have been submitted to NRC in the USA.

The Hitachi-GE ABWR is a 1350 MWe reactor which was certified in the US in 1997 (but is not yet licensed in the UK). Two ABWR reactors have been operating in Japan since 1996 and two more since 2006. Two more have been under construction in China since 1997. Construction experience with the ABWR – a key influence on costs – is excellent, but reliability in service has been less satisfactory. Current data indicate that the most reliable of the four operational ABWRs in Japan is Kashiwazaki Kariwa 6 with a reported lifetime load factor (since 1996) of 71%. The least reliable has been Hamaoka 5 (since 2004) with a load factor of 38%. [ref: *Nuclear Engineering International*, July 2012, pp. 38-39]

The DECC Calculator carefully avoids specifying which reactor type should be chosen, but it assumes that the construction schedule will be consistent with the schedule for closure of the existing reactors given in Table 3.1. The corollary is that the UK needs to reach decisions on the choice of operator consortia and reactor types very quickly, if it is to avoid the need for further life extensions of the existing fleet, or alternatively, allow the nuclear component of its energy mix to wither away.

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[36] *The Guardian*, 29 March 2012 http://www.guardian.co.uk/environment/2012/mar/29/nuclear-reactors-rwe-eon-energy
[37] *The Independent*, 4 January 2013 http://www.independent.co.uk/news/business/news/rollsroyce-looks-to-take-stake-in-nuclear-power-as-hitachi-buys-horizon-project-8252449.html
[38] *Financial Times*, 30 October 2012 http://www.ft.com/cms/s/0/174ae282-227e-11e2-b606-00144feabdc0.html#axzz2BNLE4IRk
[39] http://www.world-nuclear-news.org/NN-Olkiluoto_3_delayed_beyond_2014-1707124.html

3.2.3 Fuel availability

So far, the UK government has taken the view that the new build reactors should be operated on a 'once-through' fuel cycle, with the arising spent fuel held in interim storage facilities until a facility becomes available for its long-term disposal. A corollary is that the new fleet will make no demands on the existing reprocessing capability at Sellafield, or require the construction of a new reprocessing facility. If this once-through policy is sustained, it will be necessary to be assured that the required fuel will remain available and affordable, not only up to 2050 but beyond – at least up to the design lifetime of the reactors. It has been argued that a rapid, worldwide 'nuclear renaissance' would lead to a shortage of uranium and a corresponding increase in price. In response, the World Nuclear Association (formerly the Uranium Institute) has estimated that, at the present rate of use, the world's readily available reserves are sufficient to last for about 80 years. If there were a significant worldwide expansion of nuclear generation, this figure could decrease to 40 or even 20 years. However further deposits undoubtedly exist. That they have not yet been discovered is simply because mining companies have no incentive to find them. In any case, fuel costs are a small component of the overall cost of nuclear energy, so that the price of uranium would have to rise significantly before it became a matter of serious concern to electricity companies.

3.2.4 Longer-term worldwide planning for 'fourth-generation' reactors

An alternative to the once-through approach is to envisage a progressive shift to a 'fourth generation' of reactors which would make a much more complete use of the energy stored in mined uranium. This would involve some combination of reprocessing of the spent fuel, to permit the un-burnt fissile material to be recycled, and deliberately generating plutonium from the (predominant) fertile isotope of uranium (U-238) by enhancing the fast neutron flux in the reactor. Such fourth generation reactors of the Fast Breeder (FBR) type could improve fuel utilisation by a factor of about 50, and would have the further advantage of reducing both the volume and radiotoxicity of the arising radioactive waste.

This approach had an important place in the R&D of the international nuclear industry during the period 1960-80, with the UK (along with the US, France, Japan and Germany) playing a leading role. In the late 1980s the UK abandoned this approach: at that time, uranium prices were very low, the UK had access to coal, North Sea oil and gas, climate change was not yet a concern, and the FBR was still some way from commercial exploitation. Other countries chose to continue work on this concept, but in 2006 the UK decided to become an 'inactive' member of the 'Generation 4 International Forum' (GIF) which coordinates international R&D in this area. By this time, the UK had a well-established reprocessing capability, which it continued to operate, and it has by now accumulated a stockpile of about 100 tons of separated plutonium, together with some 80 thousand tons of depleted uranium.

During this period, a number of countries decided to implement an alternative strategy to utilise the excess of available plutonium, by using it to fabricate 'mixed oxide' (MOX) fuel for use in LWRs. The UK did not pursue this MOX strategy for its own nuclear programme, although it did build a MOX plant to support, on a commercial basis, other countries which were doing so. This option is discussed further in Chapter 4.

As regards the future, we also consider in Chapter 4 whether the UK government should now re-examine its disengaged policy on fourth-generation reactors, in the light of climate change and rising world populations. It will be clear from the above that this is not an urgent issue – at most, fourth-generation reactors might feature towards the end of a pathway to 2050, or at least provide reassurance that the availability of fuel did not become an issue shortly thereafter. We should, however, record here that we do not regard as feasible the strategy of leap-frogging straight to a fourth-generation design. One such suggestion – that the UK should proceed immediately to the construction of a liquid metal-cooled fast reactor (for example, PRISM) – has recently received some publicity[40], but we take the view that it is unlikely that this would achieve credibility within the necessary timescale.

3.2.5 Spent nuclear fuel policy

The useful life of nuclear fuel in a thermal reactor is usually three to seven years. After that, the fuel is no longer an efficient energy producer but it remains intensely radioactive and, in consequence, continues to produce a significant amount of heat. So for the first nine to 12 months after its discharge from the reactor, the immediate requirement is to provide an effective coolant and radiation shield, and the standard approach is to provide interim storage under water in an engineered pond located next to the reactor. After that time, the fuel is either sent for reprocessing or kept in some form of interim storage (wet or dry and normally for 30-40 years) pending deep geological disposal. In the former case, the fuel is regarded as a resource from which the uranium and plutonium can be removed for recycling; in the second – the once-through approach – spent nuclear fuel is seen as a waste.

The choice between these two approaches is a fundamental one, and if the UK is to include any nuclear power in its energy mix, it is essential that the government (together with industry, regulators and R&D organisations) should have a strategy for the short- and long-term management of the arising spent fuel.

The once-through approach has the merit of simplicity, but it faces the problem that there is currently no geological disposal facility anywhere in the world that is authorised to accept either high-level waste (HLW) or spent fuel, although plans are well advanced in a few countries (but not yet in the UK). In consequence, countries that have taken this approach are currently obliged to establish 'interim storage facilities' for spent fuel. These are usually located close to the reactor site, and use large shielded casks with suitable radiation monitoring and security protection.

The alternative reprocessing approach, which has been demonstrated successfully in the UK and internationally, does not remove the eventual need for deep geological disposal of residues from spent fuel since, along with uranium and plutonium, reprocessing also produces HLW and technological wastes consisting of fuel cladding, processing chemicals and other residues. These amount to approximately 3 per cent of the mass of the spent fuel, and need to be permanently immobilised in a stable matrix, and then sent to a site for deep geological disposal. However, it is commonly agreed that these wastes are less demanding than the spent fuel from which they came. The volume of waste is smaller, and its long-lived heat generation and radiotoxicity are both greatly reduced as a result of the removal of uranium and plutonium. These can then be used in the manufacture of fresh fuel (either separately or in a mixed fuel known as MOX) for either thermal reactors or (eventually) in fast reactors.

Given that uranium is currently plentiful, and that the use of MOX in thermal reactors does not greatly improve uranium utilisation, it can be argued that it would be better to designate the separated or newly-arising plutonium as a national energy resource, to be used at some future date in fast reactors. Given that spent fuel must be cooled for some decades before it becomes suitable for deep disposal, there is time enough to consider how best to manage this resource. In the meantime, the R&D programme currently undertaken by the Nuclear Decommissioning Authority, to determine how the ultimate disposal should be carried out in an environmentally acceptable manner, should clearly continue.

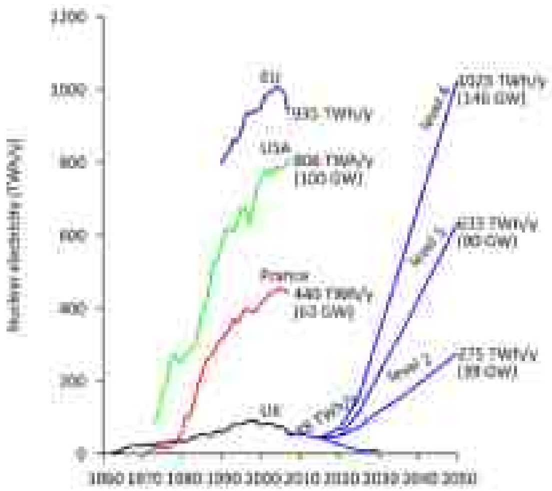
[40] For example, in *The Independent*, 8 September 2012

3.2.6 The infrastructure and human resources required for a nuclear programme

Some critics have challenged the credibility of a new build programme in the UK, particularly if it is on a scale as large as is envisaged in two of our three proposed pathways. Here, it is relevant to compare the proposed construction programmes with those undertaken in the past in the US, France and Japan. In the US, almost all 104 currently operating reactors were built in the 23-year period 1967 to 1990; in France 58 reactors were constructed and commissioned over a period of 25 years from the mid-1970s to 2000; and in Japan 54 reactors were constructed and commissioned in a 35-year period up to 2005 (see Figure 3.1). In all these cases, no more than two reactor types were selected for construction (PWRs and BWRs), though variations in detailed design evolved as operating experience grew. So if the UK were to take a decision quickly on a preferred design, it is not unreasonable to expect that a first new build PWR could become operational by about 2021, and the design could then be rolled out at a rate of one to two reactors per year.

However the words ‘not unreasonable’ here are chosen advisedly. To achieve a high rate of rollout, the UK nuclear industry would need to have a proportionate skilled workforce and industrial infrastructure. There would be a need for urgent collaborative action between the government and the private sector to rebuild the capability which has been lost in the years when nuclear power was out of favour. The recommendations of the House of Lords inquiry on nuclear R&D capabilities are very relevant here[41].

Figure 3.1 Build rate of nuclear power stations[42]



3.3 Renewables – the common ground

There is nearly universal agreement that the problem of climate change requires a major policy shift towards low-carbon solutions, and Fukushima has reinforced the reluctance of many countries to rely heavily on nuclear power as an element in the low-carbon energy mix. There is also widespread agreement that the UK renewables resource is very large, and that the technologies for exploiting it are developing rapidly[43]. A study by ARUP for DECC, for example, suggested that on a high estimate, the UK could have up to 126 GW of renewables capacity by 2030, with 76 GW of wind, 19 GW of solar PV, 6 GW of wave and tidal and around 12 GW of biomass[44]. Similarly, a report written by the energy consultancy Garrad Hassan, for the

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[41] http://www.publications.parliament.uk/pa/ld201012/ldselect/ldsctech/221/221.pdf
[42] Taken from DECC Calculator website http://2050-calculator-tool.decc.gov.uk/assets/onepage/0.pdf
[43] Boyle, G. (ed.) (2012) *Renewable Energy* Oxford University Press, Milton Keynes, pp. 388-390
[44] ARUP consultants, ‘Review of the generation costs and deployment potential of renewable electricity technologies in the UK’ http://www.decc.gov.uk/assets/decc/11/consultation/ro-banding/3237-cons-ro-banding-arup-report.pdf

Worldwide Fund for Nature, suggested that in their C1 strategy, the UK could have up to 105 GW of renewables capacity in place by 2030, supplying 88% of UK electricity[45]. An important element of their strategy was a 35 GW supergrid interconnection to a European market for the UK's excess power (generated at times of high renewable production and low demand). This would make it economic to build much more renewable capacity in the UK.

These optimistic assessments are very much in line with the consensus which is developing in continental Europe. The current EU target is to obtain 20% of all its energy, not just electricity, from renewable sources by 2020. This is to be achieved in parallel with a reduction in energy consumption by 20%, as compared with what it would have been on existing trends. Targets for the longer term are also being negotiated, and there is a proposal that the EU 2050 Roadmap should include a renewables target lying between 55% of all its energy (in the lowest scenario) and 75% (in the highest scenario). In the latter case, 97% of all electricity would by then be supplied by renewables[46]. Several countries within the EU are already approaching their 2020 targets, led by Austria, Denmark, Finland, Latvia, Portugal and Sweden[47], and some have ambitious follow- up targets. For example, Denmark aims to be 'zero carbon' by 2050[48], and Germany aims to obtain 80%[49] of its electricity (or perhaps even 100%[50]) from renewables by 2050. A number of independent studies have suggested that the EU as a whole could reach similar 2050 targets, and that similar targets might be attainable worldwide.

3.3.1 The current situation in the UK

Against this enthusiastic international background, the official position of the UK government on renewable energy has hitherto been relatively cautious. However it has made a legally binding commitment to cut its GHG emissions with respect to a 1990 baseline by at least 80% by 2050, with a target to reduce its emissions by at least 35% by 2022 (see Section 1.2). It has also made a commitment under the EC's Renewable Energy Directive to obtain15% of its energy from renewables by 2020[51]. But by European standards, its progress towards meeting even these modest targets has been relatively slow.

In terms of the UK's actual performance in installing and operating renewable generation capacity, as reported in the DECC *Digest of Energy Statistics* (DUKES) for 2011, the current (2010) 'nameplate' renewable capacity figures are dominated by Onshore wind (4.0 GWn), followed by Hydro (1.6 GWn) and

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[45] WWF (2011) 'Positive Energy: how renewable electricity can transform the UK by 2030', World Wide Fund for Nature, London, http://assets.wwf.org.uk/downloads/positive_energy_final_designed.pdf. Based on report by Garrad Hassan (2011) 'UK Generation and Demand Scenarios for 2030' http://assets.wwf.org.uk/downloads/positive_energy_glgh_technical_report.pdf

[46] EC (2011) 'Energy Roadmap 2050: a secure, competitive and low-carbon energy sector is possible', European Commission, Brussels, http://europa.eu/rapid/pressReleasesAction.do?reference=IP/11/1543&type=HTMLIEA

[47] Eclareon (2011) RES-Integration, report to the EC DG ENG, on EU member states progress http://www.eclareon.eu/en/res-integration

[48] Richardson, K. et al, (2011) 'Denmark's Road Map for Fossil Fuel Independence', *Solutions* Vol.2, Issue 4, July http://www.thesolutionsjournal.com/node/954

[49] Maue, G. (2012) Presentation to the UK Parliamentary Renewables and Sustainable Energy Group, February http://environmentalresearchweb.org/blog/2012/02/can-germany-do-it.html

[50] Sachverständigenrat für Umweltfragen (SRU) (German Advisory Council on the Environment) 'Pathways towards a 100 % renewable electricity system' http://www.umweltrat.de/SharedDocs/Downloads/EN/02_Special_Reports/2011_01__Pathways_Chapter10_ProvisionalTranslation.pdf?

[51] Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:140:0016:0062:EN:PDF

Offshore wind (1.3 GWn), with all other renewable sources making rather modest contributions. The actual power delivered to the grid from these main renewable sources in 2010 was 13.7 TWh (i.e. 1.57 GWav), as compared with the total power delivered to the grid from all sources of 43.1 GWav.

Notwithstanding its rather disappointing achievement to date, the UK is now moving forward rapidly in the installation of renewables capacity. It is now the world leader in offshore wind capacity (having overtaken Denmark in 2008), and it has a further capacity of 2.4 GWn under construction. Planning consent has either been granted or is under consideration for a further 12.9 GWn. In all, around 18 GWn could be in place by 2020. UK onshore wind capacity is also growing, but more slowly, with a target of around 15 GWn by 2020. The UK is also leading the world in wave and tidal power, with plans for around 1.6 GWn to be installed by 2020[52]. However UK solar PV power is lagging far behind other European countries, especially Germany, where over 25 GWn of capacity has been installed, and there are plans to expand this to 66 GWn by 2030[53]. This German achievement is not unrelated to its generous government subsidies and FITs: in the UK, solar PV FITs have recently been cut, and further reductions are under consideration.

3.3.2 Renewable energy supply options

One of the problems in selecting a specific set of renewable energy inputs for inclusion in a Pathway is the bewildering range of supply options that are potentially available. These can be summarised as follows:

Electricity supply options

Wind power

Onshore wind is already operational and is competitive on cost at the windiest sites. Expansion of this technology is to a large degree limited by issues of public acceptability on grounds of environmental impact and, in a few cases, objections related to air traffic and radio/TV transmission. Its visual impact is contentious, with concerns expressed about its intrusion into areas of outstanding natural beauty. Objections have also been raised to its acoustic impact. Its impact on land use is equally contentious. Wind power has a rather low energy intensity (the DECC Calculator Tab IIIa1 assumes 2.5 Wav/m^2 of land occupied), and in consequence some 1,333 turbines (with a capacity factor of 0.3) occupying an area of around 400 km^2 are needed to produce 1 GWav of electric power. Against this, it is argued that the land around the individual turbines can be used for agriculture, even if not for domestic habitation. Another issue raised is the possibility that the installation of turbines in upland regions can destroy deep peat resources, which play a major role in carbon sequestration.

Offshore wind has the advantages of higher wind speeds (and therefore a higher load factor), lower topographical interference, a larger available resource and greater public acceptability. Its principal disadvantage is its higher cost because of the difficulties in construction and transmission. The levelised cost of electricity from this technology depends on the assumptions made, and estimates range from twice that of Onshore wind to as little as 10% more expensive[54].

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[52] National Renewable Energy Action Plan for the United Kingdom, produced under Article 4 of the Renewable Energy Directive 2009/28/EC, DECC, 2009 www.decc.gov.uk/assets/decc/what%20we%20do/uk%20energy%20supply/energy%20mix/renewable%20energy/ored/25-nat-ren-energy-action-plan.pdf

[53] The Crown Estate (2011) 'Wave and Tidal energy in the Pentland Firth and Orkney waters' http://www.thecrownestate.co.uk/energy/wave-and-tidal/

[54] International Energy Agency/OECD Nuclear Energy Agency (2010) *Projected Costs of Generating Electricity* 2010 edition, Paris, p.62 http://www.oecd-nea.org/pub/egc/

Solar photovoltaics (PV)

The chief advantages of solar PV are the ubiquity of light energy, and the simplicity of its direct conversion to electrical energy. There is a theoretical limit to the efficiency of this conversion. This means that the electrical output per square metre will not increase by much in the future, but the cost can be expected to decrease further as solar panels become increasingly mass produced. The maximum (Level 4) solar PV contribution envisaged by the DECC Calculator amounts to 16 GWav (140 TWh/y): in its supporting notes it suggests that this might come either from a very large number of individual solar PV installations covering every south-facing façade in the country with solar panels of 20% efficiency and 10% capacity factor, or from 3200 km^2 of land-based solar farms, or from some combination of these. Solar PV does not produce electricity at night, of course, but demand is also lower at that time, so solar PV might make a modest contribution to a diverse renewables system.

Tidal barrage, lagoon and stream

The UK has some of the highest tidal ranges in the world and various schemes have been proposed to harness this resource. The best-known and, perhaps, most strongly opposed is the **tidal barrage**. This entails the building of a dam across an estuary. A head of water is created across the dam and this is used to drive turbines that generate electricity. If both ebb and flood tides are used, power would be produced four times per day. The DECC Calculator estimates that a Severn barrage could generate around 1.9GWav (17 TWh/y). The barrage could also carry a road or railway and would contribute to flood protection. The principal objections are environmental impact and cost. **Tidal lagoons** aim to reduce the unwanted environmental impacts of a barrage by enclosing only part of an estuary or an area off the coast. Smaller schemes would have lesser environmental effects but would be more expensive. If a pair of lagoons was created – one high, one low – this would enable power to be generated at will and they could also be used as a pumped storage facility. The DECC calculator describes only "tidal range" schemes, a category that includes both barrage and lagoon. Assuming that all the UK resource is exploited, the maximum (Level 4) potential is about 4.4 GWav (39 TWh/y). **Tidal stream** schemes entail the placing of turbines in the tide race. This technology is still at an early stage of development, but there is practical experience on a commercial scale. The DECC Calculator estimates the maximum (Level 4) resource as schemes in five locations generating a total of 7.8 GWav (68 TWh/y). The potential environmental impacts of such schemes have not as yet been fully explored.

Wave energy

Machines to convert wave energy to electrical energy have been around for almost 40 years and they continue to be developed, but there is no clear commercial contender to date. At its most ambitious level, the DECC Calculator assumes a 1000km long array of Pelamis 'sea snakes' facing out into the Atlantic. Assuming 50% availability, this would generate 8 GWav (71 TWh/y. Its cost was estimated in 2004 at around £150 per MWh but the developer now claims a prospect of quickly reaching one-third of this number[55].

Hydro

Table 2.3 indicates that the UK had some 1.5 GWn of hydroelectric capacity at the end of 2010, which generated about 0.4 GWav (3.6 TWh). The most recent example, completed in 2008, is the Glendoe plant

[55] Ocean Power Delivery Ltd http://hydropower.inel.gov/hydrokinetic_wave/pdfs/day1/09_heavesurge_wave_devices.pdf

in Scotland, which has a nameplate capacity of 0.1 GWn and an expected average annual output of 0.02 GWav (0.18 TWh). The DECC Calculator estimates that the potential resource could reach 4 GWn with an output of 1.5 GWav (13 TWh). Existing projects produce the cheapest electricity on the grid, and there is the potential for limited expansion at various scales. However, as with onshore wind, there can be public acceptability concerns related to environmental and landscape issues.

Deep geothermal ('Hot dry rocks')

Deep geothermal schemes entail deep drilling to reach hot dry rocks that are typically located 4-5 km below the surface. Water is heated by pumping it through the hot rocks (at around 200°C) and then extracted and used for district heating or for generating electricity. The source of the heat is radioactive decay of uranium in the rocks, and the best resource in the UK is located in Cornwall. Trials performed in 1985 suggested that electricity generation from this source was not technically or commercially viable in the short- or medium-term[56], but interest has revived and a number of pilot schemes are in progress. The DECC Calculator estimates that, by exploiting all the UK's practically available hot dry rock resource, the installed capacity could reach 5 GWn with an output of 4 GWav (35 TWh).

Biomass and biowastes

Energy crops, biogas from anaerobic digestion, and biomass from waste streams can be used as fuels for electricity generation, and its combustion can be seen as roughly carbon neutral, since the production of the biomass involves the absorption of CO_2. The 2012 DECC/DEFRA/DfT Bioenergy Strategy estimated that biomass could supply around 12% of the UK's primary energy by 2050, and possibly up to 21%; some of this would be used for heating and for vehicle fuel.[57] There are two principal objections to the use of biofuels, both put forward by Searchinger[58]. The first is that widespread use of energy crops will expand the area of land under cultivation and, by displacing natural forest and grassland, will release the carbon currently banked in these ecosystems so that the impact of carbon dioxide emissions could be the opposite of what was intended. The second argument is that the time delay between biofuel combustion and forest re-growth will lead to an increase in emissions over the forty years leading to 2050. This can be mitigated by the use of fast-growing plant species and short-rotation coppicing but, certainly, the use of mature trees for large-scale energy production should be avoided.

Sewage gas and land fill gas are currently the cheapest source of non-hydro renewable energy, and while they are significant, the UK resource is limited.

Gas and hot water options

Green gas for heat and power

In addition to biogas produced from biomass/wastes, 'green gas' can be produced using power that is generated from non-biomass renewable sources, for example, during periods of low demand or excess output. Because the gas can be stored, it can then be used to generate power during periods of high demand,

[56] Quoted by MacKay, op. cit. p.98
[57] http://www.decc.gov.uk/assets/decc/11/meeting-energy-demand/bio-energy/5142-bioenergy-strategy-.pdf
[58] Searchinger, T. et al (2008) 'Use of U.S. Croplands for Biofuels Increases Greenhouse Gases Through Emissions from Land-Use Change' *Science* Vol.319, no.5867, pp.1238-1240, 29 February. See also:
RSPB/Friends of the Earth/Greenpeace (2012) *Dirtier than coal: why Government plans to subsidise burning trees are bad news for the planet* http://www.rspb.org.uk/Images/biomass_report_tcm9-326672.pdf

and can therefore help to address the issue of intermittency. The best-known example is hydrogen produced by electrolysis of water. Another is methane, made by reacting hydrogen with carbon dioxide. In addition, biomethane, electrolytically-produced hydrogen, or methane made from it, can be injected into the gas main to replace or augment natural (fossil) gas. Surprisingly, perhaps, the DECC Calculator considers hydrogen only in the context of transport: it does not allow hydrogen generation to be a means of storing excess energy production for later use (perhaps because of the rather poor efficiency of the processes involved). This issue is explored further in Chapter 5. In the DECC model, this buffering function is performed by the batteries of millions of electric vehicles which, by virtue of a smart meter, would adjust their demand to meet the supply.

Combined Heat and Power (CHP)/District Heating (DH)/Heat stores

As an alternative to natural (fossil) gas, biomass (in solid, liquid or gaseous form) can be used directly for heating – for example, in domestic micro-CHP units – or more efficiently in large-scale CHP plants linked to DH networks. CHP can also significantly improve the overall energy usage of fossil fuel-fired electricity generating plants, although it slightly reduces the thermal efficiency of electricity production.

This technology has a relatively low penetration in the UK, probably because of the widespread use of natural gas for home heating. The DECC Calculator allows users to express their preferences regarding CHP through the combination of two headings "home heating electrification" and "home heating that isn't electric". It then implements these using an internal algorithm explained in Tab IXa of the Excel spreadsheet. As an illustration, the Calculator allows a maximum of 90% of building heating to come from CHP of various kinds.

Heat pumps

A possible source of low-grade heat suitable for central heating is ground- or air-source heat pumps. These are mostly deployed at individual premises. In the Calculator this is termed "Environmental heat" and, as with CHP, is chosen through combination of two headings "home heating electrification" and "home heating that isn't electric". The Calculator again allows a maximum of 90% of building heating to come from heat pumps. This is a simple, if relatively expensive, technology that is already in use. Domestic heat pumps can have a Coefficient of Performance (COP – the ratio of the heat delivered from its source to the energy consumed in pumping it) of 3, but large CHP/DH systems can have a COP of up to 9, or much more if lower temperature water is used.[59] However installing DH networks is disruptive, whereas it is relatively easy to install domestic heat pumps, although the cost per tonne of carbon saved is high.[60] (See also the discussion on this point in Section 6.3.3)

Solar water heating can also play a role in reducing the demand for water heating in homes, and can help to meet central heating demand if linked to DH with storage. Level 4 of the DECC Calculator assumes that by 2050, all suitable buildings could have 60% of their annual hot water demand met by solar thermal. This requires 3.1 m^2 of heating panels per person, delivering a total of 13 GWav (116 TWh/y). To meet all-year-round demand, water heated in the summer would have to be stored for use in the colder seasons, and this could be done at a district or community level, as is practised in Denmark.

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[59] Lowe, R. (2011) 'Combined heat and power considered as a virtual steam cycle heat pump' *Energy Policy* Vol.39, Issue 9, pp. 5528-5534, September http://dx.doi.org/10.1016/j.enpol.2011.05.007

[60] Kelly, S. and Pollitt, M. (2009) 'Making Combined Heat and Power District Heating (CHP-DH) networks in the United Kingdom economically viable: a comparative approach', EPRG Working Paper 0925, Electricity Policy Research Group, University of Cambridge www.eprg.group.cam.ac.uk/wp-content/uploads/2009/11/eprg09251.pdf

3.3.3 The issue of intermittency of renewable energy sources

Most sources of renewable energy are naturally variable and intermittent, albeit in different ways. The majority ultimately derive their energy from the sun. Solar energy naturally follows the local cycle of day and night, modified by cloud cover. Wind and wave energy, created by the differential solar heating of air, land and sea, have a more complex variability. Tidal flows are almost unrelated to the sun or to weather systems, being due primarily to the gravitational pull of the moon, and vary with the lunar cycle[61]. The variability/intermittency of most renewables is often portrayed as a major potential constraint on their effective use, and certainly there needs to be a strategy to address this issue. Candidates for inclusion in a strategy to solve the problem are:

- Balancing supply and demand using grid management, with gas plants for backup
- Reducing the need for backup by extending grids; building international supergrid links
- Investing in energy storage – for example, pumped storage
- Avoiding some excess renewable inputs by curtailing generation
- Shifting to gas for easier transmission and storage
- Making use of biogas or green gas made from surplus renewable electricity
- Using CHP/DH/heat stores.

To produce a definitive strategy, it is necessary to quantify each of these candidate elements, and to assess their mutual compatibility and cost. Each candidate is discussed in more detail in Chapter 5. The overall effectiveness of the combination of measures used to counter intermittency in a given strategy is measured by the DECC Intermittency Stress Test, mentioned in Section 2.4, and described in Section 3.6.2.

3.4 Carbon Capture and Storage (CCS) – the common ground

Much of the UK's current electricity production leads directly to the discharge of CO_2 into the atmosphere. It is therefore natural to consider the option of capturing this CO_2, and placing it in secure storage in a location which will ensure that it cannot return to the atmosphere, at least for many centuries. A slow leakage on a sufficiently long timescale may be acceptable, if by then mankind has moved on to some new sources of energy which do not cause GHG emissions.

3.4.1 Carbon Capture

The US Energy Information Administration estimates that current world coal reserves are sufficient to last for 126 years at the current rate of production[62]. For natural gas the figure is 150 years and, if unconventional gas (i.e. shale gas) is included, this would be at least doubled[63]. Furthermore, both coal and gas deposits are easily available and are widely distributed geographically. The difficulty, of course, is that the burning of gas and especially, coal produces the GHG emissions that we are seeking to reduce.

All the carbon capture technologies that are currently under development require very significant capital investment and are therefore applicable only to large producers of CO_2. These are primarily fossil-fuelled

[61] Boyle, G. (ed.) (2012) 'Renewable Energy' op. cit.

[62] US Energy Information Administration, *International Energy Outlook 2011*, p.79 http://www.eia.gov/forecasts/ieo/pdf/0484%282011%29.pdf

[63] International Energy Agency (2011) *Are we entering a golden age for gas?* World Energy Outlook Special Report 2011,OECD/IEA, Paris, p.17 http://www.worldenergyoutlook.org/goldenageofgas/

electricity producers (currently emitting 9.6 Gt CO_2 per annum worldwide) and, to a lesser extent, cement manufacture, refineries, steel production, etc[64]. A typical 1 GWe power station emits around 8 million tonnes of CO_2 e per year[65].

There are three main methods for CO_2 capture, known under the names of post-combustion, oxy-combustion and pre-combustion[66]. Post-combustion uses proprietary organic compounds (amines) to scrub CO_2 from the flue gas emerging from an energy-producing plant. The scrubbing compounds are then treated with steam, which liberates the CO_2 (which can then be compressed and transported away) while the compounds are regenerated for re-use. A complication is that the scrubbing compounds cannot be regenerated if the flue gas contains sulphur and/or nitrogen oxides. Sulphur is present as an impurity in the fuel while nitrogen compounds arise when the fuel is burnt using air. To prevent the loss of the scrubbing compounds, it is necessary to introduce an initial flue gas clean-up process.

Oxy-combustion avoids the formation of nitrogen oxides by burning the fuel in oxygen together with some re-circulated CO_2. This makes it possible to produce a stream of concentrated CO_2 that may need little further treatment before being compressed for transport and storage. This removes most of the expense of flue gas treatment, but introduces additional costs associated with the separation of oxygen from air.

The third technology – pre-combustion – can only be used when a fuel containing carbon is processed to produce a gaseous fuel for combustion. For example, coal or biomass is traditionally processed to produce a mixture of carbon monoxide (CO) and hydrogen for combustion:

$3C + O_2 + H_2O \rightarrow H_2 + 3CO$

In the pre-combustion CCS process, impurities (principally sulphur oxides) are removed at this stage, and the hydrogen content is then increased using the so-called 'shift' reaction:

$CO + H_2O \rightarrow CO_2 + H_2$

so that the overall reaction is

$$3C + O_2 + 4H_2O \rightarrow 4H_2 + 3CO_2$$

One might characterise this by saying that the process uses input carbon to produce hydrogen from water. The resulting CO_2 is then scrubbed out of the gas stream prior to combustion, and the resulting flue gases can be vented to the atmosphere. Pre-combustion could be used in combination with an integrated gasification combined cycle (IGCC). An advantage of IGCC is that it is an already-proven process and could be an initial step in the establishment of an energy system based on hydrogen. The main disadvantages are complexity and high capital cost[67].

All three methods are currently under investigation. In the UK, for instance, there is a 40 MWt oxy-combustion facility at Renfrew, a 4 MWe pilot post-combustion (amine scrubbing) plant at Ferrybridge, and a 5-10 MW pre-combustion IGCC plant is planned to be operational before 2015[68]. The most likely outcome is that different technologies will be found to be suitable for different types of fuel. The use of carbon

[64] Metz, B et al (eds.) (2005) IPCC Special Report *Carbon Dioxide Capture and Storage*, Cambridge University Press, UK, p. 431 http://www.ipcc.ch/publications_and_data/publications_and_data_reports.shtml#2
[65] EDF quotes 870g CO2e/kWh for typical coal-fired station (i.e. 7.6 Mt/GWy). http://www.edfenergy.com/energyfuture/coal
[66] http://en.wikipedia.org/wiki/Carbon_capture_and_storage
[67] Booras, G. and Holt, N. (2004), 'Pulverized coal and IGCC plant cost and performance', Gasification Technologies Conference 2004, Washington, DC, October 3-6
[68] DECC CCS Road map, innovation and R&D. http://www.decc.gov.uk/assets/decc/11/cutting-emissions/carbon-capture-storage/4901-ccs-roadmap--innovation-and-rd.pdf

capture introduces a need for ancillary, energy-consuming plant, which has the effect of reducing the overall thermal efficiency of the plant. This effect is significant: the thermal efficiency of coal-fired generation, for example, decreases from around 43% to 35%[69], so that demand for fuel increases by about 20%.

3.4.2 Carbon storage

The currently-preferred approach to the storage of CO_2 is to inject it into a deep geological formation. All current underground storage designs aim to store the CO_2 at a depth of greater than 800 m because these depths produce a pressure at which CO_2 exists in a supercritical state[70] – one in which the material is neither liquid nor gas but, rather, behaves like both. The advantages are two-fold: there is a volume reduction (compared to the gas at room temperature and pressure) of at least 200 times and the supercritical CO_2 can flow easily (like a gas) into the pore spaces between mineral grains in the host rock.

Three types of formations may be suitable: deep saline aquifers, non-mineable coal seams, and depleted oil and gas reservoirs. Experience with the last of these is widespread, and has been accumulating over the past 30 years or more, because the injection of CO_2 into oil reservoirs has been used as a means of boosting oil production from dwindling fields. Typically, the required CO_2 has hitherto been produced by partial oxidation of natural gas (methane) giving rise to a mixture of CO_2 and hydrogen, from which the CO_2 is separated and piped to where it is needed. Around 50 experimental CO_2 storage projects have been conducted worldwide[71] using this general approach. The largest of these is the Canadian Weyburn-Midale CO_2 storage and monitoring project, which injected more than 5 Mt of CO_2 into a depleted oilfield. An extensive monitoring network failed to detect any leakage. The fact that these reservoirs have existed for millions of years gives some confidence in their ability to contain CO_2 for the requisite period of time, though individual sites have to be examined to confirm this.

While the general principle of carbon storage has been demonstrated, even the largest of these projects is a long way short of the ~100 Mt per year envisaged by some for the UK in 2050. In terms of mass of material handled, this is broadly equivalent to the amount of oil that was extracted annually at the time of the peak of North Sea oil production. Furthermore, because at best 90% of the CO_2 produced is captured, CCS-equipped generators would release around 10 Mt/y of CO_2 to the atmosphere. Pumping CO_2 to and into storage wells also uses energy.

The UK does not at present have any electricity generators equipped with CCS: the nearest thing to an operating facility is a 30 MWe pilot plant owned by Vattenfall at Spremburg in Germany, which uses oxy-combustion. Confidence in the future of the technology comes from knowledge that industrial techniques already exist for CO_2 capture, and that the oil industry has for many years transported CO_2 at high pressure via pipelines, and pumped it into deep reservoirs. The main uncertainty surrounding CCS is that of cost: CCS will undoubtedly increase the price of electricity generation, but by how much (and how the various options will compare one with another) are open questions. This theme is reflected in Vatenfall's overall objective to "*develop commercial concepts* for CCS at coal-fired power plants by 2015-2020" [our

[69] International Energy Agency/OECD Nuclear Energy Agency (2010), *Projected Costs of Generating Electricity* 2010 edition, Paris, http://www.oecd-nea.org/pub/egc/
[70] International Energy Agency (2008), *Geologic storage of carbon dioxide: staying safely underground*, January http://www.co2crc.com.au/dls/external/geostoragesafe-IEA.pdf
[71] Scottish Centre for Carbon Storage website (accessed 3 Nov 2008) http://www.geos.ed.ac.uk/sccs/storage/storageSites.html

emphasis][72]. It seems likely that commerciality will depend on which technologies are deployed, and how they are optimised to suit the various types of fuel.

3.5 Costs

Two reports written for the Committee on Climate Change have recently reviewed all the main sources of primary energy, and assessed the likely trends in the cost of these technologies between now and 2050[73,74]. Both reports compare costs using the levelised cost of generated electricity (LCGE), which is the notional price at which electricity would need to be sold in order for the investment to break even; it excludes the costs of transmission, which are significant but which (with some bias) apply equally to all generators. The levelised cost allows different kinds of generation to be compared with one another. For example, technologies where high capital costs are combined with low fuel costs (for example, nuclear and offshore wind) may be compared with technologies where the reverse is true (for example, CCGT). This requires an estimate to be made of the cost of capital that must be sunk into establishing the plant. This capital cost is built into the levelised cost using an annual discount rate, which is intended to reflect currently available interest rates, the commercial risk of the venture, and a general preference for receiving money sooner rather than later. The calculated value of LCGE can also take account of other parameters e.g. for fossil-fuelled generators, a foreseen carbon emissions penalty. Nevertheless, for capital-intensive projects such as nuclear and renewables, the discount rate is an important determinant of LCGE.

In the first of the two reports mentioned above, discount rates were assumed to be constant (at 7.5% or 10%) across all the technologies. A range of cases was analysed but, in broad terms, the lowest cost generators were found to be nuclear, onshore wind and CCGT, while the highest were offshore wind and coal+CCS. The second report drew on a study in which the views of City of London firms were canvassed about the discount rates that they would wish to apply if they were approached to invest in the various technologies[75]. While there were considerable variations between the discount rates proposed by different investors, it was clear that large projects involving new technology (for example, wave power) were considered to be higher risk and were, therefore, assigned higher discount rates. Overall, the range of discount rates proposed was 6-18%. This study had the effect of widening the spread in LCGE values across the various technologies.

Using these findings, this second report calculated LCGEs at three time points – 2011, 2020 and 2040 – assuming that the penalty on carbon emissions rose over the period, but that discount rates fell as experience was gained with the new technologies. The cheapest technologies throughout the 2011-2040 period were anaerobic digestion, hydroelectric, municipal solid waste, onshore wind and nuclear. The most expensive in 2011 were wave power, tidal schemes and solar PV. All technologies decreased in price over the 29-year period but only solar PV and offshore wind fell sufficiently to bring them close to being competitive with the lowest cost options. Because CCS is not completely effective at trapping carbon, the increasing penalty on carbon emissions meant that, while CCGT+CCS was competitive with nuclear in 2011, by 2040 it

[72] http://www.vattenfall.com/en/ccs/demonstration-plants.htm
[73]Mott MacDonald (2010) 'UK Electricity generation costs-update', consultants report for the Department of Energy and Climate Change, June http://www.decc.gov.uk/assets/decc/what%20we%20do/uk%20energy%20supply/energy%20mix/1823-mott-macdonald-report-costs.pdf
[74] Mott MacDonald (2011) 'Costs of low-carbon generation technologies', Mott MacDonald Ltd report for the Committee on Climate Change, May http://hmccc.s3.amazonaws.com/Renewables%20Review/MML%20final%20report%20for%20CCC%209%20may%202011.pdf
[75] Oxera Consulting (2011) 'Discount rates for low carbon and renewable generation technologies', prepared for the Committee on Climate Change, May http://hmccc.s3.amazonaws.com/Renewables%20Review/Oxera%20low%20carbon%20discount%20rates%20180411.pdf

became 50% more expensive. Similarly, the levelised cost of Coal+CCS was 50% greater than nuclear in 2011 but more than double that of nuclear in 2040.

Overall, these LCGE calculations showed the importance of three factors: (i) discount rates, which depend upon the perceived investment risk, (ii) the penalty placed on carbon emissions and (iii) the impact of replication and mass production on the capital cost of plant. In a situation where the government expects the private sector to make the necessary investments, it is inevitable that discount rates will be affected by the perceived commercial risk – how else can a private investor operate? But, while discount rates are the economic orthodoxy, we should be wary of applying them over long timescales. As Arrow[76] has pointed out, the ethical basis of radioactive waste disposal, in which future generations – perhaps those living thousands of years in the future – are to be given the same degree of protection as the present one, implies a discount rate that is close to zero. This view was reflected by the Stern Review on the Economics of Climate Change[77] which used a central discount rate of only 1.4%. In the same vein, Portney and Weyant[78] have concluded that considerations of intergenerational equity suggest that market discount rates should not be applied beyond 40 years – precisely the timescale of much of the energy infrastructure which is implicit in the 2050 Pathways models.

Perhaps because of the controversy over the appropriate discount rates to use, the DECC Calculator adopts a different approach. This is explained in more detail in Section 7.7, which presents the results for our three Pathways.

3.6 Use of the DECC Pathways to 2050 software to explore options

3.6.1 Pathway choices

As noted in Section 1.3, the DECC Pathways Calculator provides a very powerful and straightforward means of exploring possible pathways, by inviting the user to specify the values of 43 parameters in their proposed pathway, and then computing the implications of those choices. The 43 Headings are shown in Table 3.2 below, and the selected value of each parameter in each of the three Pathways described in this report are shown in the three following columns. It will be seen that in each case some non-integral values of the parameter in question have been chosen. This is permitted by the software, but non-integral values are interpreted in a slightly idiosyncratic manner, so the user has to engage in some experimentation to achieve the desired result.

The chosen values of these 43 Headings can be fed into one of two alternative versions of the DECC Pathways software. The simpler of these is the 'web' version, which can be initiated by running the url for the chosen Pathway, as specified in the footnotes below, for the High Nuclear Pathway[79], for the High Renewables Pathway[80] or for the Intermediate Pathway[81]. The alternative 'Excel' version can then be accessed by following the 'Share' link, and then taking the link to the 'underlying Excel spreadsheet'. The Excel version can also be used in 'stand-alone' mode, with the heading values inserted directly into column E of the 'Control' spreadsheet.

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[76] ibid

[77] Stern, N. (2007) *The Economics of Climate Change: the Stern Review*, Cambridge University Press http://webarchive.nationalarchives.gov.uk/+/http:/www.hm-treasury.gov.uk/independent_reviews/stern_review_economics_climate_change/stern_review_report.cfm

[78] Portney, P.R. and Weyant, J.P. (eds.) (1999) *Discounting and intergenerational equity* Resources for the Future, Washington

[79] http://2050-calculator-tool.decc.gov.uk/pathways/s1f3cc1111121f1102231230023222202333022023023330220123

[80] http://2050-calculator-tool.decc.gov.uk/pathways/1011ot2wr1frz4130344121004414440342304102304230410133

[81] http://2050-calculator-tool.decc.gov.uk/pathways/2023d211111212120223122002313220233302202302430220133

It will become clear from this report (and particularly from Annex 1) that neither of these versions can generate all of the relevant outputs of the DECC model on its own – they need to be used in conjunction. The home page of the web version reproduces the selected values of the first 42 of the 43 Headings in convenient tabular form (for the problem over the 43rd Heading, see Annex 1), and presents the most significant outputs of the model (UK energy demand, UK primary energy supply and GHG emissions) in graphical form. Other summary information can be obtained by following a drop-down menu called 'See implications'. However a lot of more detailed numerical information on the outputs from the model, and on some of the intermediate steps in calculating those outputs, can only be obtained from the Excel version, which consists of 73 spreadsheets, each identified by a rather un-informative tab label. The most important of these are the 'Control', 'Intermediate Output' and 'Flows' spreadsheets, which contain most of the numbers which we will discuss in this report.

The 43 Headings are divided into two blocks. The first 21 Headings relate to possible sources of 'primary energy'. The definition of this term is slightly arbitrary: it includes as primary energy sources some headings which might perhaps be regarded as secondary sources – for example, the sources which are described as 'imports' such as electricity or bioenergy. The remaining 22 Headings relate to measures which might be taken to modify the demand for energy. The software then computes the consequences of these choices, using some algorithms which are not always easy to understand. For most of these headings, a one-page summary of the implications of that choice can be found in[82].

For most purposes, the user can gain sufficient insight into the energy transformation processes incorporated into the model by examining the so-called 'Sankey diagram' for the Pathway (which can be seen on screen by running the web version of the software, and following the 'See implications' and 'Energy flows' drop-down links). This exhibits in graphical form the process by which the primary energy is converted into final end-use energy, which is presented in summary form under a set of 13 Sectors, as shown in Annex 2. The various transformation processes which effect this conversion (for example, the conversion of nuclear high-temperature steam into electricity, with the associated energy losses) are displayed at the centre of the diagram, and the energy flows involved are presented as bands with a width proportional to the magnitude of the flow. Printed versions of the Sankey diagrams for the three chosen Pathways are given in Annex 2. However these printed diagrams do not show the numerical values of energy flows, since the printable web output does not show them, but these numbers can be read off the computer screen, by running the web software, following the links to the Sankey diagram for the chosen Pathway, and then pointing the mouse pointer at any flow line. This brings up the computed energy flow for that Pathway.

Unfortunately, the Sankey diagram does not clarify all the steps in the computational process leading to the Calculator outputs. For example, readers may have noted that the list of 43 Headings does not include certain highly significant primary energy sources – for example, coal, oil, gas, pumped heat from underground. This is because the DECC software computes the energy which must implicitly be supplied from these sources, once the values of the listed headings have been specified. These implicit assumptions require some detective work to identify, but their implications are visible in the Sankey diagram, and in most cases they can be discovered by examining some of the tabs in the Excel version of the software. Some further comments on the limitations of the DECC software assumptions will be found in the following chapters.

[82] http://2050-calculator-tool.decc.gov.uk/assets/onepage/*.pdf, where * is replaced by the number in column 1 of table 3.2, although this algorithm does not always work.

3.6.2 Intermittency stress test

To assist in the assessment of proposed solutions, the Calculator package incorporates a ‘stress test’ which it applies to every proposed Pathway. This determines whether the proposed system would continue to meet consumer demand under some specific adverse meteorological conditions, namely a five-day period during which the temperature falls to -1.4 °C and the output from variable renewable generators falls throughout this period to 5% of their nameplate capacity. The Calculator then computes the measures which the grid operator will have to take to maintain continuity of supply under these circumstances. These might include halting exports, calling on standby generating capacity, drawing on interconnectors or pumped storage, shifting demand from electric vehicles etc. If the specified back-up capacity is insufficient to meet the stress test, the Pathway assumes that spare CCGT (without CCS) is available. For each Pathway, the Calculator reports the outcome of the stress test in the block labelled Energy Security Contextual Data.

Table 3.2 Choices of Headings in DECC Pathways Calculator for the three Pugwash Pathways (note that Heading 43 can only be accessed from the Excel Spreadsheet: see Annex 1)

	Tab label in Excel version	Heading description	HNuc	HRen	Interm	Max
1	II.a	Nuclear power stations	2.8	1	2	4
	I.b	**Carbon Capture Storage** (CCS)	0	0	0	
2		CCS power stations	1.5	1	2	4
3		CCS power station fuel mix	3	1	3	D
4	III.a.2	Offshore wind	1.2	2.4	1.3	4
5	III.a.1	Onshore wind	1.2	2.9	2	4
6	III.c.Wave	Wave	1	2	1	4
7	III.c.TidalStream	Tidal Stream	1	3.2	1	4
8	III.c.TidalRange	Tidal Range	1	2.7	1	4
9	I.a	Biomass power stations	1	1	1	4
10	IV.a	Solar panels for electricity	1	1.5	1	4
11	IV.b	Solar panels for hot water	2	2.7	2	4
12	III.d	Geothermal electricity	1	3.5	1	4
13	III.b	Hydroelectric power stations	1.5	4	2	4
14	IV.c	Small-scale wind	1	1	1	4
15	VII.a	Electricity imports	1	3	2	4
	VI.a	**Agriculture and land use**	0	0	0	
16		Land dedicated to bioenergy	2	3	2	4
17		Livestock and their management	2	4	2	4
18	VI.b	Volume of waste and recycling	3	4	3	D
19	VI.c	Marine algae	1	1	1	4
20	V.a	Type of fuels from biomass	2	2	2	D
21	V.b	Bioenergy imports	3	1	2	4
	Demand		0	0	0	
	XII.a	**Domestic passenger transport**	0	0	0	
22		Domestic transport behaviour	2	4	2	4
23		Shift to zero emission transport	3	4	3	4
24		Choice of fuel cells or batteries	2	1	1	4
25	XII.b	Domestic freight	2	4	3	4
26	XII.c	International aviation	2	4	2	4
27	XII.e	International shipping	2	4	2	4
	IX.a	**Domestic space heating and hot water**	0	0	0	
28		Average temperature of homes	2	3	2	4
29		Home insulation	3	4	3	4
30		Home heating electrification	3	2	3	D
31		Home heating that isn't electric	3	3	3	D
	X.a	**Domestic lighting, appliances, cooking**	0	0	0	
32		Home lighting & appliances	2	4	2	4
33		Electrification of home cooking	2	1	2	B
	XI.a	**Industrial processes**	0	0	0	
34		Growth in industry	2	2	2	C
35		Energy intensity of industry	3	3	3	3
	IX.c	**Commercial heating and cooling**	0	0	0	
36		Commercial demand for heat & cooling	2	4	2	4
37		Commercial heating electrification	3	2	4	D
38		Commercial heating that isn't electric	3	3	3	D
	X.b	**Commercial lighting, appliances, catering**	0	0	0	
39		Commercial lighting & appliances	2	4	2	4
40		Electrification of commercial cooking	2	1	2	B
		Electricity balancing etc	0	0	0	
41	XIV.a	Geosequestration	1	1	1	4
42	VII.c	Storage, demand shifting & interconnection	2	3	3	4
43	XV.b	Indigenous fossil-fuel production	3	3	3	3

The 'Max' column indicates the maximum value which can be selected for that heading. Lines shown in bold print are not headings but merely introduce a group of headings with a single theme

4 Presentation by the champion of the 'High Nuclear Pathway'

Drafted by Christine Brown

4.1 Introduction to the High Nuclear Pathway

The world is having to face up to the crisis of climate change caused by a build-up of greenhouse gases. Few people remain unconvinced. The UK is committed to reducing its GHG emissions by at least 80% by 2050 relative to 1990 levels, but at the same time needs to secure energy supplies if the economy is to be transformed. To do both, the country needs to switch to lower-carbon and more efficient technologies for power, heat and transport.

Nuclear power has been generating electricity in the UK for over half a century, and it currently provides the vast majority of our low-carbon energy. The Nuclear Industry Association recently put that figure at 70% and noted that this avoids the emission of 40 million tonnes of carbon dioxide per year[83]. The aim of this chapter is to develop a UK energy pathway that focuses on this tried and tested low-carbon energy source. By increasing the UK's nuclear generation, we can reduce the country's dependence on fossil fuels and provide clean energy, enabling CO_2 targets to be met within the timescale set (i.e. up to 2050).

The proposed plan does not rely on the completion of any technological development for a new generation of reactors prior to 2050. The initial tranche of reactors can be based on internationally tried and tested LWR designs, thereby avoiding 'first of a kind' risks, and helping to speed up the construction of multiple units. Any future changes in design will evolve from operating experience and performance.

While the plan relies heavily on nuclear capacity, considerable emphasis is also placed on reducing energy demand from both industry and domestic users. A high-nuclear approach does not imply a society which is 'profligate' in its energy use, and there is much to be gained by having national policies on energy saving and material recycling. Renewables do also play their part in our Pathway, but given their limited achievements to date, it is hard to envisage how they can provide a very large fraction of the country's energy needs during the next few decades, even with the most stringent of morally- or politically-driven energy saving campaigns.

Nuclear power generation has a relatively long history, and while there have been ups and downs – including some very large downs – it currently provides 13.5% of the world's electricity as base-load power. In response to the major incidents that have occurred, there has been a major overhaul of operational and safety standards across the world, with organisations such as the Institute of Nuclear Power Operations (INPO), the World Association of Nuclear Operators (WANO), and the International Atomic Energy Agency (IAEA) working closely together with national regulators.

With such a background, the High Nuclear Pathway can start immediately.

4.1.1 Pathway targets

The High Nuclear Pathway to 2050 proposed here addresses a number of overall objectives:

- achieving an 80% reduction in GHG emissions by 2050, to which the UK has an international commitment (see Section 1.2)

[83] http://www.niauk.org/facts-and-figures

- providing enough energy from low-carbon sources to meet foreseen demand, and thus provide security of supply – the use of nuclear can quickly reduce the country's dependence on fossil fuels and foreign imports, and allow local growth of renewables where appropriate
- limiting standby capacity to 10 GW (i.e. ~10% of total electrical supply)
- limiting reliance on CCS to reduce GHG emissions (i.e. controlling the risk associated with this developing technology)
- taking a realistic but challenging approach to reducing energy demand both in the home and in the workplace
- concentrating effort on a proven technology and, in the process, rebuilding skills in a UK industry that is in danger of losing its credibility internationally.

The chosen Pathway needs to be 'credible' throughout the timescale 2012-2050, and the technology used has to be safe and reliable. It has to be economically viable, as well as publicly and politically acceptable. The nuclear component has to be compatible with the UK's nuclear non-proliferation commitments, and should not damage UK's international relations (trade and security).

4.2 Considerations leading to the specification of the proposed Pathway

The first stage in the exercise is to make a realistic assessment of how the demand for energy (overall and electrical) will change in the UK over the years to 2050. To do this we need to consider technological developments and their impact on energy use in the home and at work, and take into account the policies that might be pursued by governments during that time period – for example, whether there will be a politically-led campaign to move commercial transport from roads to rail, and whether the move to electric cars will be given government encouragement.

The second stage is to form a judgement on what the supply mix should be, in order to meet the assessed demand over the same period, while at the same time meeting the targets set by government – particularly those referring to GHG emissions.

Assessments of this kind are inevitably subject to personal opinion, which is all too often based on limited knowledge and experience, and sometimes based on no more than a fleeting glance at the 'bigger picture'. The 43 decision headings of the DECC Pathways software are useful in helping to focus thinking.

Accordingly, in the following two sections we discuss the series of choices that we have made in relation to the 43 decision Headings. In general, it will be seen that we have avoided what DECC describes as Level 4 choices (i.e. changes that "could be achieved at the extreme upper end of what is thought to be physically plausible by the most optimistic observer"), judging that such choices would undermine the credibility of our plan. We have, however, made a number of Level 3 choices – i.e. measures that "could be achieved by applying a very ambitious level of effort that is unlikely to happen without significant change from the current system" – and these choices are explained below. The majority of our choices are at Level 1 or 2.

4.2.1 Overall energy demand forecasts

The selections that we have made relating to energy demand are shown in Table 3.2 above, and can be input into the DECC Calculator by following the url link given in[84]. The implications of these choices for overall end-use energy demand are shown in Table 4.1.

[84] http://2050-calculator-tool.decc.gov.uk/pathways/s1f3cc1111121f1102231230023222202333022023023330220123

Table 4.1 Total Energy Demand in 2010, 2030 and 2050

Energy demand from	2010		2030		2050		% change from 2010 to:	
	TWh/y	GWav	TWh/y	GWav	TWh/y	GWav	2030	2050
Lighting & Appliances	171	19.5	171	19.5	185	21.1	0%	8%
Heating & Cooling	506	57.8	464	53.0	479	54.7	-8%	-5%
Transport	702	80.1	539	61.5	527	60.2	-23%	-25%
Industry	516	58.9	398	45.4	347	39.6	-23%	-33%
Agriculture	11	1.3	11	1.3	11	1.3	0	0
Total	**1906**	**217.6**	**1583**	**180.7**	**1549**	**176.8**	**-17%**	**-19%**

All figures from Flows Tab (these figures do not agree exactly with the Intermediate output tab lines 7-18)

It will be seen that the overall decrease in energy demand resulting from our choices is 19% between 2010 and 2050. The most beneficial measures are improvements in energy efficiency in industry and in both personal and commercial transport arrangements. We have recognised that some of our choices will require a commitment on the part of government, industry and society as a whole to recognise that energy should not be wasted and that overall demand should decrease.

Within the list of demand-related choices in the list given in Table 3.2, the potentially controversial Level 3 choices are:

Shift to zero emission transport
To achieve a 25% demand reduction in this sector, personal transport (cars and vans) is expected to move away from conventional combustion engine vehicles to greener alternatives, and it assumed that while air passenger numbers will continue to increase, technical improvements will result in significant reductions in fuel use. Commercial transport will move slightly from road to rail or water, and more efficient engines will be used.

Home Insulation
We estimate that some 20 million homes would benefit from better insulation, leading to a 40% reduction in domestic heating.

Home Heating
We judge that about half of new home installations should be electric, and that non-electric home heating installations should predominantly use waste heat from power stations.

Energy Intensity of Industry
We assume that the growth rate of recent years will continue, leading to industrial output increasing by 30% in the years to 2050. At the same time, however, it is assumed that there is a 40% improvement in energy efficiency and at least a 25% average reduction in process emission intensity. Of the energy demanded, 66% is for electricity. CCS is rolled out quickly after 2025 and by 2050 about half of industrial emissions are captured.

Commercial Heating
We assume that about half of non-domestic heat will be electrified, and that the dominant non-electric heat source will be waste heat from power stations.

4.2.2 Primary energy supply

This report recognises that the forecast energy demand outlined above can be met in a variety of ways. However, for the reasons given in Section 4.1, the Pathway proposed in this chapter includes the largest defensible nuclear contribution, though we do not envisage the abandonment of the steps that have already been taken (or are currently under development) to exploit the UK's renewable resources, and we do not exclude that the steps that are currently being taken to establish the viability of CCS will succeed, though we regard this as a comparatively risky option.

Having a mix of energy supplies is a prudent way forward for any UK energy pathway, and although on the dominant component is nuclear generation, the pathway choices made here seek to ensure that the remaining energy supply is provided in a balanced way between fossil fuels (which are used in combination with CCS when generating electricity) and renewables. In terms of these three main categories (nuclear, CCS and renewables), the overall contributions of each in 2050 (from Table 4.2) are 58%, 21% and 21% respectively. With these considerations in mind, we have made the choices shown in Table 3.2.

The Level 3 choices that we have made (or considered) are:

<u>Nuclear power stations</u>

This assumes an eight-fold increase in capacity over the 2010 levels by 2050. The installed capacity would reach approximately 80 GWe, with an assumed load factor of 80%. This would deliver an electrical output of 561 TWh/y, equivalent to 64 GWav. The DECC Calculator makes no assumptions about the type of nuclear power stations that will be built, but it assumes that each station will deliver 3 GWe. This means around 27 power stations would be required by 2050 to match the requirements of this High Nuclear Pathway. This would be equivalent to the build rate in France in the 1980s.

<u>CCS power station fuel mix</u>

The CCS power stations can be fuelled by solid fuel (coal or biomass as available) or gaseous fuel (natural gas or biogas as available) – the Pathway will use biofuel in preference to the equivalent fossil fuel. The choices made carry the implication that two-thirds of CCS power stations will use gas, and the rest will use solid fuel.

The assumptions made regarding actual CCS power station use are intermediate between Levels 1 and 2 – i.e. we assume that apart from the coal and gas demonstration projects currently planned, there will be rather limited further construction of new CCS plants or retrofitting of CCS technology.

<u>Land dedicated to bioenergy</u>

We gave serious consideration to giving 'Land dedicated to bio-energy' a Level 3 assessment. However this would imply that 10% of UK land would be used for growing energy crops by 2050, and that this would be achieved by taking advantage of considerable improvements in soil and crop management technologies. On balance, we decided that this was too large a change in agricultural practice to be credible, so we have retained the Level 2 setting. This assumes that current trends and drivers in land management continue from now to 2050, with an increasing take-up of land by housing. At the same time, the area planted with bio-energy crops also increases so that 13 times more energy crops are produced in 2050 than today, and the total UK bio-energy (including wastes) comes to 170 TWh/y (i.e. 19 GWav).

Bio-Energy Imports

The UK currently imports about 14 TWh/y of liquid and solid biofuels from overseas producers. The International Energy Agency (IEA) has made estimates based on land available globally and the potential energy supply that could be exported to the UK on a 'fair market share' basis. The 2050 Calculator assumes that such global supplies are only imported if there is a demand for it and after all domestic bio-energy supplies have been used up. The Level 3 chosen for the current Pathway implies that the UK will import its fair market share, which means an eightfold increase in imports, providing some 108 TWh/y of bio-energy.

Volumes of waste and recycling

The UK faces a need to manage its steadily rising production of waste, which we assume will be offset by increases in recycling rates and energy generated from the waste.

With these choices, the primary energy supply is divided between 12 categories, as shown below in Table 4.2.

Table 4.2 Breakdown of Primary Energy Supply in 2010 and 2050

Primary Energy	**2010**			**2050**		
	TWh/y	**GWav**	**%**	**TWh/y**	**GWav**	**%**
Natural gas	955	109.0	38	143	16.3	5
Oil	853	97.4	34	483.5	55.2	16
Coal	455	51.9	18	1.9	0.2	0
Wind	15	1.7	1	57.9	6.6	2
Nuclear	161	18.4	6	1714.2	195.7	58
Bioenergy	60	6.8	2	278.0	31.7	9
Solar	1	0.1	0	19.3	2.2	1
Environmental heat	0	0.0	0	247.7	28.3	8
Hydro	5	0.6	1	6.2	0.7	0
Wave	0	0	0	0	0	0
Geothermal	0	0	0	0	0	0
TOTAL	**2505**	**286**	**100.0**	**2951.7**	**337**	**100.0**

Source: figures taken from Flow tab lines 6-35

4.2.3 Electricity Demand and Supply

Within the overall demand and primary energy supply choices described above, the specific figures for electricity demand and supply resulting from these choices are discussed below. The split in demand is as shown in Table 4.3.

Electricity supply, however, will have to exceed this demand level in order to make up for usage at the site of production and for transmission losses. The choices made on energy supply in this High Nuclear Pathway have ensured that the electricity generated in 2050 will be greater than the increased demand by approximately 25%.

Table 4.4 shows how this supply is generated and indicates that nuclear will provide 74.5%, and CCS approximately 17%. The remaining 8.5% will be sourced from renewables – a mixture of wind and hydro. Note that in this table, unlike Table 4.2, all the figures represent electrical energy supplied to the grid (i.e. they exclude energy losses in the process of generation).

Table 4.3 Breakdown of Electricity Demand in 2010 and 2050

Electricity Demand	**2010**		**2050**		**% Change**
	TWh/y	GWav	TWh/y	GWav	%
Lighting & Appliances	155	17.7	185	21.1	+19
Heating & Cooling	56	6.5	146	16.7	+156
Transport (incl H_2)	8	0.9	63	7.2	+687
Industry	128	15.1	202	23.1	+153
Agriculture	4	.5	5	.5	+7
TOTAL	**351**	**40.2**	**601**	**68.6**	**+71%**

Source: All figures taken from Flow tab lines 6-35

Table 4.4 Breakdown of Electricity Supply in 2010 and 2050

Electricity Supply	**2010**			**2050**		
	TWh/y	GWav	%	TWh/y	GWav	%
Unabated thermal	306	34.9	80.7	0	0.0	0
Nuclear power	53	6.1	14.0	561	64.0	74.5
CCS	0	0	0	128	14.6	17
Off Shore Wind	4	0.5	1.1	47	5.4	6.2
On Shore Wind	11	1.3	2.9	11	1.3	1.4
Hydro	5	0.6	1.3	6	0.7	0.8
Tidal and wave	0	0	0	0	0	0
Geothermal	0	0	0	0	0	0
Solar PV	0	0	0	0	0	0
TOTAL Supplied to Grid	**379**	**43.3**	**100.0%**	**753**	**86**	**100.0**

Source: Flow Tab for all figures except nuclear and CCS in 2050, which involve some use of Tab IIa lines 130-134)

Table 4.4 also shows that the electricity generated by CCS and renewables covers approximately half the increase in demand, while nuclear generation covers both the remainder and the deficit caused by the disappearance of unabated fossil-fuel generation.

The installed capacity in GWn is estimated as shown in Table 4.5.

Table 4.5 Breakdown of Installed Capacity in GWn

Installed Capacity	2010	2020	2030	2040	2050
Oil/Bio Fuel	4.1 (6%)	0	0	0	0
Coal/Biomass	28.1 (37%)	17.1	1.8	0.6	0
Gas/Bio gas	26.7 (35%)	32.6	25.3	3.2	0
CCS	0	1.7	5.9	13.4	20.9 (18%)
Nuclear	10.0 (13%)	6.8	28.4	53.6	80.0 (67%)
Onshore Wind	4.0 (5%)	10.4	10.6	6.2	4.0 (3%)
Offshore Wind	1.3 (2%)	8.3	14.5	13.6	12.0 (10%)
Hydroelectric	1.6 (2%)	1.7	1.8	1.8	1.9 (2%)
Wave	0	0.1	0.2	0	0
Tidal Stream	0	0	0	0	0
Tidal Range	0	0	0	0	0
Geothermal	0	0	0	0	0
Solar PV	0	0	0	0	0
Standby /Peaking Gas	0	0	4.3	10.3	0
TOTAL GENERATION	**75.8**	**78.4**	**92.8**	**102.7**	**118.8 (100%)**

Source: Figures taken from Intermediate Output tab lines 117-132

4.2.4 Greenhouse gas emissions

With these choices the DECC Calculator indicates GHG emissions fall by 80% of 1990 levels to 149 Mt per year (see Table 4.6). International aviation and shipping emissions are not included in the UK's 2050 target but are included in these calculations to enable emissions from all sectors to be considered. Interested readers can check this result using the Excel version of the DECC Calculator, entering the High Nuclear selections given in Table 3.1 and consulting the detailed GHG calculations given in the tabs labeled 2007-2050.

Table 4.6 High Nuclear greenhouse gas emissions using IPCC sectors

IPCC Sector Mt CO_2e	2007	2010	2030	2050
Fuel Combustion	527.5	513	263.1	149
Industrial Processes	27.9	26.3	18.9	14
Agriculture	43.3	42.3	38.5	38
Land Use, Land-Use Change and Forestry	-1.8	2.6	12.1	7
Waste	22.9	15.2	7.5	4
International Aviation and Shipping	52.7	46.5	61.9	70
Bioenergy Credit	(10.2)	(12.3)	(46.4)	(68)
Carbon Capture	0	0	(19.2)	(65)
TOTAL	**662.3**	**633.8**	**336.4**	**149**
% of baseline figure (783.1 Mt CO_2e in 1990)	**84.5%**	**80.9%**	**43%**	**19%**

It will be seen that Fuel Combustion is the largest contributor to GHG emissions, but in 2050 this is mostly offset by Carbon Capture and Bioenergy Credit. Of the remaining contributors, International Aviation and Shipping followed by Agriculture are the most significant emitters.

4.3 Credibility of chosen nuclear technologies and timescales

As we have seen in Section 3.2, the history of civil nuclear power in the UK is a story with a number of very real successes, interspersed with a number of seriously bad decisions which have marred an otherwise creditable record. The good news is that the Magnox and AGR fleets between them built up to a peak generating capacity of 12.9 GWn in 1996, which at that time represented 17.5% of UK generating capacity, and produced 25% of its electrical consumption. The less good news is that since then, apart from the construction of one PWR at Sizewell, the UK nuclear industry has been in a state of decline, with most of its activities related to the decommissioning of redundant nuclear facilities in the UK, and providing nuclear services for overseas customers.

The UK's existing fleet of reactors is coming to the end of its useful life, and reactors at 14 sites have already been shut down, and are at various stages of decommissioning, with all the remainder scheduled for closure by 2023. The exception is Sizewell B, which is scheduled to close in 2035, but with a life extension it could continue until 2055 or beyond. Fortunately, the worldwide nuclear industry has continued to develop, though with a number of setbacks, particularly following the major incidents at Chernobyl and Fukushima. A number of countries still have flourishing nuclear industries – notably the US, France, Russia and (until very recently) Japan, and others are well on the way to establishing their own, such as India, China, and Korea.

4.3.1 Current planning for a 'new build' to replace existing UK reactors

Against this background, in the last few years the British government has taken a decision of principle that a new build programme should be undertaken by the private sector to replace the entire fleet of Magnox and AGR reactors, using 'third-generation' LWR technology. It has argued that this approach will ensure that the UK benefits from the extensive worldwide experience of LWR technology, and will be based on 'tried and tested' reactor designs, preferably of a single type. There are several possible choices of third-generation LWR thermal reactors, but so far only two designs have received preliminary approval from the UK regulator – EPR and AP1000. As noted in Section 3.2, both of these designs are being constructed in a number of countries, with EPRs in Finland, France and China and AP1000s in China and the US. The choice between these two designs (or indeed some other candidates such as the Hitachi-GE ABWR which have not yet received UK regulatory approval) remains open.

The current status of the main candidate designs is described in Section 3.2.2. It is sufficient to say that whichever system were chosen for deployment in the UK, it would not be a 'first of a kind' construction: we would be choosing an internationally tried and tested third-generation LWR design to meet the UK's nuclear power requirements up to 2050. The proposed High Nuclear Pathway can start right away, and does not require the completion of technological development of a new generation of reactor. Any future changes in design will evolve from operating experience and performance.

Looking beyond 2050, the way forward comes less clear. However a modern LWR has an expected operational life of 60 years, perhaps more, so if the first of the UK's replacement fleet starts operating in 2022, it will only be nearing retirement around 2080. So we have plenty of time in which to consider how to proceed after 2050. By then, the key issues may be the sustainability of our fuel supply (do we have enough resources to proceed without making full use of the unused energy trapped in 'spent' nuclear fuel?) and the safe and efficient management of our spent fuel. A responsible nuclear industry has to engage in forward planning on these matters.

4.3.2 Longer-term planning for fourth-generation reactors

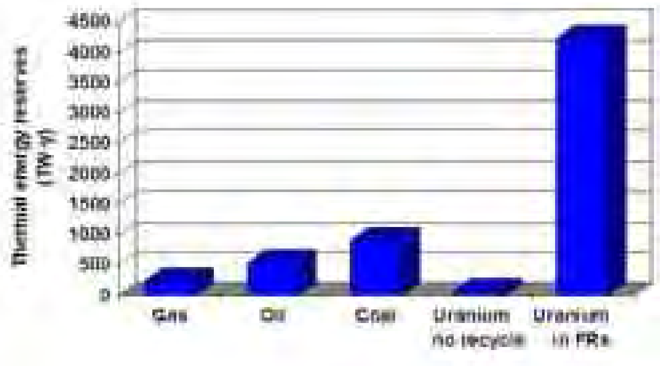
Although we have ruled out the seductive strategy of leap-frogging straight to a fourth-generation design (see Section 3.2.4 above), this author is convinced that the UK should become involved in international efforts that are already under way to develop a fourth-generation reactor. This international activity is being coordinated by the Generation IV International Forum (GIF), which was launched in 2001, and is currently looking into six possible reactor concepts, mostly fast reactors. By 2050 there is a very real possibility that one or more Generation IV reactors will be mature enough for consideration (and may perhaps have already been fully commercialised).

4.3.3 The choice of fuel cycle materials and technology

As discussed in Section 3.2.3 above, reliance on light water reactors as the principal power source in the High Nuclear Pathway raises a question about the long-term availability of uranium, and hence the sustainability of this energy source. Fortunately, as argued there, on any plausible rate of increase in nuclear power worldwide, known proven reserves of uranium will be sufficient at least until 2050. However that should not be regarded as a 'cliff edge', since (as we have seen in Section 3.2.4) the introduction of fourth-generation reactors around then would guarantee sustainability and security of supply for many decades, while at the same time reducing both the volume and the radiotoxicity of the arising radioactive waste. By recycling the unused fuel trapped in the spent fuel discharged from the first, second and third-generation LWRs in future fourth-generation reactors designed specifically to do this, we can increase significantly the efficiency of nuclear power (i.e. produce much more energy for each kg of uranium mined) and provide the industry with a clear long-term insurance against resource shortages, unlike coal, oil and gas. By developing a specific type of reactor, the Fast Breeder Reactor (FBR), we can multiply the uranium resources by a factor of at least 50.

The significance of this for our security of energy supply can be seen in Figure 4.3, which shows the available energy resources of the UK, and indicates what a large resource remains to be tapped if we burn the uranium already mined in Fast Reactors.

Figure 4.3 Sustainable Use of Resources[85]



We would urge that the UK government should consider not only the advantages of nuclear power in the near term, but also what it can offer beyond 2050, in terms of sustainability and security of supply, for a nation which (by then) will have few, if any, remaining indigenous oil and gas resources.

[85] Source: US DOE Energy Information Administration *International Energy Outlook 2004*, DOE/EIA-0484(2004). Note: Gas and Oil include speculative reserves; Coal and Uranium do not.

The UK could in principle re-establish itself as one of the leading centres for R&D in this area, if the necessary support became available once more. Historically, the UK fast breeder programme began in 1954, when the UK set up the Atomic Energy Authority, and decided that it should build a breeder reactor at Dounreay in the north of Scotland to ensure energy security in years to come. The Dounreay Fast Breeder Reactor (DFR) started up in 1959, and seven years later the government announced its decision to build a prototype FBR (PFR) alongside it, with a design output of 600 MWth (250 MWe).

At that stage, DFR was the most powerful fast reactor in the world. Its principal role during a life of over 17 years was as an experimental irradiation facility, primarily as a test bed for plutonium-based fuels and core materials for the prototype and commercial fast reactors that were planned to follow DFR. The purpose of its successor, PFR, was to provide, and give confidence in, the information necessary for the installation and operation of commercial fast reactors (CFR) in the United Kingdom in the late 1970s or early 1980s. PFR reached full thermal power in 1977, and the reactor continued operation until shutdown in 1994, successfully combining the potentially conflicting roles of being both a prototype power plant, supplying electricity to the national grid, and a versatile irradiation facility. The reactor itself proved flexible and stable in operation over the whole power range, and was capable of sustained power generation at its designed output for long periods without detriment to the aims of its experimental fuels and materials programmes. In so doing, it identified the strengths and (in a few cases) weaknesses of its many major innovations in component design and operating parameters. It also demonstrated the validity of the original concept of the FBR – the ability to breed Pu, separate it out by reprocessing, use it to manufacture fresh fuel and thereby to close the cycle, all in the same reactor. This was first achieved in June 1982, and the fuel efficiency was found to be far greater than first anticipated.

4.3.4 Spent Fuel Management

As we saw in Section 3.2.5, any pathway that includes nuclear power in its mix requires not only a plan for the licensing, construction and operation of the reactors, but also for the management of the spent fuel. If the UK is to pursue the High Nuclear Pathway, it is essential that the government should consider the options available. Together with industry, regulators and R&D organisations, it should set out a strategy for the short- and long-term management of the spent fuel produced by the third-generation LWRs which we are proposing within the preferred High Nuclear Pathway up to 2050.

Because there is no current intention to recycle any of the unburnt fissile or fertile material in the spent fuel prior to 2050, there is no compelling reason to reprocess it until a decision has been taken on the strategy after 2050, including the choice of a next-generation reactor system. It could, however, be argued that since the UK already has a stockpile of separated Pu and an operating reprocessing plant, adopting an interim strategy of burning the Pu as MOX fuel in the third-generation LWRs might be the most sensible way forward. Such a strategy would both reduce the stockpile and avoid large accumulations of spent fuel assemblies requiring interim storage (see Section 3.2.5).

Under the current government strategy (i.e. no immediate recycle), the spent fuel management options, after the normal initial period of cooling off in a storage pond, would be either to continue to store it in such a way that the ability to recycle it in due course is retained, or to dispose of it permanently in a geological disposal facility. Currently there is no operating civil geological disposal facility anywhere in the world, but plans are well advanced in a number of countries (though not so far in the UK).

The recycle option, on the other hand, has been demonstrated successfully in the UK and internationally. Reprocessing the spent fuel separates it into two components — uranium and plutonium, which can be re-used as reactor fuel – and waste fission products. This process leaves approximately 3 per cent of the fuel as high-level waste, which is then permanently immobilised in a stable matrix (for example, borosilicate glass) making it safer for long-term storage or disposal. Reprocessing spent fuel significantly reduces the volume of waste (compared to treating all used fuel as waste). The recovered uranium and plutonium can be used in the manufacture of fresh fuel (MOX) for either thermal reactors or fast reactors.

When used to fuel existing thermal reactors, however, MOX fuel is limited in the number of recycles it can efficiently undergo, so that the improvement in utilisation is modest (usually estimated at less than 20%). Furthermore, the additional costs that arise in the fabrication and reprocessing of MOX fuel, and the difficulties in storage and disposal caused by the higher heat output of spent MOX fuel, are significant, and may outweigh any savings that accrue from the avoided costs of uranium purchase and enrichment.

In the case of the UK, a plutonium stockpile already exists (and has hitherto been allocated zero value), and there is an argument that the UK should use the plutonium that it has. The UK no longer has its own MOX fuel fabrication facility, but the UK government is currently 'minded' to construct a new one, although that will depend on the availability of funding. Given that uranium fuel is plentiful, and MOX used in thermal reactors does not greatly improve uranium utilisation, it can be argued that it would be better to designate the stockpiled plutonium as a national energy resource, for use in future fast reactors or, failing that, as waste for disposal. In the meantime, we propose that the new LWR fleet should run on a once-through uranium fuel cycle, with interim storage of spent fuel in suitable casks.

4.3.5 The need for further R&D, and for prototype testing

As indicated above, in the proposed Pathway the nuclear reactor will be of an internationally proven design, for which the UK regulator either has or will rapidly give approval. Any UK modifications of that design will be minimal and will not require validation by the construction of a new build prototype. There will, however, be a need for R&D to finalise the strategy for the management of the arising spent fuel. If, as is proposed here, the spent fuel is to be held in interim storage, decisions will need to be taken on the location of these stores (whether at each reactor site or at one or more centralised location), and on the arrangements to ensure its physical protection and security. Plans will also need to be made for the continued safe and secure interim storage of the existing stockpile of separated plutonium.

Such interim storage could be sustained for a period of 50 years or longer, but eventually the decision will have to be taken on whether to dispose of the spent fuel permanently, presumably in a deep geological repository, or whether to reprocess it, and use its contained uranium and plutonium for further energy production. If the UK is to be in a position to take an informed decision on this, it needs to get involved in the international programme to develop a fourth-generation reactor and a new generation of reprocessing and waste management technology. There is therefore a strong case for re-establishing a UK R&D capability in this area, so that it can take an informed view on the technical and economic issues involved. Although this is a long-term objective, the lead times for reactor development are such that practical work should begin within the next decade.

4.3.6 The infrastructure, human resources and timescale required for rollout

In this section we consider the credibility of the scale and timescale that we are proposing for the High Nuclear Pathway. We are proposing that by 2050 there will be an eight-fold increase in the UK's nuclear capacity over the 2010 level, reaching a nameplate capacity of around 80 GWn. If we accept the DECC

Calculator's assumption that each new reactor will have a nameplate capacity of 3GWe, then we are envisaging building 27 new reactors in 38 years. As we have seen in Section 3.2.6, the construction programmes undertaken in the past in the US, France and Japan, provide plenty of evidence that if there is a will and determination to implement such a programme, then it is feasible. In those cases, each country selected no more than two reactor designs for construction, so the construction programmes benefitted from standardisation, although variations in detailed design evolved as operating experience grew. If the UK can take a decision on its preferred design quickly, it seems feasible to expect that a first 'new build' LWR could become operational by about 2021, and the design could then be rolled out at a rate of about one reactor per year, permitting the proposed capacity to be achieved by 2050.

However, as was noted in Section 3.2.6, to achieve this rate of rollout, the UK nuclear industry will have to rebuild the skilled nuclear workforce and industrial infrastructure which it possessed in the 1970s but has partially lost in recent years. So there is an urgent need for collaborative action between the government and the private sector to achieve this. The recommendations of the House of Lords inquiry on nuclear R&D capabilities are very relevant here[86].

As explained in the preceding section, if the UK wishes to remain a leading member of the international nuclear industry, it would be well-advised to become involved in the development of the fourth-generation design in good time. Participation in this R&D programme will enable the UK to remain in a leading position in the supply of nuclear technology worldwide.

4.4 Credibility of Carbon Capture and Storage (CCS) technology

As noted in Section 3.4, the technology of CCS is still at a rather early stage of development, and we have argued in Section 4.2.2 that the High Nuclear Pathway should not place heavy reliance on it achieving maturity before 2050. However some variants of this technology (for example, when used in conjunction with biomass production) have the advantage over both nuclear and other renewable energy of offering negative carbon emissions. Without such savings, it would be difficult for our Pathway to meet the GHG emissions target of 80% reduction by 2050, because there are some energy uses to which nuclear-generated electricity is not well adapted, but which currently have high emissions. Accordingly we have set the CCS power stations heading at level 1.5, which implies CCS capacity of 20.9 GWn, sending 14.6 GWav of electricity to the grid by 2050 – i.e. about 17% of total electricity generation. This gives an emissions saving of 65 $MtCO_2e$/y (Table 4.6).

As noted in Section 3.4, the CCS figures which we are proposing here represent a very significant increase on anything achieved with CCS to date, and they can only be achieved by 2050 if the current programme of prototype demonstrations is successful. This is discussed in more detail in Section 6.3.2, where it is noted that the UK does not at present have any full-scale power generators with CCS. However there is some confidence that the commercialisation will succeed, since industrial technologies exist for carbon capture, and the oil industry has been transporting CO_2 into deep reservoirs for many years.

4.5 Credibility of proposed Renewables technology

Within our High Nuclear Pathway we only require a two-fold increase in renewable energy capacity over the forty years to 2050. Wind and hydro were selected, on the basis of experience to date, as the most likely to

[86] http://www.publications.parliament.uk/pa/ld201012/ldselect/ldsctech/221/221.pdf

make reliable contributions to energy supply with low emissions and at reasonable cost. Because of the intermittency of Solar energy, we have confined it to water heating systems, and not proposed any significant Solar PV capacity.

Biomass power stations require CCS if they are to avoid excess emissions, and this need for supplementary energy-consuming plant reduces their overall efficiency. They would also need significant areas of agricultural land to be dedicated to growing energy crops if they are to make a significant contribution to the country's energy requirement. For these reasons, the biomass option has been set at Level 2. Wave, tidal, marine algae, geothermal and small-scale wind plant were all rejected on the grounds that, based on current information and experience, their actual contribution was unlikely to justify the investment, both financial and environmental.

These considerations give rise to a mix of renewable energy supplies in 2050 dominated by UK-derived bio-energy of 170 TWh/y (19.4 GWav) and bio-energy imports of 108 TWh/yr (12 GWav), both being used in conjunction with CCS.

4.5.1 Balancing Supply and Demand (load variations and supply intermittency)

The renewables component of the overall electrical supply in this High Nuclear Pathway does not exceed the 20% level, at which the UK grid can be balanced without the need to introduce additional mechanisms such as energy storage (see Section 2.4).

Our main concern in determining the balancing requirements has been to limit to less than 10 GW the amount of CCGT plant that would be needed as back-up for non-availability of renewable sources. The Level 2 option taken for the 'balancing' heading (no 42) implies 4 GW of storage with a capacity of 30 GWh, together with 10 GW of interconnectors (to which 2 GW are added by the Calculator to cover planned exports). Around 25% of all electric vehicles and plug-in hybrid electric vehicles are assumed to allow flexible sharing, enabling co-ordinated electricity demand shifting. With these choices, the stress test applied by the Calculator (see Section 3.6.2) indicates that no back-up generation capacity is required.

4.6 Comparison with DECC High Nuclear Pathway

DECC have included on its Calculator website a number of 'example' pathways, including one entitled 'High Nuclear – Less Energy Efficiency'. The key difference between the DECC version and the version proposed here is in energy demand. We have set industry a major challenge to improve its energy efficiency and reduce its process emission intensity. Without this reduction in industrial demand and emissions, the DECC example pathway has been forced to place much greater emphasis on bioenergy (UK and imported) and marine algae to keep emissions on target.

The High Nuclear Pathway described in this report is based on the premise that only by a combination of energy efficiency, a realistic rate of introduction of CCS technology and a robust plan for nuclear build can we meet the energy requirements of the UK and meet GHG emission targets. This author would argue that Renewables cannot meet the energy capacity requirements of a nation with such an energy-intense industrial base. They certainly have their place, but supplying large industrial areas with dense populations on a continuous basis is not one of them.

4.7 Conclusion/Summary

The High Nuclear Pathway presented in this section aims to deliver energy security with the required 80% reductions in GHG emissions by 2050. We believe that while it may well be technically possible sometime in the future to achieve this without nuclear power, the clock is ticking fast and the UK needs to act now, using available resources with tried and tested technology.

Nuclear power has the potential to ensure energy security for many years well beyond 2050 but this requires decisions now if we are to benefit in the future. Investment in nuclear power requires long-term vision and a strong feeling of responsibility for future generations. The energy trapped within the spent fuel from thermal nuclear power stations can be made available in the future if it is properly managed, and advances in technology are pointed in the right direction. The management of the spent fuel from any nuclear programme requires as much planning as the construction and operation of the power plants themselves.

The choices made in this High Nuclear Pathway would result in a rise from 6% to 58% in the nuclear contribution to the UK's total energy supply over the 40 years 2010 to 2050, and from 14% to 74% in the electricity supply. This would be achieved with the construction of around 27 3 GWe reactors over this period. The feasibility of such a programme being completed within the 40-year timescale is supported by history – in the USA, over a hundred reactors were built within a 25-year period, while in France and Japan similar plans saw over fifty reactors built and in operation within 25 to 35 years. The technology exists and is well tried and tested. The technical know-how that it will inevitably create can be used to provide energy security with low-carbon emissions well beyond 2050.

5 Presentation by the champions of the 'High Renewables Pathway'

Drafted by David Elliott and David Finney

5.1 Introduction to the High Renewables Pathway

There is general agreement that the potential renewables resource is very large, and that the technologies for exploiting it are developing rapidly (see Section 3.3). The UK has been relatively slow in developing its large renewable source, but is now beginning to make progress. The official UK figures for renewables capacity and supply in 2010 are shown in Table 5.1[87].

Table 5.1 Installed Capacity and power generated from renewables in 2010

	GWn	TWh/y	GWav	Load factor
Onshore wind	4.04	7.1	0.81	0.20
Offshore wind (incl Beatrice platform)	1.34	3.0	0.35	0.26
Shoreline wave/tidal	0.003		0.00	
Solar photovoltaics	0.08	0.03	0.00	0.05
Hydro (excl pumped storage stations)	1.65	3.6	0.41	0.54
Biomass (incl waste combustion)	2.10	11.9	1.36	0.65
Total	**9.20**	**25.7**	**2.94**	**0.32**

In this table, the 'nameplate' figures GWn indicate the maximum feasible output at full power. The power actually delivered (on average over the whole year), is given in the column labelled GWav, and the ratio of these two is shown in the column labelled 'load factor'. It will be seen that the total renewable power actually delivered to the grid in 2010 amounted to 2.94 GWav, as compared with the total UK electrical generation in that year of 43.1 GWav (i.e. about 7%). However the renewables figure is rising: DECC reports[88] that in 2011, renewable electricity contributed 9.4% of the UK's grid mix – up from 6.8% in 2010.

The UK is now moving forward rapidly in the installation of renewables capacity. It is now the world leader in offshore wind capacity (having overtaken Denmark in 2008). It has a further capacity of 2.4 GWn under construction, and planning consent has either been granted or is under consideration for an additional 12.9 GWn. In all, around 18 GWn could be in place by 2020. UK onshore capacity is also growing, but more slowly, with a target set of around 15 GWn by 2020[89]. The world leader for onshore wind is China, with 62 GWn, followed by the US with 40 GWn and Germany with 29 GWn[90]. All three are also developing offshore projects.

[87] DUKES (2011) p.214 (note that these figures differ from those given in Section 2.1.1 above for the reason given there)
[88] DECC DUKES (2012) Chapter 6, p.160
http://www.decc.gov.uk/assets/decc/11/stats/publications/dukes/5956-dukes-2012-chapter-6-renewable.pdf
[89] DECC (2009) National Renewable Energy Action Plan for the United Kingdom, produced under Article 4 of the Renewable Energy Directive 2009/28/EC
www.decc.gov.uk/assets/decc/what%20we%20do/uk%20energy%20supply/energy%20mix/renewable%20energy/ored/25-nat-ren-energy-action-plan.pdf
[90] Global Wind Energy Council (2012) *Global Wind Statistics 2011* Brussels http://gwec.net/wp-content/uploads/2012/06/GWEC_-_Global_Wind_Statistics_2011.pdf

The UK is also leading the world in wave and tidal power, with plans for around 1.6 GW to be installed by around 2020[91]. On the other hand, UK solar PV power, with 1 GWn installed by 2012, is lagging far behind other European countries, especially Germany, where over 25 GWn of solar PV capacity has been installed, and there are plans to expand this to 66 GWn by 2030[92]. By contrast, the UK solar PV industry suffered a setback in June 2011, when the feed-in tariffs which the Government was offering for electricity fed into the UK grid from private solar installations were significantly reduced. Further reductions in government support for PV took effect in April and August 2012, and quarterly reviews are foreseen thereafter[93]. These cutbacks, and similar cuts in Germany, Spain, France and Italy, in part reflect the fact that the production cost of PV systems has fallen, so less subsidy is required. The optimistic view is that PV will continue to expand, although perhaps less rapidly.

5.2 Studies on possible developments

A number of independent groups and industrial interests have been actively engaged in the development of radical ideas for the expansion of renewable energy in the UK, keen to respond quickly to climate change and oil depletion issues (see Section 3.3). For example, the 2008 'Oil Crunch' Report, from the Industry Task Force on Peak Oil and Energy Security (ITPOES)[94], developed a UK scenario in which renewables supplied around 50% of electricity, 27% of heat, 10% of transport fuel and overall, about 20% of primary energy by 2020. More radically, the Centre for Alternative Technology (CAT) has produced two studies developing ideas for a 'Zero Carbon Britain'[95, 96]. The more recent study (published in 2010) sets 2030 as its target date. A third iteration of the CAT Zero Carbon Britain scenario is due in 2013.

The ITPOES report makes rather traditional assumptions about the scope for demand reduction, and it assumes that heat and transport requirements will continue to be met by a substantial contribution from nuclear, gas and petroleum sources, whereas the CAT report proposes a much greater reduction in overall energy demand. This is envisaged as falling by 55%, principally through technical efficiency measures, modest behavioural and lifestyle changes, including dietary changes, and a much greater shift to renewable sources for heat and transport.

A rather different independent study has been undertaken by the energy consultancy Garrad Hassan (commissioned by the Worldwide Fund for Nature), which suggested that the UK could have up to 105 GW of renewables capacity in place by 2030, supplying 88% of UK electricity[97]. This study emphasised the importance of UK access to the worldwide energy market, and suggested that a 35 GW supergrid interconnection could create a substantial European market for the UK's excess power (generated at times of

[91] The Crown Estate (2011) 'Wave and Tidal Energy in the Pentland Firth and Orkney waters', op. cit. http://www.thecrownestate.co.uk/energy/wave-and-tidal/

[92] Fraunhofer Institute, Electricity production from solar and wind in Germany in 2012 http://www.ise.fraunhofer.de/en/downloads-englisch/pdf-files-englisch/news/electricity-production-from-solar-and-wind-in-germany-in-2012.pdf/view

[93] Feed-in-Tariff, DECC update May 2012 http://www.decc.gov.uk/en/content/cms/meeting_energy/Renewable_ener/feedin_tariff/feedin_tariff.aspx

[94] ITPOES (2008) 'Oil Crunch' Report, from the Industry Task Force on Peak Oil and Energy Security, whose members included Arup, FirstGroup, Foster and Partners, Scottish and Southern Energy, Solarcentury, Stagecoach Group, Virgin Group, Yahoo!. http://www.peakoiltaskforce.net

[95] Centre for Alternative Technology (2007) *Zero Carbon Britain: an alternative energy strategy* http://www.mng.org.uk/gh/scenarios/zerocarbonbritain.pdf

[96] Centre for Alternative Technology (2010) 'Zero Carbon Britain', Machynlleth, ZCB http://www.zerocarbonbritain.com/

[97] World Wide Fund for Nature, London (2011) 'Positive Energy: how renewable electricity can transform the UK by 2030' http://assets.wwf.org.uk/downloads/positive_energy_final_designed.pdf

high renewable production and low demand), which would make it economic to build much more renewable capacity in the UK.

In parallel with these independent studies, DECC has recently become actively engaged in long-term energy policy planning. It set out to formulate a meaningful energy strategy for the UK up to the year 2050, including approximate targets for its fossil fuel, nuclear and renewable components. In doing so, it has produced a series of reports and open access computer programmes aimed at exploring energy options up to 2050. These have been briefly summarised in Section 3.3, which identified two reports as particularly influential:

- '2050 Pathways Analysis'(July 2010)[98]

This report looked at each key energy technology and offered four different 'levels' of possible response, using the criteria described in Section 1.3. Their conclusion was that the potential contributions of the various technologies, based on the Level 2, 3 and 4 criteria, could be as shown in Table 5.2, in which the nameplate generation capacity (GWn) and annual energy output estimates (GWav and TWh/y) for each of the key renewable electricity options is shown.

Table 5.2: Technology potentials for electricity generation in DECC Pathways analysis

Level (by 2050)	2			3			4		
	GWn	GWav	TWh/y	GWn	GWav	TWh/y	GWn	GWav	TWh/y
On land wind	20	6.1	53	32	9.6	84	50	15.1	132
Offshore wind	60	21.0	184	100	35.0	307	140	49.1	430
Tidal Range	1.7	0.4	3.4	13	3.0	26	20	4.6	40
Wave/tidal stream	11.5	2.9	25	29	7.8	68	58	15.9	139
PV solar	70	6.8	60	95	9.1	80	165	16.0	140

Source: ref. 98 pp186-210

Using these assessments, DECC then constructed a set of six possible low-carbon 'Pathways', incorporating different proportions of the various technologies, and commented on their strengths and weaknesses.

- 'The Carbon Plan; Delivering our low-carbon future' (December 2011)[99]

This report gave a much more detailed sector-by-sector analysis of the scope and timescale for changes in the current pattern of energy use, and then gave an outline strategy for meeting our emission targets, decade by decade. It indicated that modelling studies had suggested that the UK might need 60–80 GW of new electricity capacity to be built by 2030 and 100-130 GW by 2050. It endorsed the Committee on Climate Change's 'Renewable Energy Review', which suggested that we could have over 55 GW of renewable electricity capacity by 2030, subject to resolution of current uncertainties such as cost reductions and barriers to deployment. Industry has expressed similar levels of ambition. Its overall conclusion was that it was "happy for the market to decide what combination of fossil fuels with CCS, nuclear and renewables is used to make up as much as possible of the 40-70 GW we think we may need by 2030".

[98] DECC (2010) Pathways Analysis: Consultation, Department of Energy and Climate Change, London http://www.decc.gov.uk/assets/decc/what%20we%20do/a%20low%20carbon%20uk/2050/216-2050-pathways-analysis-report.pdf

[99] DECC (2011) *The Carbon Plan: Delivering our low carbon future*, Department of Energy and Climate Change, London http://www.decc.gov.uk/assets/decc/11/tackling-climate-change/carbon-plan/3702-the-carbon-plan-delivering-our-low-carbon-future.pdf

See also http://www.theccc.org.uk/reports/renewable-energy-review

The conclusions and policies outlined in DECC's 2011 Carbon Plan are based on some assumptions and projections which have been challenged. Its forecasts of the demand for new construction have been challenged as unrealistic by Bailey and Blair[100], who argue that DECC has largely ignored the potential for energy savings (for example those identified by Olivier[101]). Its policy decision is to leave the choice and balance of technologies in the future up to the market, arguing that "the mix of low-carbon technologies that is built on the way to 2050 is for the market to decide: the technologies with the lowest costs will win the biggest market share" (see p.72). This policy formulation has been criticised on the grounds that DECC is not actually operating a level playing field, but is selectively providing funding or hidden subsidies for technologies which it judges to be promising.

In addition to its own internal studies described above, DECC and/or the Committee of Climate Change have commissioned a number of studies by consultants, to complement their own work. These include a study by the major engineering consultants ARUP, which suggested that on a high estimate the UK could have up to 126 GW of renewables capacity by 2030, including 76 GW of wind, 6 GW of wave and tidal and some 12 GW of biomass[102]. Two reports by the consultants Mott MacDonald, commissioned by the Committee of Climate Change, reviewed all the main sources of primary energy, and assessed the likely trends in the cost of these technologies between now and 2050[103,104]. This influential work is discussed in more detail below.

5.3 Constraints and opportunities for further developments

The various studies mentioned above on the potential for renewables have all recognised that their exploitation is subject to some constraints. The most obvious potential constraints relate to the (as yet unclear) economics of some of the renewables, and the problems caused by the variability/intermittency of some renewable resources. It is also recognised that there may be a need to build in some degree of diversity to insure against the risk of failure of any specific technology.

5.3.1 Economic constraints on the exploitation of renewables

There is no doubt that the unit costs of almost all sources of renewable energy are coming down, some faster than others. These cost reductions reflect progress along their learning curves, as the technology develops and markets build up. For example solar PV costs are moving rapidly down a steep slope (currently ~ 35% pa), as market volume grows, and new technology emerges. The learning curve slopes for wave, wind and

[100] Bailey, R. and Blair, L. (2012) 'A Corruption of Governance', Unlock Democracy and the Association for the Conservation of Energy, London

[101] Olivier, D. and Simmonds, A. (2012) *Less is More: Energy Security after Oil* Association for Environment Conscious Building (AECB) http://aecb.net/news/2012/02/less-is-more-energy-security-after-oil-lim-from-the-aecb/

[102] DECC (2011) ARUP consultants report for the DECC renewables review www.decc.gov.uk/assets/decc/Whatwedo/UKenergysupply/Energymix/Renewableenergy/policy/renew_obs/1834-review-costs-potential-renewable-tech.pdf

[103] Mott MacDonald Ltd (2010) 'UK Electricity generation costs-update', consultants report for the Department of Energy and Climate Change, June http://www.decc.gov.uk/publications/Default.aspx?term=Mott%20Macdonald%20&tags=&urn=&fromdate=&todate=&alpha=#result

[104] Mott MacDonald Ltd (2011) 'Costs of low-carbon technologies' report for the Committee of Climate Change, May http://www.decc.gov.uk/assets/decc/11/consultation/ro-banding/3237-cons-ro-banding-arup-report.pdf

tidal stream energy are less steep – they are put by consultants Mott MacDonald, in its report to the Committee of Climate Change, as ~ 18% pa for wave, 15% for wind, and 14% for tidal stream energy[105].

The Mott MacDonald study surveyed in detail the costs of each of the main low-carbon options. It began by analysing the capital and operating costs of the options which are currently available on a commercial scale, and combined these into a single 'levelised' cost per MWh delivered for each option, using a 'central discount rate projection' of 10% pa and a carbon price which rises sharply after 2020. They then factored in their best estimates of cost reductions to be expected during the next 30 years, and produced further estimates for facilities of the same type operating in 2020 and 2040. The conclusions of their study[106] are summarised in Table 5.3.

Table 5.3 Generation cost estimates per MWh delivered, based on Mott MacDonald data

Electricity	**Current levelised cost**	**Levelised cost in 2020**			**Levelised cost in 2040**	
Generating	**in £/MWh**	**in £/MWh**			**in £/MWh**	
Option	**Ch.3 and fig 2**	**Ch. 3**	**Ch. 7 (7.3)**		**Ch. 3**	**Ch. 7 (7.4)**
Onshore wind	83-93	63-72	55-77		51-61	48-62
Offshore wind	169	103-114	80-140		69-82	55-110
Tidal stream	293	180	135-240		120	85-185
Wave energy	368	300	140-300		200	95-230
Photovoltaics (PV)	330-375	137-198	110-240		63-120	50-145
Nuclear (PWR & BWR)	89	63	48-85		50	35-75
Gas-CCS	100-105		90-160		91-98	90-110
Coal-CCS	145-152		75-145		85-119	85-140
Biomass	51-171	43-149	48-150		32-129	40-120
Geothermal	159	115	80-170		80	50-130

Source: ref. 106 Chapters 3 and 7

(The wide ranges reflect differences in assumptions: chapter 3 of ref. 106 gives central estimates and chapter 7 gives various different assumptions about progress down learning curves)

It will be seen that, on their estimates, **onshore wind** comes out as the cheapest option, both now and in 2040, although by 2040 its cost range largely overlaps with those of solar PV and nuclear. It should be noted that these calculations do not include any costs associated with the intermittency of the supply for wind or PV. However it can be argued that these costs should be relatively small, even for large contributions. For example, the additional cost to the operator of making provision for the intermittency of onshore wind, by paying for backup and balancing services, has been put by Milborrow at up to £2.5/MWh for contributions to supply of up to 20%, and up to £7/MWh for a 40% contribution[107]. For still larger contributions, the cost will increase further, perhaps to £20/MWh, but the actual cost will depend on what measures are taken to ensure balancing (see Section 5.3.2 below).

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[105] Mott MacDonald Ltd (2010) 'UK Electricity generation costs-update', op cit
http://www.decc.gov.uk/publications/Default.aspx?term=Mott%20Macdonald%20&tags=&urn=&fromdate=&todate=&alpha=#result

[106] Mott MacDonald Ltd (2011) 'Costs of low-carbon technologies' op cit
http://hmccc.s3.amazonaws.com/Renewables%20Review/MML%20final%20report%20for%20CCC%209%20may%202011.pdf

[107] Milborrow, D. (2009) 'Wind Power: Managing Variability' Energy consultants report for Greenpeace
http://www.greenpeace.org.uk/media/reports/wind-power-managing-variability

Mott MacDonald's onshore wind figures also assume that sites will be available at a reasonable cost. This can be questioned, since wind farms take up relatively large areas (MacKay gives a figure of 2 MWav/km^2), and the number of sites in the UK is limited. For example, it has been claimed that even if 10% of the surface area of Scotland were devoted to wind farms, these would only generate 16 GWav. It is not easy to predict the public reaction to widespread deployment of onshore wind farms, because some people object to what they perceive as unwelcome visual and acoustic intrusion, whereas others find them attractive. In simple land-use terms, it should be noted that the turbine tower bases themselves do not occupy much space, and the areas around them can still be farmed.

Offshore wind may be less intrusive and has no direct land-use implications. There are no serious limitations in principle on the amount of power that could be generated, but it is more expensive now and will remain so until ~ 2040. It should be noted that Mott MacDonald's figures are significantly lower than those in DECC's 2011 Renewables Roadmap, which put the range at £102-176/MWh. However, more optimistically, the European Wind Energy Association is predicting that offshore wind will get down to €75 /MWh (i.e. about £63/MWh) by 2020[108].

It will be seen that Mott MacDonald's estimate for **Tidal stream** energy and for fixed **Wave energy** devices are very high for an initial installation, though at least tidal stream facilities have a prospect of becoming competitive with wind or nuclear by 2040. On both of these options, the Carbon Trust[109] is more optimistic, arguing that although on initial commercial deployment, tidal energy could cost £160/MWh and wave energy £400/MWh, by 2025 the cost of both wave and tidal stream power could be brought down to £150/MWh. With continued targeted innovation, "the UK's best marine energy sites could generate electricity at costs comparable with nuclear and onshore wind" by 2025. As regards **Solar PV,** Mott MacDonald's estimates are very high for current installations, but become competitive by 2040 at £50/MWh.

Mott MacDonald admit that they may have been 'bullish' about **nuclear** costs, for example, by proposing an extreme low estimate of <£40/MWh for 2040, and some critics (for example, No2NuclearPower[110]) have challenged their low estimates for future nuclear costs as unrealistic. In which case, as the technology develops, some of the other renewables may become competitive, including wave and tidal stream and also offshore wind.

In summary, if the Mott MacDonald estimates are accepted, onshore wind and possibly PV look as if they have a good chance of competing economically in due course with current-generation nuclear.

5.3.2 The issue of the Variability/Intermittency of Renewables

The variability/intermittency of most renewables is often portrayed as a major potential constraint on their effective use, and there certainly needs to be a strategy to address this issue. The nature of the problem was described in Section 3.3.3. Candidates for inclusion in a strategy to solve the problem, which were also listed there, are considered in the following sub-sections.

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[108] EWEA (2012) 'French nuclear set to become more expensive than wind', European Wind Energy Association, February http://blog.ewea.org/2012/02/french-nuclear-set-to-become-more-expensive-than-wind-power/

[109] Carbon Trust (2011) 'Accelerating marine energy' Carbon Trust report CTC797, London, July http://www.carbontrust.com/media/5675/ctc797.pdf

[110] No2NuclearPower (2011) 'The Cost of Nuclear Power' No2 NuclearPower Briefing, February http://www.no2nuclearpower.org.uk/reports/EconomicsBriefing.pdf

5.3.2.1 Balancing supply and demand using the national grid

The national grid system already has to deal with the regular daily peaks and troughs in energy demand, and with the occasional loss of power from large fossil fuel or nuclear plants (see Sections 2.2-2.4). The consensus is that, if the renewables contribution can be kept within around 20% of the total input to the national grid, its variability can be accommodated[111]. Above this proportion, the renewable output will from time to time exceed the demand, making it available for export or, in the future, for the generation of hydrogen[112]. If the renewables input is insufficient, the amount of back-up capacity required depends on many factors, as explained by Laughton[113]. The ability of the existing grid to balance supply and demand could be enhanced by the development of 'smarter' load and grid management techniques, which could re-phase demand and reduce peak demand using price signals or contractual restrictions.

5.3.2.2 Reducing the need for backup by extending the grid or building supergrid links

There is certainly scope for extending the national grid system, so as to facilitate the transport of renewable energy from its source to locations of high demand. In addition, as we have seen in Section 2.4, there has been a steady increase in the construction of interconnects linking the UK to the French and Dutch grids and there are plans for further interconnects to Norway and across the Mediterranean, linking up to Concentrating Solar Power (CSP) projects in North Africa[114]. Interconnects are expensive: for example, the 260-kilometre long BritNed interconnector cost €600M to build. However being able to shift energy between regions (and time zones) has commercial attractions, enabling suppliers to compete in a wider market. How far it can address the intermittency problem is controversial. For example, Pöyry's 'North European Wind and Solar Intermittency Study' claimed that "heavy reinforcement of interconnection doesn't appear to offset the need for very much backup plant"[115]. However that study had a relatively narrow geographical footprint – if North African links had been added, then the gains would have been greater[116]. A study by Aboumahboub et al has suggested that the need for back-up could be halved[117].

5.3.2.3 Energy Storage

Energy storage facilities can reduce the need for backup supplies, especially given the fact that, at times, some renewables will supply more electricity than is needed. The UK currently has 2.7 GW capacity of pumped storage generators linked to the grid, of which the largest is Dinorwig, which has a capacity of 1.8GW, and can generate full power from a standing start in 100 seconds. Unfortunately, this capacity is already fully utilised at times, and it appears that there is only rather limited scope for constructing further large-scale pumped water stores in the UK. Other countries, for example Germany, are looking at new pumped storage options – using old mine workings, or converting existing hydro plants to have pumped storage capacity. The UK may find that it is cheaper to access storage plants in other countries via supergrid links than to build new energy storage facilities of its own.

Another approach is to make use of the batteries of electric vehicles, charging them overnight from excess grid power – for example, from wind and/or nuclear – and then drawing on this stored electricity if there is

[111] Boyle, G. (ed.) (2009) *Renewable Electricity and the Grid: The Challenge of Variability*, Earthscan, London, p.47
[112] ibid pp.47-48
[113] ibid pp.18-26 in chapter by Laughton
[114] Desertec (2012) The Desertec Concept http://www.desertec.org/concept/
[115] Pöyry (2011) 'North European Wind and Solar Intermittency Study'. Pöyry consultants report http://www.poyry.com/sites/default/files/imce/files/intermittency_-_march_2011_-_energy.pdf
[116] Czisch, G. (2011) 'Scenarios for a Future Electricity Supply', IET, London
[117] Aboumahboub, T., Schaber, K., Tzscheutschler, P., Hamacher, T. (2010) 'Optimization of the Utilization of Renewable Energy Sources in the Electricity Sector', Recent Advances in Energy and Environment Conference http://www.wseas.us/e-library/conferences/2010/Cambridge/EE/EE-29.pdf

a shortfall, i.e. to use the so-called ‘vehicle to grid’ (V2G) approach. There are some potential logistical problems: there could be a major demand surge in early evening when electric vehicle batteries are first connected, and users may be unhappy to find their batteries depleted if there is drain overnight.

Some other new electric storage ideas are emerging, including compressed air storage, and various types of flow battery. Cryogenic air storage systems have also been developed[118]. Another emerging option is to produce hydrogen by electrolysis, and then store it and use it for power generation when needed. Yet another option is to convert electricity into methane or synfuels[119].

However it remains true that energy storage is expensive – basically because the plant is only used for part of the time – and at present it seems that providing energy storage capacity is much more expensive than building back-up supply plants when needed.

5.3.2.4 Output curtailment

As the preceding section mentioned, there are times when excess electricity becomes available from renewables. In the absence of other measures (for example, storage or export), the only way to deal with excess generation is by temporary output curtailment – i.e. by constraining one or more sector of the energy supply system during periods when supply exceeds demand. This already occurs regularly on the grid (in 2011, NGC curtailed around 1.49% of the total electricity generated by UK wind farms) but with the advent of more variable renewables this will increase. Such curtailment is already controversial, particularly since it is claimed that some suppliers (for example, nuclear) have ‘inflexible’ capacity which cannot be curtailed. According to EDF, the issue is likely to become critical as the intermittent renewable capacity approaches the government’s 32% proposed target[120]. The scale of this problem is indicated by the fact that the UK base-load demand falls to around 25 GW at night in summer, so if there were more than 25 GW of wind and also more than 25 GW of nuclear available on the grid, which would give way?

5.3.2.5 Shift to gas and biomethane

The current government approach to UK energy supply development, which seems to be endorsed by the NGC, is to switch increasingly to electricity to meet most end uses, including heating (using heat pumps) and transport (via overnight charging of electric vehicle batteries). This strategy has the advantage that excess generation from nuclear and renewables can then be stored in systems provided by the user, and emissions from gas and oil consumption can be reduced. It has the consequence that the use of Natural Gas would gradually decline and, by 2050, around 50% of end-use energy would be in the form of electricity, up from 15% today[121]. However this would involve building a much larger electricity distribution network, at significant cost.

An alternative approach is to make much greater use of gas for the distribution of energy. The UK electricity grid currently handles an average of 44 GW, with peaks and troughs of 60 and 20 GW respectively. The gas

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[118] Highview (2012) UK Cryogenic air storage http://www.highview-power.com/wordpress/?page_id=1320/

[119] Sterner, M. et al (2010) ‘Towards 100% renewables and beyond power: The possibility of wind to generate renewable fuels and materials’, Fraunhofer Institute, IWES/ZSW http://www.iset.uni-kassel.de/abt/FB-I/publication/2010-088_Towards-renewables.pdf

[120] EDF (2008) EDF’s submission to the UK governments renewable energy strategy consultation: ‘UK Renewable Energy Strategy: Analysis of Consultation Responses’, prepared for: Department of Energy and Climate Change, File Log Number 00439e, p.3 www.berr.gov.uk/files/file50119.pdf

[121] National Grid TBE (2011) ‘Development of Energy Scenarios’ National Grid, July http://www.nationalgrid.com/NR/rdonlyres/BC92D89F-1191-4048-BB41-A4A57F778C7C/46607/TBE_2011_Combined_20110407.pdf

grid handles around four times more energy than that on average, and delivers six times more energy than electricity during peak periods in the winter. So why not focus on gas transmission rather than electricity? Certainly, electricity transmission (with up to 10% energy losses/1000km) is much less efficient than gas transmission, and gas is much easier to store. Availability of more gas is an issue, but if significant amounts of UK shale gas can be produced, adequate supplies should be available for some time ahead. Moreover, if gas can be burned in local gas-fired power plants equipped with CCS, it could provide low-carbon electricity where needed, although at relatively high cost.

To get carbon emissions down further, biogas can be produced from municipal and farm wastes to provide a carbon neutral replacement for at least some natural/shale gas. National Grid has estimated that biogas could meet about half of UK domestic heating needs. In addition, it could be used to generate electricity and, if these plants also have CCS, there is the prospect of carbon-negative operation. The weak point in this argument is that there probably will not be enough biogas to replace all the gas currently used for heating, let alone to replace fossil fuels for electricity generation. It should be recognised that this approach does not meet the problem of the variability of renewables head on: instead, it offers lower cost energy storage and transmission.

5.3.2.6 Green gas-hydrogen

A more radical approach, which addresses some of the shortcomings of the biogas approach outlined above, is to generate ‘green gas’ synthetically from non-biomass sources. For example, hydrogen gas could be produced using electricity from excess off-peak wind and other variable renewables via electrolysis, and then stored, ready for a range of possible uses, including power generation, when needed.[122]

Another approach, the ‘wind to gas’ idea, is to react CO_2 with hydrogen to make methane or other fuels for use in vehicles. This is under development in Germany and the UK [123, 124, 125, 126]. To transmit green gas to the user, one possibility is for hydrogen admixed with methane (for example, hythane – 20% hydrogen, 80% methane) to be added to the gas main for distribution (something like the old Town Gas, which contained hydrogen). Higher ratios of hydrogen are possible, but may require changed pipework[127].

There are also problems with the economics of large green gas networks. Current technology imposes quite severe conversion loss penalties in some of the energy conversion processes involved – for example, for making, storing, transmitting and using ‘green hydrogen’. But these problems are being worked on, and a range of more efficient hydrogen production and storage technologies are being developed[128, 129].

5.3.2.7 Combined heat and power/DH/heat stores

An alternative to expanding the electric or gas transmission grids is to use hot water to distribute energy for

[122] Sterner, M. et al (2010) op cit http://www.iset.uni-kassel.de/abt/FB-I/publication/2010-088_Towards-renewables.pdf
[123] Air Fuel Synthesis, UK (2012) ‘Air Capture’ project http://www.airfuelsynthesis.com
[124] Enertag (2012) Hybrid Power plant https://www.enertrag.com/en/project-development/hybrid-power-plant.html
[125] Macogaz (2012) ‘Power to gas’ fact sheet http://www.gasnaturally.eu/uploads/Modules/Publications/marcogaz_power2gas_fact_sheet.pdf
[126] CO2chem (2012) CO2RRECT project http://co2chem.co.uk/carbon-utilisation/co2rrect
[127] Castello, P. Tzimas, E., Moretto, P. and Peteves, S. (2005) ‘Techno-economic assessment of hydrogen transmission and distribution systems in Europe in the medium and long term’, The Institute for Energy, Report EUR 21586 EN, EC Joint Research Centre, Petten, The Netherlands
[128] Safe Hydrogen (2012) Hydrogen hydride storage http://www.safehydrogen.com
[129] Gas Plas (2012) Norwegian ‘plasma’ hydrogen reformer technology: http://www.gasplas.com/w3

space and water heating, using community-wide DH networks. This approach raises some different issues although, like gas transmission, it offers the prospect of low-cost energy storage to tackle the variability of some renewables by taking the option of heat storage. The extent to which hot water transmission has been adopted varies across the world, but it is widely used in Europe, where the percentage of houses supplied by district heat ranges from 1% in the UK, though 12% in Germany, and ~50% in many Eastern European countries, to 95% in Iceland[130]. At present many of the DH networks which distribute heat in Europe use hot water generated from fossil fuels, some it of via CHP units.

However biomass-generated heat is increasingly being used. An early example was the 1980 Swedish 10,000 m^3 solar heat store at Lambohov, linked to 55 houses. In addition, solar-fired DH is also now moving ahead, usually linked to large community heat stores, and in some cases to large inter-seasonal heat stores, allowing summer heat to be used in winter (large heat stores are much more efficient than small domestic heat stores, because of their lower surface area to volume ratio). For example, in Canada, the Drake Landing scheme in Alberta has 52 houses, with 2,300 sq m of solar mounted on garages and an underground inter-seasonal heat store. Denmark plans to have 40% of its heat supplied via DH networks fed by solar inputs by 2050[131]. The largest project so far is the 13.5 MW Marstal Danish solar project.

DH only makes sense in urban or large suburban areas, and in countries such as the UK, where gas has been cheap, there has hitherto been little incentive to invest in the required water-pipe infrastructure. However, on the 2050 timescale, this should not be ruled out as a possibility. Supporters of DH argue that large-scale CHP/DH makes much more sense than heating systems in individual homes. The overall energy conversion is more efficient, the heat and electricity produced can be better balanced to meet the varying demands of large numbers of consumers, especially if there is also bulk heat storage, and they can be used to help balance varying electricity grid inputs from renewables[132]. There are nonetheless problems with a large expansion of the hot water network. Piping hot water can lead to large energy losses, as is exemplified by the enormous losses experienced in the old networks used in Russia, although modern DH systems seem to have overcome this problem. For example, in the city of Aarhus in Denmark there is a 12.3 km pipe from a waste burning plant in the city outskirts and a17km link from a CHP plant. The longest hot water link so far is the 65 km heat feed from Melnik to Prague, delivering 200 MW.

Another problem, under present competitive market conditions, is that there can be a conflict between wind energy and CHP/DH. For example, it has been said that in Denmark there is a danger that wind energy will drive CHP systems out of business: electricity production from local CHP systems in Denmark declined by 24% between 2000 and 2009.

5.3.3 The issue of diversity within the energy supply mix

All the Pathways to 2050 presented in this report are subject to technical, economic and political uncertainties. Some have argued that, given these uncertainties, it would make sense to back renewables, nuclear and CCS in parallel, in case one or more should fail to deliver all that is hoped for. That is certainly what is implied in the DECC Carbon Plan, although the proportion of each varies in the three basic

[130] http://en.wikipedia.org/wiki/District_heating#National_variation
[131] SDH (2012) Solar District Heating: Intelligent Energy Europe: http://www.solar-district-heating.eu
[132] RAe (2012) *Heat: degrees of comfort? Options for heating homes in a low carbon economy* Royal Academy of Engineering http://www.raeng.org.uk/heat

pathways it outlines. While diversity is a good strategic principle, there is a risk that spreading resources so widely over three very different areas of technology will mean that we develop none of them well. In any case, the renewables option is in fact a family of options, including a range of very diverse technologies, at different stages of development. By contrast, at present at least, nuclear is based on one technology (the variants of the LWR), while CCS technology is as yet undeveloped, and has a limited number of variants.

If diversity is a key requirement, then renewables have a lot to offer. The renewables approach could well be more robust than a conventional centralised power generation and distribution system, since it would combine a range of different technologies for electricity, heat and gas generation, operating at a range of differing scales, and linked together in a new flexible interactive system. An analogy would be the internet, with distributed, localised, computing power, compared with a large central main-frame computer linked to remote terminals.

5.3.4 Other strategic development issues

We recognise the importance of economic comparisons of the various different possible pathways to 2050, and in Section 5.4 below we report on recent attempts to quantify the costs of various renewable options. However it should be remembered that such studies are still in their infancy. Our work with the DECC Calculator has brought home to us some of the limitations of their model, particularly when trying to assess pathways in which there are energy flows crossing conventional boundaries and sectors – for example, when heat and green gas/hydrogen vectors replace electricity. It is also possible to dispute the ranges of cost forecasts which they propose. Although Professor David Mackay has rightly emphasised the need for quantification in energy planning, and has asked for "the sums to add up", at this stage, it is unfortunately hard to avoid some of the "Hot Air" which he rightly castigates. Nevertheless, in the one possible scenario mix that we set out below, we have tried to make full use of the (admittedly impressive) DECC Pathways spreadsheet.

A number of other strategic considerations, which are not readily quantified economically, also need to be taken into account:

- The likelihood of success of each Pathway, and the risks involved if we spread our efforts too widely
- The commercial and technological advantages accruing to the 'first mover' in a new technology: it is not clear that the UK should wait until technologies have been developed elsewhere, before it seeks to deploy them here. The UK has considerable strengths, particularly in the marine renewables field, and as Barack Obama has eloquently put it: "The country that harnesses the power of the clean, renewable energy will lead the 21st century".
- There are some areas where the UK stands little chance of leading – for example, in nuclear power or CCS. However in the renewables area it can be a major player. Given that the UK probably has the world's best renewable resources as well as established technological expertise, particularly in offshore engineering and marine technology, it makes good sense for it to focus on renewables.
- We do not need to be mesmerised by the claim that energy demand will have doubled by around 2050, an argument which has been used to justify the nuclear expansion. As the recent 'Corruption of Governance' report[133] has argued, the government had been poorly informed on this issue. Certainly there is no need to accept it: Germany is planning to cut electricity demand by 25% by 2050.

[133] Bailey, R. and Blair, L.(2012) op cit http://www.ukace.org/wp-content/uploads/2011/11/ACE-Campaigns-2012-01-Corruption-of-Governance-Jan-2012.pdf

5.4 Pathway targets

With the above strategic points in mind, the High Renewables Pathway to 2050 which we are proposing here has been selected so as to:

- achieve an 80% reduction in GHG emissions by 2050, to which the UK has an international commitment (see Section 1.2)
- reduce the country's dependence on fossil fuels and foreign imports, by providing enough energy from indigenous low-carbon sources to meet foreseen demand and, in the process, provide security of supply
- decrease the use of nuclear power as quickly as possible
- minimise the dependence on CCS to reduce GHG emissions, thereby reducing the risk associated with this as yet unproven technology
- limit the fossil-fuelled standby capacity required by intermittency
- minimise energy wastage, through the adoption of efficient uses of energy in all sectors
- avoid biomass imports given their biodiversity and land-use issues.

To identify a fully-optimised set of supply and demand figures for renewables would require a major assessment and modelling exercise, which is beyond our present scope. So at this point we only offer 'ballpark' figures, which are derived by selecting trajectories in the DECC Pathways 2050 spreadsheet. In making these selections, we have been influenced by the data and studies which have been reviewed above, indicating that wind, wave and tidal power, with modest contributions from other renewables, could meet most of UK annual electricity demand, and much of its non-electric energy demand, provided that attainable energy-saving measures have also been implemented.

5.4.1 Inputs to electricity supply

As regards electricity supply, we have been influenced by two recent studies by WWF and Pőyry, which present approximate capacity breakdowns as at 2030 and 2050, as shown in Table 5.4.

Table 5.4 Two existing scenarios

Electricity	WWF proposal for 2030			Pőyry proposal for 2050		
Generating	Installed	Output		Installed	Output	
Option	GWn	Gwav		GWn	GWav	TWh/y
Offshore wind	52	19		156	57	501
Onshore wind	20	4		33	7	61
Photovoltaics (PV)	10	1		38	3	27
Tidal stream/wave/hydro	12	3		31	7	63
Other/Biomass & Geothermal	10	3		6	1.5	13
Total renewables	**104**	**30**		**264**	**75.5**	**665**

In this table, the figures for 2030 are those proposed in the WWF 'Positive Energy' report[134], and represent their 'Stretch Scenario' C1. The figures for 2050 are taken from the Pőyry report[135], and follow their 'Max'

[134] WWF (2011b) 'Positive Energy: how renewable electricity can transform the UK by 2030', World Wide Fund for Nature, London, http://assets.wwf.org.uk/downloads/positive_energy_final_designed.pdf

[135] Pöyry (2011) 'Analysing technical constraints on renewable generation to 2050', Pöyry consultants report to the Committee on Climate Change, March http://hmccc.s3.amazonaws.com/Renewables%20Review/232_Report_Analysing%20the%20technical%20constraints%20on%20renewable%20generation_v8_0.pdf

scenario for 2050. However we do not take the view that Pőyry's scenario should be regarded as a 'maximum': their figures for the biomass, geothermal, wave and tidal stream contributions all look low, and the PV figure might also be revisited, given that DECC now says PV could reach 22 GW by 2020. Furthermore their load factor figures are lower than those now regarded by DECC as feasible. There could also be additional sources beyond those proposed by Pőyry – for example, tidal barrages or lagoons might contribute up to 20 GW, and could become economically viable if, by 2050, significant electricity (or hydrogen) storage capacity becomes available, or export of excess/out of phase output via a super-grid becomes feasible.

For 2050, the GWav figures given here are calculated from the annual generation figures in TWh/y quoted by Pőyry. Since WWF does not break down its figure for total output, we have estimated the breakdown using Pőyry's load factor figures as a guide – i.e. 37% for offshore wind, 21% for onshore wind, 10% for PV, 25% for marine and hydro and 50% for biomass (for comparison, the load factors used in the DECC Pathways 2050 spreadsheet are 45%, 30%, 10%, 32% (average), and 80% respectively). WWF and Pőyry both also included interconnects in their calculations (WWF had up to 35 GW), but both saw exports dominating (Pőyry calculated the net outflow as 35 TWh pa), so, although economically attractive, they cannot be considered as adding to UK capacity or net UK energy, though they provide a useful balancing option for times when renewables are contributing low or zero power, or are generating surplus energy. These two studies are broadly compatible – an extrapolation of the WWF 'Stretch scenario' to 2050 leads to a total which is close to that of Pőyry's Max scenario.

Taking account of these points, in our chosen Pathway, we have taken the Pőyry Max capacity figures as our starting point, but we have reduced their offshore wind contribution (to be cautious), and we have added in some tidal range sources (small barrages and medium-sized lagoons), as well as a range of non-electrical sources. We then selected the nearest acceptable trajectories in the DECC Pathways 2050 software (see Table 3.2, and fed these into the DECC web Calculator using the url[136].

It will be seen from Table 3.2 that we have in many cases made primary energy supply choices in the DECC model which have a level which significantly exceeds the 'safe' Level 1. For example, Offshore wind has been set at level 2.4 and Onshore wind at Level 2.9. These choices have the effect of delivering our chosen output from these sources: we would not, however, endorse the language used to describe the chosen levels in the DECC Pathways to 2050 report (p.10), where, for example, a Level 3 choice means a trajectory that "might be achieved by applying a very ambitious level of effort that is unlikely to happen without significant change from the current system". In our view, the proposed contribution of wind power is based on technology which already has an established track record and market acceptance.

Using the level choices given in Table 3.2, and with Heading 43 manually set to 3 (see Annex 1), the DECC Calculator (Excel version) gives the figures in Table 5.5 for primary energy inputs. It should be noted that the annual input figures in TWh/y are net inputs, after making appropriate adjustments for intermittency and conversion losses.

[136] http://2050-calculator-tool.decc.gov.uk/pathways/1011ot2wr1frz413034412100441444034230410230423041013 3

Table 5.5 Inputs to Electricity Supply in 2050 for the chosen High Renewables Pathway

Renewable inputs	GWn	TWh/y	GWav
Offshore wind	**76**	**299.8**	**34.2**
Onshore wind	**30.8**	**81.1**	**9.3**
Photovoltaics (PV)	**35.2**	**30**	**3.4**
Tidal stream/wave/hydro	**35.1**	**89.1**	**10.2**
Tidal stream	11.9	37.6	4.3
Tidal range	9.6	19.2	2.2
Wave	9.6	19.0	2.2
Hydro	4	13.3	1.5
Geothermal	**4**	**28.1**	**3.2**
Non-renewable inputs			
Gas-fuelled thermal generation	**1.7**	**11**	**0.6**
CHP Domestic electricity supply		**44**	**5.0**
CHP Commercial electric supply		**16.4**	**1.9**
Electricity imports		**70**	**8.0**
Total	**182.8**	**669.5**	**77**

Source: The GWn figures in this table are taken from the 'Intermediate output' tab, lines 117-132, and the TWh/y figures from lines 96-114

Our scenario does not assume any use of CCS, apart from the already-planned 1.7 GWn pilot plant. If CCS is proven, that might be an option to consider, especially since its use in biomass combustion plants could lead to negative net emissions. However we already have an outcome in which UK GHG emissions in 2050 are predicted to fall to 18% of the 1990 reference value. This pattern of electricity supply is shown graphically in Annex 3.

5.4.2 Matching to electricity demand

The demand-related choices which we have made for this Pathway, when fed into the DECC software, lead to the following pattern of end use:

Table 5.6 End uses of Electricity in 2050 for the chosen High Renewables Pathway

Electricity end use	2010		2050		% Change
	TWh/y	GWav	TWh/y	GWav	
Lighting & Appliances, Heating & Cooling	196	22.4	130.5	14.9	-35
Transport	8	0.9	61.7	7.0	+675
Industry	128	13.7	201.7	23.0	+58
Agriculture	4.2	0.48	4.3	0.5	+2.4
Losses in transmission	25.2	2.88	29.6	3.4	+18
Export of electricity	0	0	235.6	26.9	
TOTAL	**361**	**40.3**	**663.4**	**75.7**	**+84%**

Source: Flows Tab lines 65-93

These figures are at first sight surprising, and merit some comment. The demand-related choices that we have made (as shown in Table 3.2) which exceed DECC's Level 1 or 2 criteria (i.e. headings 22,23,25,26,27,28,29,31,32,35,36,38,39 and 42) are interpreted by the DECC software as meaning:

Domestic passenger transport

22 Domestic transport behaviour 4: individuals travel the same distance as today, but significantly shift to public transport.

23 Shift to zero emission transport 4: 100% zero emission vehicles; all passenger trains electrified; 50% bus electrified

25 Domestic freight 4: Road modal share falls to half; greater hybridisation; rail freight is all electric

26 International aviation 4: 85% passengers increase; 5% more fuel use

27 International shipping 4: maximum technical feasible reductions realised; emissions decrease by 46%

Domestic space heating and hot water

28 Average temperature of homes 3: Average room temperature decreases to 17°C (0.5°C decrease on 2007)

29 Home insulation 4: Over 24m homes insulated; average thermal leakiness decreases by 50%

31 Home heating that isn't electric 3: The dominant non-electric heating source is waste heat from power stations

Domestic lighting, appliances, cooking

32 Home lighting & appliances 4: Energy demand for domestic lights and appliances decreases by 60%

Industrial processes

35 Energy intensity of industry 3: High electrification; CCS captures 48% of emissions; process emissions reduced

Commercial heating and cooling

36 Commercial demand for heat & cooling 4: Space heating demand drops by 25%, hot water demand by 10%, cooling demand by 60%

38 Commercial heating that isn't electric 3: The dominant non-electric heat source is heat from power stations

Commercial lighting, appliances, catering

39 Commercial lighting & appliances 4: Energy demand for lights & appliances decreases by 30%; decreases by 25% for cooking

Electricity balancing etc

42 Storage, demand shifting & interconnection 3: 7 GW storage with 2 more pumped storage, 15 GW interconnection & some demand shifting.

It will be seen that all the above choices imply significant changes in personal, commercial and industrial energy use practice, and also considerable investment by end users in new equipment. However we judge that these are all feasible over a 40-year timescale.

Heading 42 merits some further comment. Our choice of headings implies supergrid links of 15 GW capacity, used for UK grid balancing, with imports of excess wind, Concentrated Solar Power (CSP) and Concentrated PV (CPV) outputs from continental Europe (when available and needed) and /or, more reliably, from CSP/CPV projects in North Africa and the Middle East. An additional 8 GW interconnector is provided for imports, and a further 4 GW for exports, allowing a maximum export rate of 27 GW. Within the UK, hydro, (deep) geothermal capacity and biomass CHP could also be used for grid balancing, with geothermal plants being run in CHP mode. In addition, the batteries in the electric vehicle fleet provide a V2G electricity balancing opportunity. Also 7 GW of storage and considerable demand shifting has been selected.

Further balancing could be achieved by using biomass/biogas and also green gasses and synfuels produced from excess wind, wave, tidal, and PV electricity, which could be stored ready for use to meet peak electricity demands via extra standby generation capacity. Surprisingly this is not provided for in the Pathways 2050 spreadsheet. If this option were allowed, other opportunities would also become available. Whilst most road transport would be electrified, some vehicles would use biofuels and synfuels (e.g. green diesel for trucks, biogas for some buses, biofuels/green fuels for aircraft), with storage to insulate these demands from variation in supply. (We will look at this issue further below). However in this scenario 50 TWh/y of electricity is provided for vehicles and 40 TWh/y of petrol or diesel for the balance of road vehicles, including hybrid electric vehicles. Domestic and International aviation is fuelled by 145 TWh/y of fossil aviation fuels.

Another restriction of the Pathways 2050 spreadsheet is that, as the capacity of the biomass power stations is increased, the model automatically increases the coal burn. If no biomass imports are allowed, as we initially assumed in our selection of trajectories, the biomass power stations trajectory cannot exceed Level 2.8 without seriously compromising the emissions reduction due to this unsolicited but enforced coal firing. This inflexibility has forced us to make no provision for solid biomass power stations.

Comparing Table 5.5 and 5.6, it will be seen that the total electricity supply and end use are approximately in balance in 2050, with an appropriate level of reserve capacity. However, by 2050, the total supply has increased since 2010 by 84%, in spite of heroic efforts at energy conservation in the domestic and commercial sectors. This is due to two main effects – the near-complete electrification of the road and rail sector (to reduce carbon emissions) and a massive increase in the level of electricity exports. This does not reflect what might at first sight appear to be a wasteful oversupply of electricity. Rather, it is driven by the need for a high-renewables energy system to have a coherent solution to the problem of intermittency. Fortunately, the UK is blessed with a supply of ‘free’ renewable energy which is many times larger than its demand, so that any surplus could be exported to mainland Europe by interconnects. By 2050, the UK could be earning a very substantial net income from these exports, more than offsetting the cost of the interconnections and imports. The net income from electricity exports set against imports would yield an estimated annual profit of £15.6 bn.

The discussion above indicates that the interconnectors would allow for electricity to be imported when UK supply from wind and other renewable resources was low, thus reducing the need for UK backup plant. In fact, the need for fossil-fired backup plants is reduced to zero by 2050.

We would have preferred to use some of the net exported excess wind generation to produce hydrogen gas for storage and possible conversion to methane, to be used for vehicles and also in green gas-fired plants to meet demand when wind generation was low. However the DECC Calculator will not allow this, and instead exports it all. This wind-to-gas option would have reduced our exports and would also have reduced the need for interconnection. It would also allow us to eliminate the residual fossil fuel that the DECC Calculator retains. The 100% renewable energy option is discussed in section 5.5.

5.4.3 Overall energy inputs and outputs

The previous two sections focused on energy inputs to the generation of electricity and for electrical end use. However, in a High Renewables Pathway, electricity is by no means the only form in which energy is supplied to the end user. The complete picture is given in Table 5.7 below.

The upper half of Table 5.7 gives figures in TWh/y, to facilitate comparison with figures which can be read off the computer version of the Sankey diagram. In the lower half, the same figures are given in GWav, so as to facilitate comparison with the figures for installed capacity in Table 5.5. The left hand block gives a breakdown of the total 'primary' energy input to the system, using the same headings as those adopted by DECC in its Sankey diagrams, and presenting them in the same order. The term 'primary' is used in the same (rather arbitrary) sense as that adopted in DECC reports – i.e. the energy being submitted to the processes of transformation considered in the Sankey diagram. It should be noted that in each case where the flow is subject to conversion losses or intermittency, a 'capacity factor' relating to the losses and intermittency is used by the software to convert the 'primary' input into the 'end use' figure. This pattern of overall primary energy supply is shown graphically in Annex 3.

The TWh/y figures shown here are derived from the Sankey energy flow diagram, which can be accessed in the web version of the DECC Pathways software by following the 'see implications' and 'energy flows' links. (A printed version of this diagram, in which the numerical values for the flows do not appear, can be seen in Annex 2). The figures underlying the Sankey diagrams are approximately the same as those generated in the Excel version: the various minor differences are explained in Annex 1.

It will be seen that a total of 332 TWh/y (38 GWav) of the primary energy is in the form of UK land bio-energy and/or agricultural and other organic wastes. This implies a rather significant shift in land use within the UK, since some 10% of UK land will have to be dedicated to this purpose. We argue here that this change of land use can be accommodated by reducing the amount of livestock by 20% and shifting towards a healthier diet, incorporating less animal fat. Such a shift can in any case be anticipated as a response to the predicted rise in the carbon price, which will force farmers to increase their prices for dairy and meat products, thereby reducing sales and encouraging them to shift to the very profitable alternatives of carbon sequestering and biofuel crop production.

Table 5.7 Energy flows for the High Renewables Pathway in 2050

Figures in TWh/y				End uses of energy in all forms (and electrical only)		
Pumped heat	62	**Inputs to electricity generation**			All forms	Electrical
Solar	76	Solar PV	30	Heating&cooling homes	253	24
Wind	381	Wind	381	Heating&cooling comm	80	10
Tidal/wave/hydro/geothermal	117	Tidal/wave/hydro/geothermal	117	Lighting&Appliances homes	53	46
Electricity imports	70	Electricity imports	70	Lighting&Appliances comm	58	51
Nuclear	0	Nuclear	0	Industry	347	202
Coal reserves/imports	2	Solid/gas fuel & CHP electricity	65	Road transport (incl H2)	90	50
Oil reserves/imports	336	Thermal generation & DH adjustment		Rail transport	12	12
Gas reserves/imports	110	Electric Sub-Total	**663**	Domestic aviation	14	
Biofuel imports	0	**Inputs not used for electricity generation**		International aviation	131	
Biomass imports	0	Solid & gaseous fuel direct	125	National navigation	34	
UK land bioenergy	182	Ditto via CHP/DH thermal	151	International shipping	29	
Agricultural/other waste/algae	150.2	Liquid fuel (oil & biofuel)	337	Agriculture	11	4
		Solar th & pumped heat	108	Overproduction/exports	243	234
Total	**1486.2**	Non-electric process losses	54	Losses (incl transmission)	85	30
		Non-electric Sub-Total	**775**			
		Total electric+non-electric	**1438**	**Total**	**1438**	663

Figures in GWav				End uses of energy in all forms (and electrical only)		
Pumped heat	7	**Inputs to electricity generation**			All forms	Electrical
Solar	9	Solar PV	3	Heating&cooling homes	29	3
Wind	43	Wind	43	Heating&cooling comm	9	1
Tidal/wave/hydro/geothermal	13	Tidal/wave/hydro/geothermal	13	Lighting&Appliances homes	6	5
Electricity imports	8	Electricity imports	8	Lighting&Appliances comm	7	6
Nuclear	0	Nuclear	0	Industry	40	23
Coal reserves/imports	0	Solid & gaseous fuel & CHP ele	7	Road transport	10	6
Oil reserves/imports	38	Thermal generation & DH adjus	0	Rail transport	1	1
Gas reserves/imports	13	Electric sub-total	**76**	Domestic aviation	2	0
Biofuel imports	0	**Inputs not used for electricity**		International aviation	15	0
Biomass imports	0	Solid & gaseous fuel direct	14	National navigation	4	0
UK land bioenergy	21	Ditto via CHP/DH thermal	17	International shipping	3	0
Agricultural/other waste/algae	17	Liquid fuel (oil & biofuel)	38	Agriculture	1	0
	0	Solar th & pumped heat	12	Overproduction/exports	28	27
Total	170	Non-electric process losses	6	Losses	10	3
		Non-electric Sub-Total	88			
		Total electric+non-electric	**164**	Total	164	76

Electricity production accounts for less than half of the total primary energy supplied. Of the non-electric usage, 337 TWh/y (38 GWav) of the fuel is oil used for transport, other than rail which is all electric, and the remainder is largely in the form of heat for domestic, commercial and industrial purposes. Most of the exported energy (243 TWh/y) is in the form of electricity, though 9 TWh/y is in the form of bio-solids. The losses amount to about 85 TWh/y, (30 TWh from electricity distribution and 56 TWh from CHP) though the total figure is subject to some uncertainty (see Annex 1).

Although it is roughly in line with the government's new Bioenergy Strategy (DECC/DEFRA/DfT)[137], the relatively heavy reliance on biomass in our scenario could be reduced if other renewables develop in time. For example, as noted earlier, geothermal heat and power could well become available on a significant scale. Nonetheless, biomass does offer a more direct route to biofuel production for transport than wind to green gas/fuels conversion, so it would make more sense to use any extra geothermal electricity and heat to enable biomass to be used to produce biofuels for transport. If, despite improvements in biomass energy production/conversion efficiency, UK land-use becomes an issue, we could import biomass/biofuels, but that option has been avoided in our scenario.

5.4.4 Emissions figures for the High Renewables Pathway

The emissions reductions projected by our selected Pathway are given in Table 5.8.

Table 5.8 Modelled emissions, by sector, net of capture, $MtCO_2e/y$

Sector	2010	2030	2050	% of 1990 baseline
I. Hydrocarbon power generation	184	1	1	0%
V. Bioenergy	-11	-54	-73	-10%
VI. Agriculture & waste	61	51	36	5%
IX. Heating	84	73	71	9%
X. Lighting & appliances	3	3	3	0%
XI. Industry	89	61	31	4%
XII. Transport	173	97	63	8%
XV. Fossil fuel production	31	13	10	1%
XVI. Transfers	4	1	0	0%
Total	**618**	**246**	**142**	**18%**
Percentage of 1990 baseline	79%	31%	18%	

Source: Intermediate tab lines 158-175. For baseline figure (783.1), see ref. 15

5.5 Pathway robustness and extensions

The Pathways 2050 software has a built-in 'stress test' to see if each scenario can cope with a five-day temperature of -1.4 °C with reduced variable renewables throughout the period (see Section 3.6.2). The DECC assessment of the balancing/standby power and energy available in this Pathway during the five-day shock is shown in Table 5.9:

[137] DECC/DEFRA/DfT (2012) 'UK Bioenergy Strategy', Department. of Energy and Climate Change, Department for Environment, Food and Rural Affairs, Department for Transport, London
http://www.decc.gov.uk/en/content/cms/meeting_energy/bioenergy/strategy/strategy.aspx

Table 5.9: Balancing/standby power & energy available to cover shock in 2050

Action	GWe	TWhe
Halt exports	26.9	3.2
Boost thermal plant	0.1	0.0
Draw from interconnector	15.0	1.4
Shift demand from electric vehicles	2.6	0.3
Draw from pumped storage	7.0	0.1
Totals	**51.6**	**5.0**

Source: *tab VII.c lines 239-255*

The computed shortfall in power and energy during the hypothetical shock are 32 GWe and 3.8 TWh/y respectively (see tab VIIa lines 290 and 301) so that no more than 62% of the available balancing power and 76% of the balancing energy will be called upon to cope with the defined shock. Therefore, at least after 2035, no standby generators need to be included in the list of electricity generators to provide shock resistance.

In addition to the options shown in Table 5.9, there are a range of possible extra backup options, should they be needed. For example, there is currently around 20 GW of off-grid standby emergency generation in institutions around the UK. It is currently fossil-fuel-fired, but some could be grid linked and converted to green gas/ fuel use for occasional back-up duties. There is also a large amount of unexploited off-grid capacity in the hands of industrial and commercial energy users which could be linked in for use as backup at peak periods[138]. If backup still proved to be a problem, use could be made of further electricity storage capacity, including hydrogen storage. As Table 5.9 shows, our Pathway only has 7 GW of pumped storage (Level 3): choosing Level 4 would have provided 20 GW.

Our Pathway is clearly based on high contributions from the main renewables, and there could be problems in achieving the targets we have set. For example, the ‘floating’ variant of offshore wind technology may not turn out to be as successful as hoped: 96 GWn of the 156 GWn of offshore wind assumed by Pöyry was based on floating wind systems and our DECC Pathways 2050 choices have the effect that from 2035 half the offshore turbines constructed each year will be floating ones. If that proves to be a problem, then the wind contribution in our scenario could be reduced. The main consequence would be to reduce the potential for net electricity export, albeit with fewer balancing challenges.

Another possible problem might be land-use constraints on the production of biomass, although our case argued above indicates otherwise. In particular, the model predicts that there will be improvements in biomass yield intensities, which will steadily deliver more energy from less land[139].

It should be noted that our selection of renewable contributions does not exhaust their full potential. If some contributions prove to be smaller than expected, then contributions from other sources might take over. For example, the potential for wave and tidal stream generation may be significantly larger than we have assumed in our Pathway, as could be the potential for PV solar. Deep geothermal may also be able to contribute much more than we have indicated, which would increase balancing options and enable biomass to be diverted away from electricity generation towards vehicle fuel production to displace oil and gas.

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[138] Flexitricity (2012) Flexitricty, Edinburgh http://www.flexitricity.com

[139] Ecofys (2010) ‘Evaluation of improvements in end-conversion efficiency for bioenergy production’, Ecofys Consultants report to the European Commission http://ec.europa.eu/energy/renewables/bioenergy/doc/2010_02_25_report_conversion_efficiency.pdf

While we included some small barrages and lagoons in our mix, we have avoided reliance on the Severn Tidal Barrage, in part due to concerns about the potential environmental impact of this large (perhaps 8 GWn) project. However new technologies may emerge which could reduce this, for example, VerdErg's SMEC low-impact venturi turbine concept[140]. By 2050 there may also be sufficient hydrogen storage capacity to cope with the fact that a major barrage would produce large cyclic bursts of energy, which would often be out of phase with demand. A major storage facility, although expensive, would of course also help with balancing generally, allowing an expansion in the use of other variable renewable sources. Overall then, there would seem to be adequate additional options, if some of the technology selections in our Pathway prove to be insufficient.

We recognise that the Pathway which we are proposing here does not quite reach the ultimate objective of achieving a 100% renewables scenario. This is in part because the DECC model will not allow us to eliminate oil and gas by the use of green gases and fuels produced from excess wind-derived electricity, for which there is a clear potential. The Pőyry scenario reached 94 % of electricity, and an extension using green gas could take it to 100% of all energy. Clearly, if we want to achieve 100% renewables using only national sources, transport fuels, and aviation fuels in particular, are an issue. One possible approach would be to use more of the large offshore wind input to make biofuels or alternatively we might look to imports of biofuels and possibly biogas. There have been some interesting proposals for biogas and biofuel production from algae and other biomass using solar greenhouse projects in desert areas, which might be worth exploring (see, for example, the Sahara Forest project[141]).

5.6 Economic issues

Economic studies of possible pathways to 2050 are still at a very early stage, and it would be unwise to put too much emphasis on the conclusions that have been drawn so far. As we have seen in Section 1 above, the UK government has hitherto shown some reluctance to make pronouncements on the relative costs of the various energy policy options that it has considered, preferring to 'leave it to the market to decide'. However, in recent years, it has commissioned several studies which have considered the economics of various renewable technologies. In particular, the studies by Mott MacDonald described in Section 5.3.1 developed a methodology for comparing the 'levelised cost' of various energy supply options between now and 2050. They concluded that nuclear and onshore wind energy have broadly comparable costs at present (in the range £83-98/MWh) and that these two technologies would remain similarly comparable at least until 2040. By then the absolute cost was estimated to have decreased to £51-61/MWh.

Their work stimulated DECC to undertake work in-house to produce more elaborate estimates, and this has culminated in the publication by DECC of the version of its software which we are now using. Their software unfortunately does not present results in a manner which permits an immediate comparison with the work of Mott MacDonald, and its estimates have a significantly broader range of uncertainty than the earlier work. However, for each complete Pathway, the DECC software offers a 'low', 'point', and 'high' estimate for the total cost (made up of separate figures for the capital, operating and fuel components of the total cost for each quinquennium between now and 2050) and also an annual cost per capita of the UK population over that period. Their figures will be discussed in more detail in Section 7.7, but the immediate

[140] VerdErg (2012) Spectral Marine Energy Converter (SMEC) www.verderg.com/attachments/-01_SMEC_Doc_Oct%2009.pdf /
[141] Sahara Forest (2012) Solar Greenhouse biomass/food/energy production projects in Jordan and Qatar: www.saharaforestproject.com See also http://environmentalresearchweb.org/blog/2011/01/a-bio-energy-future.html

conclusion is that all three Pathways considered in this report have a broadly similar annual cost per capita, and that the range of uncertainty for each estimate is significantly greater than the differences between them. This conclusion is in line with another recent study, by the US National Renewable Energy Laboratory (NREL), which has looked at scenarios with up to 90% of electricity supplied by renewables by 2050. It concluded that "the direct incremental cost associated with high renewable generation is comparable to published cost estimates of other clean energy scenarios"[142].

5.7 International comparisons

In this section, we look at how the issues discussed above have been playing out in practice in some of the new programmes around the world that rely heavily on renewables.

Although it is part of the UK, **Scotland** has a devolved government which has developed and followed its own distinctive energy policy. Over a third of its electricity use is already matched from renewables, reaching around 35% in 2011[143], and it has ambitious targets for expansion (see Table 5.10).

Table 5.10: Scottish Electricity Generation Output (TWh/y)

TWh	**2010**	**2015**	**2020**	**2030**
Fossil Fuels	19	14	8	0
Fossil Fuels with CCS	0	0	3	13
Nuclear	16	16	9	0
Other thermal	0.9	0.2	0.2	0.2
Pumped Storage	1.2	1.2	2	2
Biomass	0.4	0.7	0.9	1.2
Hydro	2	2	2	3
Offshore and Onshore Wind	6	15	36	46
Tidal and Wave	0	1	1.6	4
Other renewables	0.6	0.6	0.6	0.6
Total	**46**	**51**	**64**	**69**
Renewables as % total gross electricity consumption	24%	49%	102%	128%

Source: Scottish Generation Scenarios and Power Flows, SKM, Jan 2012 p.37[144]

It is aiming to match 100% of its electricity consumption from renewables by 2020, and it plans to maintain much of its existing generation fleet, for balancing and for export, with CCS for around 2.5 GW of fossil plant. Its forecasts for demand reduction are quite modest – 12% by 2020. However it plans to obtain 30% of its total energy from renewables by 2020, with renewables supplying 11% of heat by then, mainly from

[142] NERL (2012) 'The Renewable Electricity Futures Study', National Renewable Energy Laboratory (NREL), Colorado http://www.nrel.gov/analysis/re_futures/
[143] Scottish Government (2012a) 'Scotland beats 2011 green energy target,' March http://www.scotland.gov.uk/News/Releases/2012/03/geenenergytargets29032012
[144] Scottish Government (2012b) 'Electricity Generation Policy Statement', The Scottish Government, Edinburgh, March http://www.scotland.gov.uk/Topics/Business-Industry/Energy/EGPS2012/DraftEPGS2012

biomass-fired CHP[145]. By 2030 it aims to be 'largely decarbonised', and to have phased out nuclear generation altogether. To complete the decarbonisation process in the years following 2030, it will presumably seek to expand renewable heat supply, as well as developing strategies for transport fuel, possibly using excess wind, wave and/or tidal energy, along the lines suggested above for the UK as a whole. So its overall approach is broadly similar to that proposed here for the UK as a whole.

Germany aims to get 80% of its electricity from renewables by 2050, though it is only expecting to be able to get 60% of its total energy from renewables by then, despite a 50% reduction in energy demand. Given that it does not have the very large offshore wind (and wave /tidal) potential available to the UK, that is perhaps not surprising, and its current aspirations are more modest than those proposed here for the UK. More radical scenarios for Germany suggest that it could get to 100% of electricity from renewables by 2050[146]. Moreover, even given that Germany's official target is only 80%, the UK may have much to learn from its experience of phasing out nuclear while expanding renewables. Extensive information about 'Germany's nuclear exit' can be found in the current issue of the *Bulletin of Atomic Scientists*[147].

Denmark is aiming to obtain all its power and heat from renewables by 2030, and to be 'zero carbon' by 2050. It has the advantage of not having to phase out, or replace, nuclear plants, and its renewable heat supply programme is much further advanced than that in the UK. Nevertheless it might also be seen as a template for what the UK might do.

5.8 Conclusions

1. This chapter has shown that the UK enjoys the largest renewable resource in Europe. A number of studies have shown that this resource could be used to reduce UK GHG emissions to below 20% of their 1990 levels. The High Renewables Pathway exhibits one specific strategy which achieves this reduction.

2. In the High Renewables Pathway energy <u>demand</u> is reduced by 41% by 2050, and this makes a significant contribution to the achievement of the emissions target.

3. The High Renewables Pathway also meets the UK's intermediate target of achieving a 50% reduction of GHG emissions by 2027. Early reductions are important since climate modelling has indicated that a critical parameter is cumulative emissions. If early reduction targets are not met, it can become impossible to stay within the predicted safe cumulative limit.

4. The High Renewables Pathway incurs much lower conversion and transmission losses than those of the other two Pathways, thereby largely avoiding the need for cooling water.

5. Our Pathway addresses the need to manage the intermittency inherent in renewable energy generation by having significant surplus electricity generating capacity When the weather is ideal, surplus electricity is exported, and earns around £15b p a by 2050. When weather conditions are adverse, this potential surplus is diverted back to the home market. Further energy balancing is ensured by demand management via smart metering, dynamic demand and exchanges between electric vehicles and grid. These measures ensure that by 2050 no back-up plant will be required.

[145] Scottish Government (2011) 'Routemap for Renewable Energy in Scotland 2011', The Scottish Government, Edinburgh, June http://www.scotland.gov.uk/Publications/2011/08/04110353/0
[146] http://environmentalresearchweb.org/blog/2012/02/can-germany-do-it.html
[147] *Bulletin of the Atomic Scientists* (2012) Vol. 68, No. 6, pp. 6-9, November/December

6. Our Pathway has a substantial bio-energy component, made possible by changes in agricultural practice involving improved land use and reduction of livestock. The implied reduction in human consumption of animal fats will results in an improvement in most people’s health. The diversion of 10% of land to the sustainable production of bio-energy will contribute 182 TWh/y (15%) to the energy budget. Utilisation of agricultural wastes will contribute a further 120 TWh/y (10%) and wastes from the rest of the economy a further 30 TWh/y (2.5%). No bio-energy imports will be required, thereby avoiding competition with food production in other countries.

7. Substantial changes are planned in the provision of heat for buildings – 43% by CHP and district heating, 14% by solar hot water, 14% from bio-energy and 19% by electric heat pumps. Major changes are also envisaged for transport – 56% of road and 100% of rail transport will be electrified.

8. Had the Pathways software allowed, we would have retained a proportion of the exported electricity to generate green gases for use in road vehicles and despatchable electricity generation. Such techniques could permit the UK to attain the zero carbon objective UK by 2050 if not before.

6 Presentation by the champion of the 'Intermediate Pathway'

Drafted by Ian Crossland

6.1 Introduction and overview

The purpose of this chapter is to develop a middle way between a 100% renewables approach and one that relies predominantly on nuclear power. One of the aims is to create a system that combines diverse sources of energy, and thereby offers a degree of flexibility with a greater ability to withstand external shocks. We can envisage, for example, that such a system will facilitate frequency control and black start capability (i.e. an ability to re-start without a connection to the network), and will be robust with respect to fuel or component price changes. A very important consideration in the design of this Intermediate Pathway has been the need to avoid heroic assumptions about what can be achieved within a 40-year period, either as regards future energy demand or technological development. That said, any strategy will carry some risks, and one of the aims of this chapter is to identify where these lie. In this chapter, we do not attempt to discuss which of the technological variants of CCS described in Section 3.4 will be adopted.

6.1.1 Pathway targets

In developing the proposed Pathway we have focused on the 2050 endpoint. The targets that we have attempted to meet by this date are:

- an 80% (or more) reduction in GHG emissions
- a limit on standby electrical generating capacity to less than 10% of the total
- flexibility and security through the use of roughly equal amounts of nuclear, conventional thermal generation with CCS and renewables
- wildlife habitat conservation (no tidal range or marine algae schemes)
- a focus on energy sources that promise to offer cost-effective energy delivery on a large scale to avoid dissipation of effort.

The above targets do not, of course, determine the Pathway, and in defining one specific 'Intermediate Pathway', it is necessary to make a large number of choices. In doing so, we have been guided by the over-riding requirement that the Pathway should be credible, given our actual starting position and the rate at which the UK could plausibly move forward from that. Section 6.2 describes the choices that were made to construct our proposed Intermediate Pathway and, where the choice does not naturally flow from the principles just outlined, to provide justification. The process has been strongly influenced by, and developed in the context of, the DECC Pathways software[148] and background[149], which present the various decisions in a structured way. In Section 6.3 we describe the three main energy sources that we have selected: nuclear, CCS and renewables. Section 6.4 considers the robustness of the Pathway and Section 6.5 sets out the conclusions.

[148] Department of Energy and Climate Change website, with links to both Excel and Web versions of the 2050 Pathways Calculator: http://www.decc.gov.uk/en/content/cms/tackling/2050/2050.aspx

[149] http://2050-calculator-tool.decc.gov.uk/assets/onepage/*.pdf (where *=the number of the heading) or http://2050-wiki.greenonblack.com/pages/72 etc

6.2 Considerations leading to the specification of the proposed Pathway

The initial stage in planning an Intermediate Pathway is to estimate future energy requirements and, more specifically, the demand for electrical energy between now and 2050, taking account of plausible developments in technology and public policy during that period. The next step is to produce a corresponding set of figures for the mix of sources which will supply energy to meet that demand. This planning process can be systematised by using the 43 input Headings of the DECC Pathways Calculator software (see Section 3.5), of which about half relate to energy demand, and the other half to supply. In both cases, in choosing values for these 43 parameters, our principal consideration has been to avoid over-ambitious choices: other arguments that have guided our demand choices are set out in Section 6.2.1 (for overall energy demand) and in Section 6.2.3 (for specifically electrical energy demand). The corresponding choices for overall energy supply and specifically electrical supply are explained in sections 6.2.2 and 6.2.4. The 43 inputs which we have selected for the Intermediate Pathway are brought together in Table 3.2 and can be viewed on the web interface at[150].

6.2.1 Overall energy demand

In line with the 'moderation in all things' approach described in Section 6.1, we rejected all changes in demand patterns that "could be achieved with effort at the extreme upper end of what is thought to be physically plausible by the most optimistic observer" (the definition given by DECC for the Level 4 options in its Calculator). We also generally sought to avoid changes at Level 3 (i.e. changes which "might be achieved by applying a very ambitious level of effort, that is unlikely to happen without significant change from the current system, and which would involve significant technological breakthroughs"). In consequence, most of our demand choices were at Levels 1 or 2, and were made with the overall aim of maintaining credibility by avoiding, wherever possible, potentially over-ambitious targets. Thus Level 2, under the heading of "domestic transport behaviour", allows that in 2050 each of us will travel 900 km further than in 2007. 80% of this is by road (i.e. private transport), 6% by rail, 9% by bus, 2% on foot, 2% by air and 0.7% by bicycle. Compared to the present day, this represents a 1.5% increase in distance travelled and roughly a 5% shift from road to bus[151]. Similarly, under the heading of "average temperature of homes" an increase from 17.5°C in 2007 to 18°C in 2050 is envisaged together with a rise in energy consumption for cooling, from near zero to 31 TWh/y (3.5 GWav). Industrial growth was assumed to continue at the recent historic rate, producing an increase of 30% by 2050. These and the other Level 2 changes may be described as modestly ambitious and eminently achievable.

However, in order to achieve significant reductions in overall energy demand, four choices were made at Level 3 namely:

- Shift to zero emission vehicles
- Domestic freight
- Home insulation
- Energy intensity of industry.

The first of these assumes, by 2050, an almost 50% penetration by zero emission vehicles; the second assumes a 10% drop in goods-movements per person, lower emissions per lorry-mile and increased use of

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[150] http://2050-calculator-tool.decc.gov.uk/pathways/2023d211111212120223122002313220233302202302430220133

[151] Department for Transport, National Travel Survey2008/09, dataset NTS9904, 6 Oct 2011, http://www.dft.gov.uk/statistics?tag=distance-travelled%2C+personal-travel (migrated to National Archives)

rail; the third envisages a wide roll-out of home insulation measures, including 18 million homes with extra loft insulation (three times as many as under Level 1). This choice produces a relatively small decrease in emissions of around 1 Mt CO_2 per year but it also has the effect of reducing peak electricity demand so that the required amount of standby generation is constrained. The fourth, and most beneficial in terms of energy savings, is the Level 3 choice for the energy intensity of industry. According to the help page for this heading[152], this assumes:

- a 40% improvement in the energy efficiency of industry
- 25% reduction in process emissions
- 66% of industrial energy demand is met by electricity.

CCS is rolled out quickly after 2025 so that, by 2050, about half of industrial emissions are captured including 80% of emissions from steel, ammonia and cement plants.

These decisions led to the demand-related input values shown in Table 3.1. The Calculator has its own default assumptions about the phasing of changes in energy demand between 2010 and 2050, and using the demand inputs of Table 3.1, it produces the figures shown in Table 6.1 for energy demand changes between 2010 and 2050 grouped into five demand sectors.

Table 6.1 Total energy demand in the Intermediate Pathway

	2010		**2030**		**2050**	
	TWh/y	**GWav**	**TWh/y**	**GWav**	**TWh/y**	**GWav**
Transport	702	80	511	58	483	55
Industry	516	59	398	45	347	40
Heating and cooling	506	58	462	53	473	54
Lighting & appliances	171	20	172	20	185	21
Agriculture	11	1	11	1	11	1
Total Use	**1905**	**218**	**1553**	**177**	**1499**	**171**
Percentage of 2010 level	100%		82%		79%	

Source: Flows tab of DECC Calculator lines 24-92

It will be seen that overall energy demand falls by 21% over the planning period, which we regard as reasonably attainable.

6.2.2 Primary energy supply

To meet this demand for energy, there is a very wide range of possible supply options. In making our choices, we have been guided by the principles set out in Section 6.1.1, in particular, aiming for a roughly equal balance of nuclear, CCS and renewables and avoiding over-ambitious targets. Level 2 choices were made for

- nuclear power

[152] DECC Calculator website, http://2050-calculator-tool.decc.gov.uk/assets/onepage/38.pdf
Also accessible from the Web version of the Calculator by clicking on the ‘Energy Intensity of Industry’ heading on the home page

- CCS power stations
- onshore wind
- solar panels for hot water
- hydroelectric power stations
- electricity imports
- land dedicated to bioenergy crops
- livestock and their management
- bioenergy imports.

Only two Level 3 choices were made. One was for “storage, demand shifting and interconnection”. The aim of this was to facilitate meeting peaks in electricity demand, and to have alternative sources to hand in case of breakdowns or low wind/high demand conditions. A benefit of this choice is that it becomes possible to have a greater contribution from wind power without needing to build an almost equal amount of stand-by generation that may only be needed for a few days each year. A disadvantage is increased system complexity, and hence potentiality for failure.

The other Level 3 choice related to “volume of waste & recycling”, which was set at trajectory C (equivalent to Level 3), meaning that the volume of waste increases by only 13% between 2007 and 2050, but recycling and waste management improve significantly, creating a further 59 TWh/y (6.7 GWav) of primary energy. Such a strategy places most of the burden of improvement on the waste management industry, rather than attempting to change people’s behaviour.

These choices produce a balanced mix of nuclear, carbon capture and renewables. Other potential sources were rejected, largely because of the need to avoid over-extension of resources, not least technical staff. The precise choices for input to the Calculator are shown in Table 3.2 and the Calculator’s default assumptions were accepted for the phasing over years. For example, the first new build nuclear power station is assumed to be operational by 2025, and the number of stations then increases linearly with time, at a rate which is about half what was achieved in France during the 1980s (see Figure 3.1). CCS build is envisaged as a two-stage process starting with a small number of pilots, the first of which is in operation by 2015, followed by a roll-out of commercial plant from about 2022 onwards so that generating capacity reaches the required level in 2050. Renewable energy grows relatively fast from its current low base up to about 2030 and then stabilises. These aspects are further discussed in Section 6.4.

With these choices, primary energy supply (i.e. including the energy supplied but subsequently lost during the conversion of heat to electricity) breaks down into the categories shown in Table 6.2. This shows that in 2050, nuclear supplies 36% of primary energy, renewables 27% and fossil fuel (both with and without carbon capture) 37% respectively. Renewables include solar heat, wind, hydro, environmental heat and biomass, with the last two items respectively providing 39 and 38% of the total. It is notable that, while energy demand falls by 21% over the period 2010-40 (Table 6.1), primary energy production falls by only 7%. This is because electrification of energy supply introduces additional losses from waste heat.

Note that ‘environmental heat’ is energy removed from the environment by heat pumps and ‘biomass’ includes waste, agriculture and import**s.** Where coal, natural gas and biomass are used for large-scale electricity production, they are combined with CCS.

Table 6.2 Breakdown of primary energy supply in 2010, 2020, 2030 and 2050

	2010			2020			2030			2050		
Primary energy source	TWh/y	GWav	%	TWh/y	GWav	%	TWh/y	GWav	%	TWh/y	GWav	%
Nuclear	161	18	6	146	17	6	351	40	17	840	96	36
Solar	1	0	0	4	0	0	8	1	0	19	2	1
Wind	16	2	1	68	8	3	122	14	6	124	14	5
Tidal & wave	0	0	0	0	0	0	1	0.5	0	0	0	0
Hydro	5	1	0	6	1	0	6	1	0	7	1	0
Envir'l heat	0	0	0	33	4	1	98	11	5	248	28	11
Biomass	56	6	2	124	14	5	160	18	8	240	27	10
Coal	457	52	18	281	32	12	48	5	2	84	10	4
Oil products	855	98	34	759	87	33	564	65	27	477	55	21
Natural gas	954	109	38	848	99	38	720	84	35	295	34	13
Electricity losses/imports	0	0	0	3	0	0	10	1	0	30	3	0
Total Primary Supply	**2504**	**286**	**100**	**2271**	**262**	**100**	**2088**	**240**	**100**	**2364**	**270**	**100**
Percentage of 2010 value	100%			91%			83%			94%		

Source: Flows tab lines 6-95

6.2.3 Electricity demand

The choices made in terms of future energy demand (Section 6.2.1) lead inexorably to electrification of energy supply. This, when coupled with the decarbonisation of electricity generation, is an important tool for reducing GHG emissions. The electricity demand that results from these decisions is shown in Table 6.3. This uses the same four categories of use as Table 6.1 and indicates that electricity demand increases by 73% over the period 2010 to 2050 consequent upon a switch to electric vehicles, electric heating and so on.

Table 6.3 Breakdown of electricity demand in 2010, 2030 and 2050

	2010		2030		2050	
	TWh/y	GWav	TWh/y	GWav	TWh/y	GWav
Transport	8	0.9	43	5.0	60	6.9
Industry	128	14.6	157	17.9	202	23.0
Heating and cooling	56	6.4	90	10.3	156	17.8
Lighting & appliances	155	17.7	164	18.7	185	21.1
Agriculture	4	0.5	4		5	
Total	**351**	**40.1**	**458**	**52.3**	**607**	**69.3**
Percentage of total in 2010	100		130		173	

Source: Flows tab lines 6-95

6.2.4 Electricity supply

Electricity generation needs to be greater than demand because of usage at the site of production and transmission losses. The mix of electricity generators is a consequence of the choices described in Section 6.2.2, producing the results shown in Table 6.4 below. This indicates that as electricity supply increases over the period 2010 to 2050, CCS progressively replaces unabated fossil-fuel generation, while nuclear and renewables meet the increase in demand. Nuclear power and CCS between them provide 77% of the total electricity generated, with renewable sources and imports (also from renewable sources) contributing the remainder. The reduced contribution of renewables to electricity production (23%), compared to their contribution to primary energy (27%), may seem surprising given that waste heat dominates primary energy values for non-renewable generators. The reason is that environmental heat, which does not contribute to electricity production, is the single largest component of renewable primary energy in this Pathway.

Table 6.4 Breakdown of annual electricity supply in 2010, 2030 and 2050

	2010		**2030**		**2050**	
	TWh/y	GWav	TWh/y	GWav	TWh/y	GWav
Unabated thermal generation	305.4	34.8	177.0	20.3	0.0	0.0
Carbon Capture Storage (CCS)	0.0	0.0	61.3	7.5	257.3	29.4
Nuclear power	52.6	6.0	115.0	13.1	274.9	31.4
Renewables (total)	20.9	2.4	128.4	14.7	130.7	14.9
Onshore wind	11.5	1.3	52.7	6.0	52.7	6.0
Offshore wind	4.1	0.5	68.9	7.9	71.0	8.1
Hydroelectric	5.3	0.6	6.3	0.7	7.0	0.8
Tidal and Wave	0.0	0.0	0.5	0.1	0.0	0.0
Electricity imports	0.0	0.0	9.9	1.1	30.0	3.4
Total generation supplied to grid	**379.0**	**43.2**	**491.6**	**56.7**	**692.8**	**79.1**
Percentage of 2010	100		131		183	

Source: lines 95-111 of Intermediate Output of Excel Calculator for all rows except CCS which comes from a combination of the Flows tab and the Intermediate Output tab

In terms of installed electricity capacity, the Intermediate Pathway produces an equal three-way split between, nuclear, CCS and wind: all provide about 40 GW (Table 6.5). On top of this there is (in 2050) about 11 GW of standby provided by unabated gas. A decision was taken at the outset to try to limit standby capacity to about 10% of the total. Three main factors that help to achieve this are:

- maximising storage, demand shifting and interconnection
- avoidance of over-reliance on wind power
- large thermal and nuclear capacity whose output can be increased marginally (at the request of grid control) when there is a shortage.

In addition, the Intermediate Pathway has an inbuilt over-capacity of about 5 GWe in 2050 (but none in earlier years). The Calculator assumes that this is normally exported abroad (via the interconnectors) but can be put to UK use at times of stress.

Table 6.5 Installed electricity generation in 2010, 2030 and 2050

GW installed capacity	2010	2020	2030	2050
Unabated thermal generation				
Oil / Biofuel	4.1	0.0	0.0	0.0
Coal / Biomass	28.1	17.1	1.8	0.0
Gas / Biogas	26.6	29.9	27.0	0.0
Carbon Capture Storage (CCS)	0.0	1.7	10.1	40.1
Nuclear power (GWe)	10.0	6.8	16.4	39.2
Renewables				
Onshore wind	4.4	14.4	20.0	20.0
Offshore wind	1.3	9.2	18.3	18.0
Hydroelectric	1.6	1.8	1.9	2.1
Wave	0.0	0.1	0.2	0.0
Renewables subtotal	7.3	25.5	40.5	40.1
`Standby / peaking gas	0.0	0.0	2.7	10.9
Total generation	**76.1**	**80.9**	**98.6**	**130.3**

Source: Intermediate Output spreadsheet of DECC Calculator lines 116-132

6.2.5 Greenhouse gas emissions

Using the choices described above, the DECC Calculator estimates that GHG emissions will fall by 80% of 1990 levels to 155 Mt per year (Table 6.6). Fuel combustion is the largest single contributor but this is greatly offset by CCS and bioenergy credit. If these two are conflated, international aviation & shipping and agriculture have the most significant emissions.

Table 6.6 Greenhouse gas emissions in 2010, 2030 and 2050 by IPCC sectors

IPCC Sector Mt CO_2e	2010	2030	2050
Fuel Combustion	512.4	273	196.5
Industrial Processes	26.3	19	14
Agriculture	42.3	38.5	38
Land Use, Land-Use Change and Forestry	2.6	12	7
Waste	15.2	7.5	4
International Aviation and Shipping	46.5	62	70
Bioenergy credit	(11)	(36)	(59)
Carbon capture	-	(31)	(116)
Total	**634.5**	**345.1**	**155**
Percentage of baseline 1990 value	81%	44%	20%

Source: DECC Calculator tabs for 2010, 2030 and 2050 line 109

6.3 Credibility of the chosen technologies and timescales

6.3.1 Nuclear power

As Table 6.5 shows, the Intermediate Pathway proposes that by 2050 the UK's nuclear capacity will have increased four-fold compared to the 2010 level. By 2050, an installed nuclear capacity of 39 GWe is envisaged, with an assumed load factor of 80%, delivering an electrical output of 275 TWh/y (31.4 GWav). The DECC Calculator makes no assumptions about the type of nuclear stations involved, and nor do we. As indicated in Section 3.2, the almost certain outcome is a fleet of light water reactors that, by comparison with previous build rates in France and Japan, could be constructed within the required timescale. That said, the Intermediate Pathway assumes that the first reactor will be operational by about 2020 which is barely credible!

6.3.2 Carbon capture and storage (CCS)

With CCS set at Level 2 in the Calculator, the Intermediate Pathway assumes 900 MWe of installed capacity by 2015, 10.1 GW at 2030 and 40.1 GW at 2050[153]. There is no doubt that the 2015 target is over-optimistic: even Vattenfall, who are world leaders in this field, do not anticipate such a rapid start. At present they plan to follow up the Spremburg oxy-combustion pilot with a 250-350 MWe demonstration plant (probably around 2015) and to have a full-size commercial plant around 2020[154]. Failure to meet the 2015 target will, of course, increase the difficulty of reaching the later targets, so we might suppose that 10 GW will need to be installed in the years 2020 to 2029. This, we contend, remains feasible.

As regards the fuel for these CCS stations, the Calculator assumes that, provided that they are available, biofuels will always be used in preference to coal and natural gas and that UK-produced coal and natural gas will be used in preference to imported sources. Although biofuel represents a minor component of primary energy (see Table 6.7), it is very significant in achieving GHG targets because the combination of biofuel and CCS provides an important means of producing negative emissions. The amount of available biofuel is set by the choices made with respect to five headings shown (for 2050) in Table 6.7. These headings are explained and the numbers quoted in Table 6.7 are given in refs[155].

Table 6.7 Energy supplied by the various biofuel options in the DECC Calculator (*Those chosen for the Intermediate Pathway are shown by the shaded cells)*

Heading (energy source)	Energy supplied TWh/y (GWav) in 2050			
	Level 1	Level 2	Level 3	Level 4
Land dedicated to bioenergy	55 (6.3)	117 (13.3)	324 (37.0)	545 (62.2)
Livestock and their management	55 (6.3)	48 (5.5)	46 (5.2)	43 (4.9)
Volume of waste and its recycling	55 (6.3)	59 (6.7)	59 (6.7)	30 (3.4)
Marine algae	0 (0)	4 (0.5)	9 (1.0)	46 (5.2)
Bioenergy imports	0 (0)	70 (8.0)	140 (16.0)	280 (31.9)

[153] DECC Calculator Line 121 of Intermediate Output table
[154] DECC Calculator website, http://www.vattenfall.com/en/ccs/index.htm?WT.ac=search_success
[155] DECC Calculator website, http://2050-calculator-tool.decc.gov.uk/assets/onepage/*.pdf, where * is replaced by15,16,17,18, or 20 respectively

Summing the energy values in the shaded cells in Table 6.7, the total energy from biofuels in the Intermediate Pathway is 294 TWh/y (33.5 GWav) which represents around 13% of primary energy supply (Table 6.2) in 2050. Further explanation of the five choices shown in Table 6.7 follows.

According to the Calculator, with "land dedicated to bioenergy" set at Level 2, UK energy crop production in 2050 would utilise around 5% of the total UK agricultural land area of 174,000 km^2, which would be a five-fold increase over the present day[156]. Only about one third[157] of this land is cropable, however, and while some pasture land may be suitable for growing, say, short-coppice willow, energy crops will nevertheless compete for land with food production. In the Calculator this issue is mitigated by an assumption that (for this Pathway) crop yield will increase by 0.9% year-on-year. Over 40 years this produces an overall increase of 43% but, against this, the same period sees a population increase of 23%. Moreover, the calculation makes no allowance for the view of Searchinger et al. [ref. 58] that biofuel production could increase greenhouse emissions, nor does the assumption of increased yields allow for the possibly deleterious impact of climate change. Consequently, a more conservative approach was thought to be necessary, leading to a Level 2 choice.

A Level 2 choice under the heading of "livestock and their management" assumes that livestock numbers remain constant through to 2050 but that, increasingly, manure is used to generate energy so that it contributes 48 TWh/y (5.5 GWav) in 2050[158].

Level 3 under the heading "volume of waste and recycling" assumes the volume of waste in 2050 to be 13% greater than in 2007; this is coupled with improved conversion to biofuel compared to the present day. An associated heading "types of fuels from biomass" (not shown in Table 6.7) dictates the fuel mix from these two sources. Level 2 was chosen corresponding to 33% coal/biomass and 66% natural gas/biogas that, when combined with the other choices, provides the most effective use of the fuel in terms of GHG emissions[159,160].

The Calculator assumes that "bioenergy imports" are equally split between solid and liquid forms as direct replacements for coal and oil respectively. The 70 TWh/y (8.0 GWav) imported in 2050 is a ten-fold increase on the present day and, based on the International Energy Agency's estimate of potential bioenergy production, it is equivalent to half the UK's "fair market share" of the available resource based on its population[161]. Again, a cautious approach makes some allowance for the views of Searchinger et al. [ref. 58].

CCS generates 265 TWh/y (30.2 GWav) of electricity (Table 6.4). Assuming a thermal efficiency of 35%, this is equivalent to a primary energy demand of about 760 TWh/y (87 GWav). If we allow that imported biomass, which represents half of bioenergy imports, and all the biofuel from the other sources in Table 6.7 are used for CCS electricity production, this produces a total of 259 TWh/y (29.5 GWav) – i.e. about 34% of the primary energy required for CCS electricity generation. The remainder comes from fossil fuels (chiefly natural gas and coal), much of which will be imported. The Calculator is largely silent on the source of these and, in particular, appears to ignore the possibility that unconventional gas (for example, shale gas) could

[156] DECC Calculator website, http://2050-calculator-tool.decc.gov.uk/assets/onepage/15.pdf
[157] DEFRA (2010) *Agriculture in the United Kingdom*, p.13 http://www.defra.gov.uk/statistics/files/defra-stats-foodfarm-crosscutting-auk-auk2010-110525.pdf
[158] DECC Calculator website, http://2050-calculator-tool.decc.gov.uk/assets/onepage/16.pdf
[159] DECC Calculator website, http://2050-calculator-tool.decc.gov.uk/assets/onepage/17.pdf
[160] DECC Calculator website, http://2050-calculator-tool.decc.gov.uk/assets/onepage/19.pdf
[161] DECC Calculator website, http://2050-calculator-tool.decc.gov.uk/assets/onepage/20.pdf

make a significant contribution. If it does then the issue of fugitive emissions, which are likely to be much greater than for conventional gas, will need to be resolved. A recent International Energy Agency publication[162] takes an optimistic view of this despite the dearth of reliable data.

6.3.3 Renewables

General approach

Our approach to selecting renewable generators for inclusion in the Intermediate Pathway was to opt for sources that were likely to deliver significant contributions to energy supply at reasonable cost with low emissions. This led us to ignore wave power, tidal stream, solar electricity, geothermal electricity and small-scale wind. Tidal range and marine algae schemes were rejected for similar reasons, but also because of environmental damage resulting from loss of habitat. Biomass power stations were also rejected because, without CCS, it was found to be too difficult to meet the GHG reductions target.

As shown by Table 6.2, the Intermediate Pathway focuses on five main renewable sources – namely environmental heat (i.e. heat pumps producing 39% of total renewable energy in 2050), biofuels and waste (38%), wind (19%), solar heat (3%) and hydro (1%). Renewables as a whole constitute 28% of total primary energy in 2050, which is more than an eight-fold increase over 2010 figures. The 2009 EU Renewable Energy Directive[163] requires Member States to implement policies that will allow 20% of EU energy to come from renewable sources by 2020. For the UK this entails a 15% contribution from renewables. Table 6.2 shows that, under the proposed Intermediate Pathway, this target would be missed – only 10% would come from renewable sources. This is further discussed in the following sub-sections.

In terms of renewable electricity-generating capacity in 2050, Table 6.5 shows 38 GWe from wind and 2.1 GWe from hydro. To this must be added 13.6 GWe, which is the proportion of CCS generation (34%) that comes from biofuels (discussed in Section 6.3.2). In terms of electricity produced (Table 6.4), this translates into 124 TWh/y (14 GWav) from wind, 7 TWh/y from hydro (0.8 GWav) and 90 TWh/y (10 GWav) from CCS making a total of 221 TWh/y (25 GWav). This figure, which comprises 31% of total 2050 electricity production, is more than a ten-fold increase over 2010.

Wind power

Table 6.5 shows wind generation capacity over the period 2010 to 2050 for the Intermediate Pathway. It reaches a peak in 2030 and then remains essentially unchanged through to 2050. As we have seen, there is a shortfall in meeting the 2009 EU Renewables Directive that amounts to a “missing” 109 TWh/y (12.4 GWav) of renewable energy. To meet this by building more offshore turbines would require additional capacity amounting to about 28 GWn (at 45% load factor) i.e. more than is planned for 2050. What this illustrates is that the 2020 EU target will be difficult to meet unless reductions in overall energy consumption and/or additional renewable sources go well beyond those embedded in our Intermediate Pathway.

The DECC Calculator model assumes that the minimum option for wind power (i.e. Level 1) should discontinue the use of the existing capacity at 2025 giving, as likely justification, the public concern over the loss of visual amenity for onshore wind and the current cost for offshore wind power. Because of the

[162] International Energy Agency (2012) *Golden Rules for a Golden Age of Gas* World Energy Outlook Special Report on Unconventional Gas, OECD/IEA, Paris, November http://www.worldenergyoutlook.org/goldenrules/

[163] Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC available at http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:140:0016:0062:EN:PDF accessed 10 June 2012

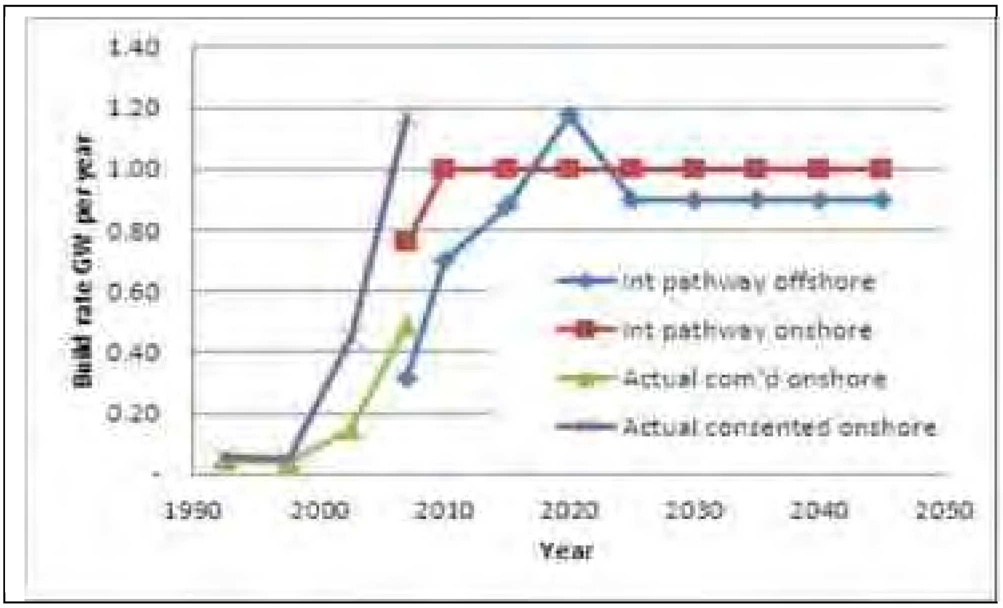
difficulty of accommodating wind generators with relatively inflexible producers such as nuclear power stations, there was a temptation to take this option and look for other renewable sources instead. Ultimately, however, we took the view that, where investments have already been made to create facilities, it is reasonable (especially offshore) to extend their life through to 2050. This led to the capacities and load factors shown in Table 6.8.

Table 6.8 Capacity and load factor for wind power between 2010 and 2050

Wind power	2010		2020		2030		2050	
	Capacity GWn	Load factor%	Capacit y GWn	Load factor%	Capacity GWn	Load factor%	Capacit y GWn	Load factor%
Onshore	4.4	30	14.4	30	20.0	30	20.0	30
Offshore	1.3	35	9.2	37	18.3	43	18.0	45

Allowing for retirements, this capacity profile requires the annual new build rates shown in Figure 6.4. A British Wind Industry Association (BWEA) publication provides figures for wind energy capacity – both consented and commissioned – between 1989 and 2009[164]. This shows that the rate of commissioning of new capacity and planning consents for future capacity have accelerated over the study period ("actual" data in Figure 6.4). The highest rates of commissioning were achieved for onshore wind in 2007-2009 when they reached about 0.5 GWn per year. Onshore consents, which appear to anticipate commissioning by three to four years, were running at about 1.2 GWn/year in the same period. On that basis, the build rates assumed by the Intermediate Pathway fall between those that actually occurred in 2007-2009 and what one might expect in the near future. Data for offshore wind are more limited but, in broad terms, indicate a similar pattern. This suggests that the wind capacities assumed by the Intermediate Pathway are feasible.

Figure 6.4 Annual new build rates of onshore and offshore wind (GWn per year)



[164] British Wind Energy Association (2009) Wind Energy in the UK: State of the Industry Report, October http://www.bwea.com/pdf/publications/SOI-report.pdf

A problem that is often cited in connection with wind power is its possible non-availability during times of peak demand. This could occur when a large high pressure weather system settles over the UK in midwinter. When wind generation has a low share of the energy mix, any missing wind output can be easily made up by boosting the output of thermal plant, calling upon spinning or standing reserve or via the various balancing mechanisms. But as the number of wind sources increases, additional back-up generation must be installed to cover specifically for low wind conditions. For example, in expectation that the UK will have 32 GWn of renewable wind generation (out of a total of about 100 GWn) in 2020, NGC suggests that on one in twenty occasions of peak demand, wind generator output may not exceed 15% of its nameplate capacity[165]. According to figures presented by the Committee on Climate Change, the additional cost associated with the intermittency of wind produces an increase of 10-20% in the levelised cost of onshore wind generation[166].

As a way of addressing this issue, the DECC Calculator applies a "stress test" which assumes that, over a five-day period, the average air temperature falls to zero, while onshore and offshore wind are contributing only 17% and 15% respectively of their average output. After allowing for the relevant load factors, this means that their likely contribution (known as the capacity credit) in these circumstances is 5-7% of their nameplate capacity. This is more conservative than the NGC provisional figure of 15% just mentioned.

As noted, one of the key objectives in formulating the Intermediate Pathway was to limit standby capacity to no more than 10% of the total. To do this it was found necessary to set the "storage, demand shifting and interconnection" heading at Level 3 – the only instance of such a choice on the supply side. This assumes 7 GW of storage with a capacity of 100 GWh and 15 GW interconnectors[167]. In this case the storage capacity would be about ten times the size of the existing Dinorwig plant; much of it would be located in Scotland so that additional interconnections would be needed. Electricity demand shifting is applied through off-peak recharging of half of all electric vehicles. With these assumptions, the Calculator produced a figure of 11 GW for the amount of standby needed in 2050, which is around 8% of the total installed capacity in 2050. However standby would reach 11% in 2045, an effect that could be prevented by bringing forward the introduction of nuclear and/or CCS capacity by a few years.

From the Calculator we find that the estimate of the required standby capacity depends not so much on the power available but on the balance between energy demand and supply. This is, perhaps, not surprising given that the stress test extends over five days of low wind and low temperature conditions. Low temperatures result in an increase in demand that depends on the amount of building insulation, while low wind produces a reduced supply as just described. In the Intermediate Pathway in 2050 the increase is demand is roughly double the decrease in supply. The total shortfall in supply (4.4 TWh or 0.5 GWav) that results from these two factors is mitigated by (1) diversion of exports (i.e. redirecting to UK use any output that would otherwise be exported), thereby releasing 0.6 TWh, 0.07 GWav; (2) boosting of thermal and nuclear plant output by exploiting the difference between the average load factor and its actual availability (typically 5 to 10%) for non-renewable plant (0.7 TWh, 0.08 GWav); and (3) balancing – i.e. the use of storage, demand shifting and interconnections (1.8 TWh, 0.2 GWav). The total shortfall is 1.3 TWh (0.15

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165 National Grid (2009), Operating the electricity transmission networks in 2020: Initial Consultation, June http://www.nationalgrid.com/NR/rdonlyres/32879A26-D6F2-4D82-9441-40FB2B0E2E0C/39517/Operatingin2020Consulation1.pdf

166 The Committee on Climate Change (2008) Building a low-carbon economy – The UK's contribution to tackling climate change. The First Report of the Committee on Climate Change , TSO, London, December, p.185 http://www.theccc.org.uk/pdf/7980-TSO%20Book%20Chap%205.pdf

167 DECC Calculator website, http://2050-calculator-tool.decc.gov.uk/assets/onepage/48.pdf

GWav) that, when spread over five days, requires an additional electrical capacity of 10.9 GW. It is notable that, if CCS or nuclear capacity is reduced to remove some of the overcapacity in 2050, the removed generating capacity reappears as an increase in the required standby.

Hydroelectric power

Hydroelectric power currently produces 5.3 TWh/y (0.6 GWav). This was assumed to increase slowly to 7 TWh/y (0.8 GWav) by 2050. This is a small enhancement that is, perhaps, only marginally helpful. To that extent it runs contrary to our original decision to focus on technologies that can make major contributions. On the other hand, it is a well-established technology and, according to the DECC July 2010 Pathways Analysis Report[168] the increase is ambitious yet reasonable. For that reason it is retained at Level 2, but it could be dropped back to Level 1 with relatively little impact.

Solar panels for hot water

While photovoltaic sources were rejected on grounds of cost and energy produced, solar panels generating hot water for domestic or commercial use deploy relatively simple technology and provide a useful level of heat storage. On that basis it is assumed that they will be a more cost-effective proposition that photovoltaic technology. Level 2 was selected, which assumes that 30% of buildings will obtain 30% of their hot water supply from south-facing roof panels, requiring, for an average house, an area of about 3 m^2. In 2050 this would produce about 20 TWh/y (2 GWav). As with hydroelectric power, it could be dropped back to Level 1 with relatively little impact.

Environmental heat

As explained above, environmental heat (from heat pumps) is chosen through the two headings “home heating electrification” and “home heating that isn’t electric”. According to the relevant help page[169], the values selected in the Intermediate Pathway (Level C for both) result in 88% of home heating appliances running from heat pumps by 2050, with the remainder mostly using CHP schemes. These choices were made because they happen to produce the lowest GHG emissions and, as shown by Table 6.2, the result is that environmental heat makes a significant contribution (39%) to renewable energy in this proposed Pathway. The relatively small contribution from CHP reflects the advantages of heat pumps in terms of ease of installation, albeit with a somewhat lower efficiency[170].

6.3.4 Other issues

Electricity imports

At present there is a 2 GW interconnector with France that allows the annual importation of (typically) 10 TWh (1.1 GWav) of electricity generated from nuclear power. The chosen option (Level 2) under the “electricity imports” heading assumes that the existing interconnection would be increased to 4 GW to allow the annual importation of up to 30 TWh (3.4 GWav) of solar electricity from southern Europe or North Africa. Some preliminary allowance for the cost of these interconnects is given in tab VIIa.

[168] http://www.decc.gov.uk/assets/decc/what%20we%20do/a%20low%20carbon%20uk/2050/216-2050-pathways-analysis-report.pdf
[169] DECC Calculator website http://2050-calculator-tool.decc.gov.uk/assets/onepage/31.pdf
[170] MacKay, D.J.C. (2009) *Sustainable Energy – Without the Hot Air* op cit, pp.146 et seq www.withouthotair.com/

Geosequestration

Geosequestration is the removal of CO_2 from the atmosphere by technological means followed by its permanent burial. The DECC Calculator has four options for this heading. Level 1 amounts to a rejection of this technology; Levels 2 to 4 respectively remove successively greater amounts of CO_2 per year. Level 1 was selected on the grounds that Level 2 made an insignificant contribution and higher levels required huge amounts of energy to support them: Level 3, for instance, would require a dedicated 100 GW fleet of nuclear power stations.

6.4 Sensitivity of the results to the chosen supply and demand settings

The Intermediate Pathway presented here aims to find a way of meeting the UK's energy needs and the 2050 target on GHG emissions through a combination of technologies and without going to any extraordinary lengths. In the language of the DECC Calculator, this translates into an outright rejection of all Level 4 choices and, so far as possible, an avoidance of Level 3 choices also. Section 6.3 has shown that the Intermediate Pathway broadly meets this criterion. On the supply side, the number of Level 3 choices was limited to one for "storage, demand shifting and interconnection". This is surely reasonable, because such a choice allows the use of wind generation whilst helping to avoid the need for a large fleet of back-up generators.

On the demand side, there were four Level 3 (i.e. very "ambitious") choices indicating a higher level of effort in this direction. This, we argue, is as it should be: a decrease in energy demand is a universal good that provides benefits in terms of GHG emissions, conservation of resources, reduction of energy poverty and so on. The more contentious choices are examined below.

6.4.1 Energy demand

Section 6.2.1 has indicated that the choices under the energy demand headings for the Intermediate Pathway (Table 3.2) lead to a saving of 21% in primary energy demand by 2050. This is combined with an increase in demand for electricity of 75%, largely due to the electrification of home heating, transport and industry. Given that this involved making Level 3 (i.e. "very ambitious") settings under four key headings (Table 6.9), we scrutinise these more closely.

Table 6.9 Energy savings (TWh/y) made by setting four key energy demand headings at Level 3

Heading	Reduction TWh/y (GWav)		
	Level 2	**Level 3**	**Level 4**
Shift to zero emission transport	61 (7)	82 (9)	116 (13)
Domestic freight	44 (5)	85 (10)	90 (10)
Home insulation	35 (4)	71 (8)	108 (12)
Energy intensity of industry	116 (13)	281 (32)	n/a

Source: DECC help pages[171]: Level 3 chosen in the Intermediate Pathway

[171] DECC Calculator website, http://2050-calculator-tool.decc.gov.uk/assets/onepage/*.pdf where * is replaced by15,25,30,38

It will be seen that the outcome is relatively insensitive to the choice between Level 2 and Level 3 for the first three headings, so these could be reduced to Level 2 without a major impact on the overall GHG emissions, though these would then not quite meet the 80% target. However the last of the four – energy intensity of industry – has a much larger impact on energy usage and GHG emissions. Reducing this heading to Level 2 brings the GHG emissions up to 25% of 1990 values – well above the 20% target. Table 6.9 makes it clear why this is so: industry is by far the heaviest user of energy and is, therefore, likely to be the area where the greatest savings could be made.

6.4.2 Energy supply

Bioenergy production has a marked effect on GHG emissions because of the swing from positive to negative emissions as the amount of biofuel burnt in CCS power stations is increased (see Section 6.3.2), Table 6.7 shows the available choices in the Calculator for each heading related to biofuel production. It is clear that, in terms of increasing the available amount of biofuel, two headings dominate – namely “land dedicated to energy crops” and “bioenergy imports”.

We have judged that the dedication of 10% of UK agricultural land to bioenergy crop production (Level 3) was unlikely to be feasible (as explained in Section 6.4.1). We also avoid excessive reliance on energy crops to acknowledge that their impact on climate may not be wholly benign. Thus, while recognising that this is one of the most effective levers in the Calculator, the level has been set at 2. If, however, one were to decide that Level 3 is achievable, it would then be possible to reduce bioenergy imports to Level 1 and reduce the energy intensity of industry to Level 2.

Given the stated intention to avoid heroic energy demand and supply targets, it may be felt that one of the boldest assumptions of the Intermediate Pathway is the development of 40 GW of CCS electricity generation capacity by 2050. A defence of this assumption is offered in Section 6.3.2. If this strategy were to fail, however, it would have severe consequences. It would not be sufficient to simply replace CCS with carbon-neutral sources (for example, nuclear) because CCS is needed, in conjunction with biofuels, to produce the negative emissions that are necessary to meet the 2050 GHG target. The viability of the Intermediate Pathway therefore hangs on the success of the various CCS trials, including the German prototype, and the ability to scale up and replicate these designs to produce CCS generation at reasonable cost.

6.4.3 Comparison with other published Pathways

The pathway proposed here has some similarities to three of the pathways that are included as examples alongside the Calculator on the DECC website, namely “Markal”, “more CCS higher bioenergy” and “National Grid”. All three aim to meet the UK’s energy needs through a broad mix of energy suppliers. A key difference from the Pathway presented here is that all three recommend 10% of UK agricultural land to be dedicated to bioenergy crops. As explained above, this is a very effective way of reducing the GHG emissions estimated by the Calculator but, in our view, it has low credibility. Markal also deploys more aggressive measures to reduce energy demand so that it falls by about 33%. In the context of rising fuel prices, measures such as improved insulation and electric vehicles will, we believe, be widely accepted. The same cannot be said of reductions in the average temperature of homes, where a perceived fall in living standards is likely to be widely resisted.

6.5 Conclusion/Summary

The Intermediate Pathway presented in this chapter aims to deliver energy security though a balanced mix of reductions in energy demand, CCS, nuclear fission and renewable energy that leads to an 80% reduction in GHG emissions by 2050. An important aspect of the Intermediate Pathway is that it does this without making any extraordinary efforts or extravagant assumptions.

The main risks associated with the Intermediate Pathway are its dependence on the use of biofuels and electricity generation with CCS. This makes the proposal dependent on the UK's ability to grow or import from abroad significant quantities of biofuels and on the successful commercialisation of the ongoing CCS trials. Another important embedded risk is the assumption that industry will reduce its energy demand and emissions to the required extent. Adoption of the Intermediate Pathway would not allow the UK to meet its 2020 target under the 2009 EU Renewables Directive.

The key features of the Intermediate Pathway are as follows.

- By 2050, a 21% reduction in energy demand compared to 2010. This is, perhaps, the most challenging feature of the Intermediate Pathway, but it is argued that this is appropriate because reducing demand is a universal good. Nevertheless, the Pathway anticipates economic growth at historical levels and focuses on improved home insulation, electrification of transport and industry and near-universal use of heat pumps for heating buildings.

- Electricity generating capacity (though not output) is equally split between nuclear fission, generation from both fossil and biofuels coupled with CCS, and wind & hydroelectric power.

- Use of biofuels is an important factor in meeting the 2050 GHG target because, when used with CCS, it provides a means of achieving negative emissions. The Pathway nevertheless avoids making over-ambitious assumptions about biofuel production and imports by, for instance, restricting the amount of UK land dedicated to bioenergy crops to 5%.

- The Intermediate Pathway aims to limit the amount of standby generation that would be needed under midwinter low wind conditions to less than about 10% of total electrical capacity. Two features contribute to this, namely (i) the use of storage, demand shifting & interconnection and (ii) the deployment of nuclear and CCS plant that can be boosted in time of shortage.

- The Intermediate Pathway aims to preserve wildlife habitat by avoiding tidal range or marine algae schemes.

7 An inter-comparison of the three Pathways and their national and international implications

7.1 Overall energy supply and demand figures for the three Pathways

The energy supply and end-use parameters of the three Pathways proposed by the champions in the three preceding chapters can be summarised as follows:

Table 7.1 Comparison of the energy mix in the three Pathways

Table 7.1.1 Installed generating capacity in 2030 and 2050

Pathway to 2050	Nuclear generating capacity in GWe		Renewable generating capacity in GWn		Fossil/CCS generating capacity in GWn		Total generating capacity in GW	
	2030	2050	2030	2050	2030	2050	2030	2050
High Nuclear	28	80	27	18	37	21	92	119
High Renewable	1	0	99	181	12	2	112	183
Intermediate	16	39	40	40	42	51	98	130

Source: DECC Excel spreadsheet Intermediate output Tab lines 117-131

Table 7.1.2 Overall energy supply and demand position in 2050

Pathway to 2050	Nuclear energy supply in 2050 (in each case thermal energy)		Renewable energy supply in 2050 (mostly electrical)		Fossil/CCS energy supply in 2050 (thermal energy)		End use demand in 2050			
							Electrical		Thermal/ mechanical	
	TWh/y	GWav	TWh/y	GWav	TWh/y	GWav	TWh/y	GWav	TWh/y	GWav
High Nuclear	1714	196	609	70	629	72	753	86	2199	251
High Renewable	0	0	1038	118	448	51	663	76	775	88
Intermediate	840	96	667	76	856	98	693	79	1667	190

Source: These figures have been calculated from the Flows Tab lines 6-85

It will be seen from Table 7.1.1 that the three Pathways are sharply differentiated by their use of nuclear energy, which in 2050 ranges from zero for the High Renewables Pathway to 80 GWe (delivering 196 GWav of thermal energy or 64 GWav of electrical energy into the grid) for the High Nuclear Pathway. All three make significant use of renewable energy, though the trend between 2030 and 2050 differs sharply – an 80% increase in the High Renewables case and a flat or decreasing tendency in the other two. All three recognise that even by 2050, it will be difficult to eliminate the use of fossil fuels altogether, because of their current use in all forms of transport, though they differ in the extent to which they use CCS and/or biofuels to ameliorate the situation.

Table 7.1.2 generally reflects the differences shown in Table 7.1.1, but it will be seen that the differences between the three Pathways lie largely in the amount of non-electrical energy produced – the differences in electrical energy are relatively minor. This reflects the fact that the total energy produced is much lower in the High Renewables Pathway than in the other two, because of the high heat losses incurred during fossil- and nuclear-fuelled generation. The non-electrical energy delivered in the High Renewables Pathway is significantly lower, reflecting the much greater emphasis on energy savings made in that Pathway.

It is relevant to compare the totals in Table 7.1with the figures given in Tables 2.1, 2.2 and 2.3 for the year 2010:

Table 7.1.3 Comparison of proposed breakdown with actual figures in 2010

	2010		2030				2050		
Electric Capacity (GWn)	Actual		HN	HR	Int		HN	HR	Int
Nuclear	11		28	1	16		80	0	39
Renewable	9		27	99	40		18	181	40
Fossil/CCS	71		37	12	42		21	2	51
Total electric capacity (GWn)	**91**		**120**	**112**	**126**		**119**	**183**	**130**
Electric energy supplied (GWav)	**44**		**57**	**46**	**56**		**86**	**76**	**79**
Total energy supplied (GWav)	**211**		**257**	**170**	**238**		**337**	**164**	**269**

This table conforms to the energy accounting convention of DECC that when presenting capacity values, it is the nameplate electrical capacity (i.e. GWe, not GWth) that should be shown. It will be seen that although the total capacity is mostly on a downward or approximately flat trend, the exception is in the High Renewables Pathway, where a significant increase is required, mainly to cope with the intermittency problem. However there are also large changes in the make-up of this capacity in the High Nuclear and Intermediate Pathways over the years, because the existing plant is obsolescent and/or has unacceptable emissions. So all three Pathways will require very substantial new investment over the next 40 years.

More detailed breakdowns of both the supply and end-use figures for each of the three Pathways in 2050 are given in the summary Table 7.2. The bottom line totals in this table are consistent with the summary figures for 2050 in Tables 7.1.1 and 7.1.2. Points to be noted in this table include:

- All three Pathways make use of renewable energy. For the High Nuclear and Intermediate Pathways, environmental heat and bioenergy make the largest contributions, while wind energy is relatively small and solar smaller still. In the High Renewables Pathway, by contrast, offshore wind is largest single primary energy source, while solar energy PV) also features.
- The Intermediate Pathway and, to a lesser extent, the High Nuclear Pathway make significant use of CCS, using biofuel and fossil fuel.
- Some of the figures in this table may be inaccurate because of software errors in the DECC Calculator. These are discussed in Annex 1, and are not thought to be significant enough to affect the main conclusions.

Table 7.2 Breakdown of the supply and end-use figures proposed in the three Pathways in 2050

Figures in TWh/y	**Primary energy supply**				**Conversion processes**			**End uses of energy in all forms (and electrical only)**						
	High Nuc	**High Ren**	**Intermed**		**High Nuc**	**High Ren**	**Intermed**		**High Nuclear**		**High Renewal**		**Intermediate**	
Pumped heat	248	62	247.8	**Inputs to electricity generation**					All	(Elec)	All	(Elec)	All	(Elec)
Solar	19	76	19.3	Solar PV		30		Heating&cooling homes	345	105	253	24	345	105.4
Wind	58	381	123.7	Wind	58	381	123.7	Heating&cooling comm	134	41	80	10	127.5	50.6
Tidal/wave/hydro/geothermal	6	117	7	Tidal/wave/hydro/geothermal	6	117	7	Lighting&Appliances homes	95	95	53	46	94.9	94.9
Electricity imports		70	30	Electricity imports		70	30	Lighting&Appliances comm	90	90	58	51	90	90.0
Nuclear	1714	0	840	Nuclear	1714	0	840	Industry	347	202	347	202	347	201.7
Coal reserves/imports	2	2	84.1	Solid/gas fuel & CHP electricity	194	65	508	Road transport (incl H2)	191	55	90	50	152.5	51.8
Oil reserves/imports	484	336	477	Thermal generation & DH adjustment	-1219		-815.7	Rail transport	12	8	12	12	11.8	8.6
Gas reserves/imports	143	110	294.9	Electric Sub-Total	**753**	**663**	**693**	Domestic aviation	15		14		14.5	
Biofuel imports	70	0	35	**Inputs not used for electricity generation**				International aviation	180		131		180.3	
Biomass imports	38	0	35	Solid & gaseous fuel direct	74	125	59.4	National navigation	33		34		28	
UK land bioenergy	63	182	63.1	Ditto via CHP/DH thermal	72	151	55.7	International shipping	96		29		96.2	
Agricultural/other waste/algae	107	150.2	106.9	Liquid fuel (oil & biofuel)	554	337	512.6	Agriculture	11	5	11	4	11.1	4.5
				Solar th & pumped heat	267	108	266.9	Overproduction/exports	121	105	243	234	39.9	39.9
Total	**2952**	**1486.2**	**2363.8**	Non-electric process losses	1232	54	772.9	Losses (incl transmission)	1282	48	85	30	821.7	45.4
				Non-electric Sub-Total	**2199**	**775**	**1667.5**							
				Total electric +non-electric	2952	1438	2360.5	**Total**	**2952**	753	**1438**	663	**2360.4**	692.8

Figures in GWav	**Primary energy supply**				**Conversion processes**			**End uses of energy in all forms (and electrical only)**						
	High Nuc	**High Ren**	**Intermed**		**High Nuc**	**High Ren**	**Intermed**		**High Nuc**		**High Ren**		**Intermed**	
Pumped heat	28	7	28	**Inputs to electricity generation**					All	(Elec)	All	(Elec)	All	(Elec)
Solar	2	9	2	Solar PV	0	3	0	Heating&cooling homes	39	12	29	3	39	12
Wind	7	43	14	Wind	7	43	14	Heating&cooling comm	15	5	9	1	15	6
Tidal/wave/hydro/geothermal	1	13	1	Tidal/wave/hydro/geothermal	1	13	1	Lighting&Appliances homes	11	11	6	5	11	11
Electricity imports	0	8	3	Electricity imports	0	8	3	Lighting&Appliances comm	10	10	7	6	10	10
Nuclear	196	0	96	Nuclear	196	0	96	Industry	40	23	40	23	40	23
Coal reserves/imports	0	0	10	Solid & gaseous fuel & CHP electr	22	7	58	Road transport	22	6	10	6	17	6
Oil reserves/imports	55	38	54	Thermal generation & DH adjustment	-139	0	-93	Rail transport	1	1	1	1	1	1
Gas reserves/imports	16	13	34	Electric Sub-Total	**86**	**76**	**79**	Domestic aviation	2	0	2	0	2	0
Biofuel imports	8	0	4	**Inputs not used for electricity generation**				International aviation	21	0	15	0	21	0
Biomass imports	4	0	4	Solid & gaseous fuel direct	8	14	7	National navigation	4	0	4	0	3	0
UK land bioenergy	7	21	7	Ditto via CHP/DH thermal	8	17	6	International shipping	11	0	3	0	11	0
Agricultural/other waste/algae	12	17	12	Liquid fuel (oil & biofuel)	63	38	59	Agriculture	1	1	1	0	1	1
	0	0	0	Solar th & pumped heat	30	12	30	Overproduction/exports	14	12	28	27	5	5
Total	337	170	270	Non-electric process losses	141	6	88	Losses	146	5	10	3	94	5
				Non-electric Sub-Total	251	88	190							
				Total electric +non-electric	337	164	269	Total	337	86	164	76	269	79

The figures in TWh/y in Table 7.2 are derived from the tables contained in the Calculator's 'Flows' Tab, which gives the numerical values of all the energy flows through the overall system. These flows are presented graphically in the so-called Sankey diagrams, which can be viewed using the Web version of the software, and are printed for our three Pathways in Annex 2. Unfortunately the numerical values of the energy flows cannot be shown in those printouts, though they can be read off the computer screen version (see Annex 1 for the details), and Table 7.2 presents a summary version of these, with all figures shown in TWh/y in the upper panels, and in GWav, in the lower panels (where the GWav figures are obtained by dividing the TWh/y by 8.76). The figures in the central block, labelled 'Conversion processes', summarise the rather complex processes by which the primary energy flows get converted into the output flows supplied to the end user. It will be seen that for the thermal generators (nuclear and CCS) under half the primary energy gets converted into electricity before transmission to the end user, with considerable associated losses; part of the other half is supplied direct to the end user, either as heat or as mechanical energy (for example, for manufacture or transport).

A significant difference between the three Pathways is seen in the (mostly electrical) energy described as 'Overproduction or export'. This is energy which is surplus to the immediate user requirement and can be made available for export. While the Calculator does not allow it, this excess generation could in fact be used to produce so-called 'green fuels' that could be used for transport and to supply missing generation during low wind conditions. In this way, near to 100% renewables energy supply could be achieved.

7.2 Technical credibility of the Pathways up to 2050

As we have stated above, our objective in this report is to define three Pathways which are based on technologies which have already reached full-scale commercial maturity, or can reasonably be expected to have reached it in time for them to be rolled out to meet the likely UK energy demands in the year 2050, and to meet the government's emissions target by that date. The three Pathways outlined here all presuppose that a considerable amount of further technological development will take place. That is in itself unremarkable – all the technologies concerned have been evolving over the past few decades, and it is reasonable to expect that this will continue. However this report assumes that this development will in each case be successful, and will lead to plant designs which can be rolled out on the required scale by certain specific dates. It is notoriously difficult to predict with confidence that high technology target dates will be met, so there is necessarily an element of judgement over the technical credibility of each of the Pathways. In this section we look at the various intermediate targets which will have to be met if the various overall objectives are to be achieved.

7.2.1 Credibility of target dates for First of a Kind (FOAK) power plants

All three Pathways presuppose that one or more new technologies will be ready to roll out by a date which is in most cases no later than about 2020.

The High Nuclear (and to a slightly lesser extent also the **Intermediate**) Pathway depends on the availability of a fully-operational prototype third-generation new build LWR by about 2021, with a design that can then be rolled out at a rate of one or perhaps even two reactors per year. As noted in Section 3.2.2, two promising candidates are the European EPR and the Westinghouse AP1000 designs. Prototypes of both are currently under construction, with imminent planned completion dates. So in principle the question of their readiness for rollout should become a matter of fact very shortly. There are reports of significant delays in the construction of the Olkiluoto and Flamanville EPR plants [see ref. 39]. The third candidate, the GE

Hitachi ABWR, has also been constructed and is in operation at several sites in Japan, but has been suffering from operational reliability problems. Therefore some credibility problems remain.

The High Renewables Pathway proposes a mixture of six main technologies – bioenergy, wind, tidal, geothermal, solar PV and wave – with contributions of 37, 43, 6, 3, 3 and 2 GW respectively by 2050. All of these technologies are arguably some way short of full commercial maturity.

Bioenergy, as considered in this Pathway, is mainly produced by so-called 'second-generation biocrops', along with wastes. The data on this source used by the DECC Pathways model comes from a study commissioned by the Carbon Trust from an independent consultant, E4tech[172] which in 2012 produced a report entitled Bioenergy Technology Innovation Needs Assessment (TINA). As we have seen, Searchinger [ref. 58] has raised some doubts about the validity of taking 'carbon credits' from the use of biomass such as trees, and there certainly seem to be some land-use, biodiversity and environmental limits to reliance on biomass. The Committee on Climate Change suggested that they might be limited to supplying 10% of UK energy by 2050[173]. DECC put the figure at 12%, or possibly higher[174]. The Mott MacDonald report [ref. 106] gives technical details on the many schemes for converting biomass into usable energy, some of which are at an early stage of development, and need to come down in cost by a significant factor.

Wind energy's competitive position depends on the forecast capital cost of the onshore wind turbines dropping at the rate foreseen, and on the floating offshore design being successfully implemented. Mott MacDonald foresees the levelised cost of onshore systems dropping from £90/MWh now to £70 in 2020 and £55 in 2040. As regards offshore wind farms, the situation is much less clear cut, since offshore wind is at a relatively early stage of deployment, with only a decade since the first commercial installation in Denmark. In the UK, there have been demonstration projects quite close to shore (less than 10km) in shallow water (less than 15 metres) and with a total capacity between 60 and 90 MW. The next round of projects, still under construction, has a capacity of 150-500 MW and is in water depths up to 30 metres, with the furthest offshore project only 30km offshore. Construction of Round 3 projects, which will have a size of more than 1 GW in water depths of 30-60 m and with distances to shore in excess of 50 km are only expected to start construction in 2015. So cost estimates are still very tentative. However, Mott MacDonald has suggested a capital cost for an early Round 3 project of ~£3000/kW, giving a levelised cost of £169/MWh. Further extrapolation gives £103-114/MWh in 2020 and £69-82/MWh in 2040. So the competitiveness of this technology still has to be demonstrated.

Tidal barrage schemes, such as the frequently-studied Severn barrage scheme, are based on fairly well-established technology, but have capital costs which have hitherto been a deterrent – typically £2800-4000/kW, plus possible additional costs to compensate for the damage to the environment. Mott MacDonald estimate levelised costs of £403-439/MWh in 2020 and £271-312/MWh in 2040, which would be rather prohibitive unless political factors intervened. There is also the problem of balancing the highly intermittent nature of the power delivered – the tidal cycle is not well correlated with the demand cycle. For major tidal barrages, this would require either energy storage or an interconnect to other parts of Europe with a different demand cycle, both of which would be expensive. For smaller dispersed tidal current turbines (which the High Renewables scenario adopts in preference to Barrages) this problem is less, since they would deliver

[172] http://2050-calculator-tool-wiki.decc.gov.uk/cost_sources/46
[173] www.theccc.org.uk/reports/bioenergy-review
[174] www.decc.gov.uk/en/content/cms/news/charlesh_bgbio/charlesh_bgbio.aspx

peak output at different times from different sites around the coast. Their environmental impact would also be much less. However, the technology is at a relatively early stage of development, and costs are still high.

Geothermal systems have been explored on an experimental basis in the UK. A project at Rosemanowes Quarry in Cornwall was funded by the (then) Department of Energy from 1977 to 1991, which included a 2.8 km borehole. That project found that the technology was unable to compete with (by then) relatively cheap fossil fuels. More recently, a 1.8 km deep test borehole at Southampton has become a key heat input for that city's heat network, at a level of ~100 kW. There are currently two plans to construct more commercial plants. EGS Energy in partnership with the Eden project is developing a 3 MWe plant which is expected to come on stream in late 2012, and may later be scaled up so that it eventually generates between 25–50 MWe. Geothermal Engineering Ltd is developing a 10 MWe/55 MWt CHP power plant at Redruth in Cornwall. It hopes that the plant will be operational in 2013. Mott MacDonald have estimated the cost of the current technology at ~£4600/KW, and are extrapolating levelised electricity costs to £80-170/MWh in 2020 and £50-130/MWh in 2040.

Wave energy systems are still at an early stage in development (the largest UK deployed system, the experimental Pelamis system in Orkney, has an output of ~ 0.75 MW). A comparable device in Portugal is reported to have cost £3,226 /kW. Cost estimates have been prepared for a floating device with a notional output of ~1 MW at £4000/kW in 2015, and Mott MacDonald have tentatively estimated £3569/kW in 2020 and £2956/kW in 2040. Shoreline devices, such as Wave Dragon and Wavegen, are estimated by Mott MacDonald to have somewhat lower costs – £3270/kW now, falling to £2548/kW in 2020 and £1896/kW in 2040, but these have relatively limited potential because of the shortage of suitable sites.

The other renewable technologies that feature in one or more of our Pathways are arguably less ready for large-scale fully-commercial deployment. Within the UK, solar photovoltaic systems currently make a relatively small contribution, with a national total of under 2 GW: individual installations typically have a capacity of less than 20 MWp (peak output), and a capital cost of ~ £1200/kWp for the modules, and a further £1100/kWp for the other equipment required. Mott MacDonald envisage that internationally the system cost might fall to ~£600/kWp by 2040, giving a levelised electricity cost of £110-240/MWh by 2020 and £50-145/MWh by 2040. Clearly confirmation of these estimates, and probably some further developments in this technology, are required to make it competitive with onshore wind.

The Intermediate Pathway uses CCS as a central part of its strategy. As we have seen in Section 3.4.1, there is some confidence over the technical feasibility of CCS. The principal uncertainties are its cost and its infrastructure requirement. Estimates by Mott Macdonald (see Table 5.3) put the levelised electricity cost of Gas-CCS at around £100/MWh; this is expected to fall marginally in the period to 2040. The estimated current cost of electricity from Coal-CCS is considerable more than this, at around £150/MWh but its cost is expected to fall, becoming comparable with Gas-CCS by 2040. Significant uncertainty is attached to these figures (if only because the Mott MacDonald analysis makes use of variable discount rates which discriminate in favour of currently available, low commercial risk technologies) but, in very broad terms, one might class the cost of CCS as being comparable with that of offshore wind.

As regards the required CCS infrastructure, the Intermediate Pathway anticipates that this will handle over a hundred million tonnes of CO_2 annually. This capacity somewhat exceeds that of the National Transmission System, which was constructed by British Gas in the 1970s and 1980s to deliver North Sea gas to power stations through large-diameter pipes. Such an infrastructure may be difficult to achieve on the required timescale, and cost estimates are still very preliminary.

7.2.2 Credibility of the proposed replication by 2030

It is clear from the output of the Calculator that, in terms of credibility of the Pathways, the key date is not 2050 but, rather, something closer to 2020 or, at latest, 2030. By then, all of the proposed technologies must have been developed to a point where they are commercial and ready for replication. It will be seen from the preceding section that none of the proposed technologies has really developed to the point where it is possible to be absolutely confident that it will be ready for commercial rollout on the envisaged scale by 2020, or even by 2030. The early stages in the development of new technology are almost always beset by delays, and it is a brave planner who does not make contingency provision for them. But none of the planned dates are sacrosanct – even the UK government's commitment to achieve an 80% reduction in GHG might eventually slip by a few years. However, as we have seen in Section 3.2.8, the proposed rate of rollout of third-generation nuclear reactors is well within the rates that have been achieved elsewhere in the world, and so can be regarded as credible. Similarly the proposed rate of rollout of onshore wind power is consistent with recent achievement in the UK, and provided that no critical technological problems arise in the integration of carbon capture technology with carbon storage systems, the proposed rate of rollout of CCS technology again seems reasonable. The required reduction in the cost of offshore wind is arguably less certain.

7.2.3 Need for further technological development before 2050

Once the technologies proposed in this report have been established, and a serial roll-out has taken place, all the energy systems which are then in place should have a lifetime of at least 50 years, so there should be no obvious need for further technological development. The only exception to this statement which we have discussed above is in the area of nuclear technology where, as we have seen in Sections 3.2.5-3.2.7, the UK may well wish to get involved in international efforts to develop fourth-generation reactor technology and better fuel cycle technology.

7.2.4 Credibility of the proposed supply target by 2050

As we have seen in the preceding sections, several of the most significant technologies seem to have a good chance of achieving the planned rate of rollout, making it possible to hope that all three Pathways can meet the proposed overall energy supply and emission reduction targets. However all three are in some measure dependent on technologies which are still in the course of commercial development, and have hitherto been reliant on subsidies to achieve their current level of market penetration. They will all need to demonstrate the further reduction in levelised costs that their protagonists foresee.

7.3 Compliance with UK commitments on carbon emissions

The UK has made a parliamentary budgetary commitment to achieve a reduction in our GHG emissions of 50% by 2027, and an international commitment to reduce our GHG emissions by 80% by 2050, in each case with respect to our 'baseline' level of 783.1 Mt CO_2 e in 1990. Both of these percentage reduction targets are subject to certain qualifications, which we discuss below.

As shown in Table 7.3 below, all three Pathways meet the 2050 GHG emission target, although only just. As regards the 2027 target, the High Renewables Pathway meets the target comfortably: the other two Pathways fail by a narrow margin, due to a combination of two factors:

- They do not have the rapid increase in energy efficiency foreseen in the High Renewables Pathway.
- The low-carbon nuclear capacity drops sharply as old stations are decommissioned, and the new build capacity does not make a large contribution until 2030.

As noted in Section 1.2, the 50% target is a commitment to the UK Parliament, not an international commitment, and in fact the DECC Carbon Plan (published in December 2011) envisaged the possibility that we might not meet this target without purchasing international carbon credits.

Table 7.3 Emissions as % of 1990 value

	High Nuclear	High Renewables	Intermediate
1990	100	100	100
2010	81	79	81
2020	67	58	66
2025	55	45	55
2030	43	31	44
2040	29	25	31
2050	19	18	20

Source: Excel spreadsheet tabs labelled 1990-2050 cell DH109

7.4 Safety and environmental acceptability

All three Pathways to 2050 proposed in this report are massive industrial activities, involving in each case an annual expenditure of at least 8% of UK GNP [175] at current prices. It is therefore inevitable that public concerns will arise over the safety and environmental acceptability of the activities concerned, and that there will need to be regulatory mechanisms in place to ensure that the risks and environmental impacts are commensurate with the benefits resulting from the activity – i.e. the supply of energy in all the required forms and at the agreed power levels, with an acceptable degree of load following and an adequately low level of interruption of supply. This regulatory process will be for the most part an ongoing activity, undertaken by governmental or otherwise adequately independent authorities, with costs charged to the ultimate consumer of the energy in appropriate ways (which are assumed to be included in the cost estimates discussed in this report).

However in each case there are some safety and environmental issues which are too large to be regarded as adequately covered by regulation, and which some might claim to be 'show-stoppers' – i.e. sufficiently serious that it is reasonable to claim that the entire Pathway (or significant elements of it) should be rejected as unacceptable. This section seeks to identify such possible 'show-stoppers'.

7.4.1 Safety issues

The safety issues which cannot be adequately covered by regulation are typically those which have low probability but very high human consequences. Examples of such issues which might arise in relation to our three Pathways are:

7.4.1.1 Major disasters in nuclear plant, leading to a massive release of radioactivity

It is well-known that the nuclear industry has experienced a number of major disasters during its 50-year history, of which the Windscale Pile, Three Mile Island, Chernobyl and Fukushima disasters are the most frequently cited. In each case, the consequences were due to a mixture of defects in the design of the reactor, operator error as the incident unfolded, and inadequate or inappropriate responses to the release of radiation which occurred. The precise sequence of events was different in each case, as was the scale of human and economic implications. However the overall cost to mankind has been serious, and it is understandable that

[175] UK GNP is currently £1160bn pa: DUKES table 1.4 gives the Value of inland consumption of energy as £95bn.

many people believe that such events should never be allowed to occur again, and that nuclear energy should be phased out as quickly as possible. Against this, it has been argued that the actual loss of human life due to these nuclear disasters has been much smaller than that due to any other form of energy production on a national scale. Even the worst of these incidents, Chernobyl, only cost about 50 prompt deaths due to radiation, as compared with (for example) the 100,000 lives lost in the UK coal industry during the twentieth century[176]. See also an OECD/NEA study on this subject.[177]

A counter-argument is that it is also necessary to take account of non-prompt deaths during the years following an accident, due to radiation-induced morbidity. These are much less easy to quantify and assess: however a recent assessment by Frank von Hippel[178] puts the number of such deaths resulting from Chernobyl and Fukushima at 16,000 and 1,000 respectively. As for the future, it is arguable that lessons have been learned from these historic disasters, so that it is unlikely that those particular errors will be exactly repeated, provided that there is effective regulation. The UK has undertaken a major study of the Fukushima accident, led by its independent Office for Nuclear Regulation[179], which concluded that none of the specific design defects which contributed to that accident are relevant to the current or planned reactor types in the UK, and it has identified weaknesses in reactor operator practices which we should avoid. Although some governments (notably the Japanese and German governments) have implemented major changes in policy as a result of Fukushima, many countries which have (or are planning) nuclear industries have decided not to do so.

7.4.1.2 Prolonged ongoing releases of radioactivity, seriously affecting human health

Concern is often expressed over the ongoing releases of radioactivity which result from the activities of the nuclear industry, particularly in areas such as uranium mining, fuel reprocessing and management of radioactive wastes arising during normal operations. Figures are quoted by the opponents of nuclear power suggesting that these releases lead to an insidious death toll which greatly exceeds the prompt death toll during major accidents. Such claims have been repeatedly examined by the scientific community over the years, and are not supported by the evidence. The average dose to the UK public attributable to the nuclear industry is currently less than 2 μSv/y[180], and this gives rise to a probability that an individual will die prematurely from cancer due to this cause of about 10^{-7}/y, and hence an expectation of about 6 deaths per year. The UK nuclear safety regulations to limit such releases are stringent, and are generally well-monitored and enforced, so we do not regard this issue as critical.

7.4.1.3 Earthquakes and drinking water contamination initiated by 'fracking'

The DECC Calculator includes natural gas as a potential energy source but without specifying its origin. One possible source, which has come to public attention recently, is gas trapped in solid rock formations, which can be released by cracking the rock and injecting fluids into it at high pressure. This production technique, known as 'fracking', is already being undertaken on an experimental basis in the UK, and it is being used extensively in the US. However it has been claimed to have an effect in initiating earthquakes in rock formations which are already under geological stress, and also to lead to a contamination of drinking water by seepage of the injected fluids. It has been suggested that even comparatively minor earthquakes

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[176] http://www.guardian.co.uk/politics/reality-check-with-polly-curtis/2011/sep/28/reality-check-how-dangerous-is-mining
[177] http://www.oecd-nea.org/tools/publication?id=6862
[178] http://bos.sagepub.com/content/67/5/27
[179] http://news.hse.gov.uk/onr/2012/12/fukushima-lessons-learned-uk-action-plan-published/
[180] http://www.edfenergy.com/about-us/energy-generation/nuclear-generation/nuclear-safety-security/radiation-exposure.shtml# and then follow link to 'radiation exposure' and then 'performance data'
http://www.hpa.org.uk/webc/HPAwebFile/HPAweb_C/1194947389360 and then see sections 7.12 and 7.13

might have the effect of releasing large amounts of stored CO_2 from a CCS store. A report on the environmental implications of fracking has recently been published by the Royal Society[181]. This concluded that, provided that operational best practices are implemented and enforced through regulation, any unwanted side-effects can be managed effectively.

It may well be that some of the concerns about the practice have been exaggerated. However the purpose of fracking is to increase the availability of natural gas, and if that gas is to be used as a front-line energy source it must be accompanied by CCS if the 2050 emissions reduction target is to be met. If, on the other hand, natural gas is to be simply kept in reserve to cover for extreme circumstances (e.g. widespread low wind conditions coinciding with very cold weather), it may be possible to forgo any associated CCS. It should be mentioned that geothermal well drilling has also been known to initiate earthquakes (for example, in Switzerland).

7.4.2 Environmental issues

In this section, we exclude those environmental issues which have already been covered in Section 7.4.1 as 'safety' issues. The remaining environmental issues which cannot be adequately covered by regulation are typically those activities that, if conducted on a worldwide scale, would lead to a violation of the 'Planetary Boundaries' within which mankind has to live if the earth is to remain habitable, or which involve a major clash with values which the UK public cherishes. Examples of such issues which might arise in relation to our three Pathways are:

7.4.2.1 Rendering large areas of land uninhabitable or unusable for other purposes

The DECC Pathways software takes account of the land use implicit in the proposed deployment of energy supply systems, and gives figures for the land usage for each Pathway. These are summarised in Table 7.4:

Table 7.4 Land usage for biocrop and onshore wind production

Biocrop production (see Tab VIa lines 298-305)								
	2010			2030			2050	
High Nuclear & Intermediate	km2	%		km2	%		km2	%
Normal agriculture	175406	72		168073	69		161051	66
Forests	24786	10		27560	11		30335	12
Biocrops	1311	1		5574	2		11726	5
Other (incl built-up)	42827	18		43122	18		41219	17
Total	244330	100		244330	100		244330	100
High Renewables								
Normal agriculture	175406	72		160110	66		147111	60
Forests	24786	10		29126	12		33540	14
Biocrops	1311	1		11930	5		23850	10
Other (incl built-up)	42827	18		43164	18		39829	16
Total	244330	100%		244330	100%		244330	100%
Onshore wind energy production (see Tab IIIa1 line 134)								
High Nuclear	482	0.2		1276	0.6		484	0
High Renewables	525	0.2		3614	1.5		3700	1.5
Intermediate	525	0.2		2404	1		2404	1

[181] http://royalsociety.org/uploadedFiles/Royal_Society_Content/policy/projects/shale-gas/2012-06-28-Shale-gas.pdf

(since the High Nuclear and Intermediate Pathways have identical biocrop production, they have been grouped together).

It will be seen that the total land area assigned to energy production within the High Renewables Pathway is significantly higher than in the other two Pathways, amounting to some 11.5% of the total UK land area. As explained in Section 5.2.1.3, this is a defensible shift in the use of agricultural land if one takes account of foreseeable improvements in agricultural practice. However, as indicated in Section 4.2.2, it is open to question whether a shift of this magnitude would be acceptable to the UK public.

7.4.2.2 Serious damage to the local or national environment and eco-system

All energy technologies have environmental impacts, including emissions, visual intrusion and noise, and have an effect on the local ecosystem, including disturbance to animals, birds and plants. Most of the renewables are unique in having no direct emissions (biomass/waste combustion and geothermal plants being the exceptions). However concerns have been expressed about their other environmental impacts – for example, the visual and acoustic intrusion resulting from widespread deployment of onshore (and to a lesser extent) offshore wind turbines – see, for example, John Etherington[182]. These arguments are not easy to assess. One approach, adopted in the ExternE Project, a major study of environmental externalities by the European Commission[183], is to calculate a set of estimates for the 'external' costs in €/kWh, which should be added to the baseline cost of electricity (taken as 0.04 €/kWh) to reflect the social, health and environmental impact of the technology concerned. Their figures are generally small, in the range from 0.057 for coal to 0.001 for onshore wind. Their methodology is however open to challenge, since it is largely based on asking local residents and visitors to a region what they would be prepared to pay to be spared the impact under consideration. Unsurprisingly, the answers generally specify rather small amounts of money. If the level of concern were measured by column inches in local and national newspapers, the answer might be very different.

A specific issue which has been publicised by Etherington is public concern over the low frequency noise emitted by wind turbines in the 'infrasound' frequency range (<20 Hz and typically ~< 1Hz), particularly because of its interference with sleep. The effect is claimed to be very strong close to a turbine, and significant at a range of 500m. Other writers have dismissed this objection as spurious – for example[184,185.] It seems that the subject needs further research.

As regards the impacts of wind farms on wildlife, extensive studies have so far indicated that these are generally low[186]. Similarly, surveys of the impacts from marine renewables (for example, the MCT 1.2 MW tidal turbine) have also shown low impacts, but more work is being carried out[187].

A different environmental impact of onshore wind farms, over which concern has been expressed, is their effect on upland areas of deep peat, which currently sequester some 5 billion tons of CO_2 in the UK (equivalent to the UK's CO_2 emissions for over six years at the 1990 baseline level). This 'CO_2 bank' is sensitive to practices such as ploughing and drainage[188].

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182 John Etherington (2009) *The Wind Farm Scam* (chapters 6 and 7) Stacey International, London
183 www.externe.info/externe_2006
184 http://www.quora.com/Wind-Power/Is-the-infrasound-emitted-by-wind-turbines-harmful-to-humans-or-animals
185 http://www.nhs.uk/news/2009/08August/Pages/Arewindfarmsahealthrisk.aspx
186 http://iopscience.iop.org/1748-9326/6/3/035101
187 http://phys.org/news/2012-07-seabed-sonar-marine-energy-effect.html
188 http://www.bis.gov.uk/assets/foresight/docs/land-use/jlup/31_uk_land_use_and_soil_carbon_sequestration.pdf

Although the ExternE study assessed the externality cost of nuclear technology as low (0.004 €/kWh), there has for many years been considerable public concern about the inadequate control over radioactive releases into the environment – for example, pollution of beaches which have been contaminated by radioactive material released from nearby nuclear facilities (including in Cumbria and Dounreay), and have temporarily had to be closed to the public while clear-up work was undertaken, or had warning signs posted. Such problems can impact on tourism and the local fishing industry.

A number of environmental issues have been raised in relation to CCS technology. The European Environment Agency has suggested that, depending on the CO_2 capture technology used, there could be a net rise in some toxic emissions from the solvents used[189]. Some studies also suggest that carbon storage activities might trigger, and be susceptible to, earthquakes – releasing some or even all the stored CO_2 suddenly, with potentially lethal impacts from asphyxiation.[190] More generally, it is recognised that CCS plant is never 100% efficient in capturing all the emissions. The DECC software calculates the emission impact by assuming about 90% efficiency, and this is included in its emissions calculations (see Tab Ib)

7.4.2.3 Clashes with other industrial-scale activities (air travel, telecommunications)

Several of the technologies discussed in this report have implications for other industrial-scale activities. Examples include:

- Interference of wind turbines with radar signals used for air traffic control or with signals transmitting TV or mobile phone links [see ref. 182 Chapter 8]
- Interference with the performance of a seismic station, set up as part of the monitoring system for the Comprehensive Test Ban Treaty (for which a 50 km tolerance radius has been set for wind farm location)[191]
- Restrictions on over-flying of nuclear facilities, in order to reduce the risk of 'terrorist' attacks.
- The possibility that carbon storage or fracking could initiate earth tremors, which might make it necessary to locate these activities away from sensitive facilities such as nuclear power stations.

7.4.2.4 Leaving a legacy which later generations might resent or regret

Historically, every major source of energy has left a legacy which later generations have come to regret – areas stripped of natural forestation, coal mining waste tips, abandoned oil rigs in the North Sea, or ill-planned radioactive waste disposal systems. The energy systems which we are now planning are liable to be similarly condemned by our successors if we do not plan them wisely. Examples might include:

- Anthropogenic climate change if we fail to control CO_2 emissions
- Nuclear reactors and other nuclear industry plant requiring decommissioning
- Disposal systems for nuclear spent fuel or high-level radwaste that cease to contain it effectively
- CO_2 storage systems which release some of the CO_2 that they were intended to sequester
- Energy-producing systems which unduly deplete world reserves of exotic materials (e.g. rare earths).

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[189] www.eea.europa.eu/publications/carbon-capture-and-storage
See also Nayak, D. R.et al (2010) *Mires Peat* Vol. 4**,** No**.** 9
[190] http://m.technologyreview.com/energy/40638/
www.pnas.org/content/109/26/10164.short
[191] http://www.bbc.co.uk/news/uk-scotland-south-scotland-20079880

On the other hand if, in attempting to achieve our CO_2 targets, we failed to meet our essential energy needs, this would itself have profoundly negative implications for ourselves and our descendants.

7.5 Compatibility with UK nuclear non-proliferation commitments

The UK was one of the founder signatories of the Nuclear Non-Proliferation Treaty (NPT) on 1 July 1968, and ratified that signature on 29 November 1968. Since then, it has signed the IAEA Additional Protocol on 22 September 1998, and it has regularly participated in the quinquennial reviews of the NPT, during which it has made further commitments relating to its membership of the P5 group of nuclear weapon states, recognised as such in the NPT.

Under the NPT and the Additional Protocol, the UK is entitled to develop its own civil nuclear industry, and to assist other countries which wish to do so, provided that it does "not in any way to assist, encourage, or induce any non-nuclear-weapon State to manufacture or otherwise acquire nuclear weapons or other nuclear explosive devices". It also agrees to allow the IAEA to undertake inspections to verify its compliance with these Treaty obligations, particularly as regards transfers of fissionable material, to operate a system of nuclear materials accountancy for such materials at each relevant location, and to safeguard such material using physical containment, monitoring instruments etc.

None of the above obligations need cause the UK any specific problems in civil nuclear operations on its own soil, or indeed in participating in the worldwide 'nuclear renaissance' as a commercial supplier of goods and services. However there are three issues which it will need to address:

- The UK (exceptionally) has signed the NPT as a "nuclear weapon state", and as such is committed to working towards worldwide nuclear disarmament. Many of the non-nuclear weapon signatories are dissatisfied with the progress made to date in moving towards this goal, and might wish to withdraw from the Treaty if greater progress is not made soon. Withdrawals would threaten the NPT regime.
- The UK has accumulated over the years large stocks of isotopically-enriched uranium and plutonium, partly for civilian and partly for military purposes, and it has an obligation to protect these effectively from theft or damage by 'nuclear terrorists'. It has a strong interest in ensuring that other countries participating in the nuclear renaissance do likewise.
- If the UK proceeds with the new build, and particularly if it proceeds down the High Nuclear Pathway, it will be reinforcing its position as a leading member of the nuclear suppliers group, with a responsibility for assisting in the regulation of the international nuclear industry so as to minimise risks of proliferation and nuclear terrorism. As recent negotiations with India and Iran have shown, there is a risk of conflict of interest between these objectives and the promotion of a national industry. Some non-nuclear weapon states have expressed concern that the nuclear weapon states will seek to use their position to gain an unfair advantage in the business of supplying nuclear services (for example, enrichment, reprocessing and fuel fabrication).

In our view, these are all reasonable concerns. However it should be possible for the UK to play a leading role in international negotiations aimed at finding an acceptable nuclear security regime for the 21st century. These issues are all discussed in a Royal Society report on 'Fuel Cycle Stewardship in a Nuclear renaissance'[192].

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

7.6 Impact on the UK's international relations (trade and security of supply)

All the energy production technologies discussed in this report have implications for the UK's international trade and its need to ensure security of supply of various primary sources of energy and of the technology required to make this available to end-users. These considerations apply in rather different form to each of the main components in the energy mix proposed in the three Pathways, so we consider the nuclear, renewable and CCS components separately in the following sections.

7.6.1 International trade in nuclear materials and technology

7.6.1.1 The uranium market

We have seen in Sections 3.2.4, 3.2.5 and 4.3.3 that concerns have been expressed about the continued availability of uranium to fuel a major worldwide nuclear renaissance, and we have noted the steps that the international community is taking to address this concern. It seems that the UK should be able to remain in a strong position here, particularly if it plays a significant part in the worldwide fourth-generation reactor programme.

7.6.1.2 The front-end nuclear fuel market (enrichment, MOX and fuel fabrication)

Historically, the UK has been one of the world leaders in developing technologies for enrichment, MOX and other nuclear fuel fabrication, and it remains in a strong position to be a significant player in the worldwide market for these services, particularly if it can re-enter the industrial mainstream by selecting a widely used third-generation reactor type for its 'new build' programme. The tripartite Urenco consortium (UK, Netherlands and Germany) is currently the second largest supplier of enrichment services after Russia, with an income of ~$1B/year. However as we have noted above, energy demands are encouraging other countries to enter the field, and in some cases there are suspicions that a nuclear power programme may be used as a cover for developing a nuclear weapons capability. So the international community will have to find a solution to this problem: suggested solutions have included establishing a small number of international consortia to undertake enrichment under carefully supervised conditions, which would supply enrichment services to all countries that needed them.

7.6.1.3 The back-end nuclear fuel market (reprocessing, spent fuel and radwaste management)

Here again, the UK has historically been one of the world leaders, with Sellafield second only to France in the supply of reprocessing services. This activity suffered a setback in April 1977 when the US President Carter banned the reprocessing of commercial reactor spent nuclear fuel, citing the threat of proliferation. Although President Reagan lifted the ban in 1981, the US has never re-entered the reprocessing market, and continues to promote the view that civil reactors should be operated exclusively on a 'once-through' cycle, citing economic as well as non-proliferation arguments. A second setback occurred in 2002, in relation to an important contract to supply new nuclear fuel to Japan: British Nuclear Fuels Ltd (BNFL), the company which then operated the Sellafield plant, had its MOX fuel supply contract cancelled when it was revealed that its quality-control system was inadequate. Since then, although the reprocessing plant has generally continued to operate, its future has been increasingly in doubt.

Although fourth-generation reactors will in all probability need some form of reprocessing (see Sections 3.2.5 and 4.2.3), the technology may by then have moved on to new wet reprocessing methods or to dry ('pyro-chemical') methods, making Sellafield's existing technology redundant. The UK could nevertheless remain in this business if it so chooses. As with enrichment, other countries are being encouraged to enter the field, raising the possibility that they might use the plutonium emerging from the reprocessing plant to make nuclear weapons. Here again, the international community will have to find a solution to this problem, perhaps by establishing a small number of international consortia to undertake reprocessing of spent fuel under carefully supervised conditions, for all countries that have such material.

7.6.1.4 Reactor supply, maintenance, life extension and decommissioning

The UK has historically been a supplier of reactors (albeit on a relatively small scale) and has been a significant player in the market for maintenance, life extension and decommissioning services. If it proceeds with its new build plans, it could re-establish its nuclear infrastructure, and once more become a significant force in this very large market, competing with countries such as the US, France, Russia, Canada, Korea and Japan.

7.6.2 International trade in renewable energy technology

7.6.2.1 The wind energy technology market

The global wind power market reached 238 GW globally in 2012, and has been expanding by a 28% average for the last 15 years[193]. Depending on what happens to the US Tax Credit system following the US election, this market could double over the next five years[194]. Germany and Denmark are the current leading turbine suppliers. The EU exported €5.7bn worth of wind industry products and services in 2011.

7.6.2.2 The solar energy technology market

The growth rate of PV during 2011 was almost 70%, reaching about 70 GW globally. By 2016 it could double or possibly more than treble[195]. China is the leading supplier.

7.6.2.3 The marine energy technology market (wave, tidal, sea currents etc)

Global spending on wave and tidal energy may reach US $1.2 bn by 2015, according to the energy business analysts Douglas-Westwood[196]. According to the Carbon Trust, the total global market for both wave and tidal energies could be worth £40bn per annum by 2050[197]. The UK is well placed to participate in this expanding market.

7.6.2.4 Energy storage

The global growth in renewable energy capacity looks set to lead to a £8.4bn annual market for batteries and electricity storage technologies by 2020, according to the Boston Consulting Group[198]. The UK has some capacity in this area.

7.6.2.5 Bio-energy and electrical imports

A Technology and Policy Assessment study by UK Energy Research Centre (UKERC) suggests that up to 20% of global energy could be provided by modern biomass/biogas/Anaerobic Digestion technology

[193] http://www.gwec.net/global-figures/market-forecast-2012-2016/
[194] http://blog.ewea.org/2012/04/global-wind-power-market-is-expected-to-more-than-double-in-next-five-years/
[195] *Global Market Outlook for Photovoltaics until 2016* http://www.epia.org/fileadmin/user_upload/Publications/Global-Market-Outlook-2016.pdf
[196] Douglas-Westwood, World Wave & Tidal Market Report 2011-2015 http://www.douglas-westwood.com/files/files/598-495%20Wave%20&%20Tidal%20Market%20Report%202011-2015%20LEAFLET%20FINAL.pdf
[197] www.newscientist.com/gallery/next-wave-of-energy-from-the-sea

[198] https://www.bcgperspectives.com/content/articles/energy_environment_revisiting_energy_storage/

without damaging food production[199,200]. It is a very diverse and rapidly expanding field globally, in which the UK has some presence, while EU biomass generation is expected to quadruple by 2020[201].

Overall, the UK's potential and prospects have recently been reviewed by the DECC-backed Low Carbon Innovation Coordination Group (LCICG), which has been producing a series of Technology Innovation Needs Assessments (TINAs) for UK green energy technologies. The offshore wind TINA says "innovation is critical to enabling the deployment and cutting the cost of offshore wind power, with an estimated saving to the energy system of £18-89bn to 2050". It adds: "Innovation can also help create UK based business opportunities that could contribute an estimated £7-35bn to GDP to 2050". The Marine TINA says that "the UK has a large natural resource of marine energy that could make a meaningful contribution to the UK energy mix from around 2025. Cost of energy generated will need to reach around £100/MWh by 2025 for marine energy to be competitive with other technologies. This Pathway is ambitious but possible with significant innovation. If successful, innovation in Marine energy could save the energy system approximately £3-8bn and help create a UK industry that could contribute an estimated £1-4bn to GDP up to 2050."

The LCICG has also looked at advanced electricity networks and storage (EN&S) technologies which, it says "have the potential to address new stresses that are likely to be placed on the electricity system, and to do so more cost-effectively than would be possible through traditional methods of grid reinforcement and fossil-fuel-powered system balancing capacity. EN&S technologies could play an important role in the future energy system, supporting the uptake of renewable electricity generation, renewable heat, electric vehicles, and other low-carbon technologies. Innovation in EN&S technologies could save the UK £4-19bn to 2050 and could help create UK-based business opportunities that could contribute an estimated £6-34bn to GDP to 2050."

7.6.3 International trade in CCS technology

Countries that are major coal exporters are clearly motivated to promote CCS as a technology that may permit the continued use of coal as a means of electricity generation. Unsurprisingly therefore, the Global CCS Institute (GCCSI)[202], founded 2009, is based in Australia, the world's leading coal exporter. The Institute aims to promote global cooperation on CCS, and lists 75 large-scale integrated projects, more than half of which are planned to come into operation in the period 2015-20. The leaders in this list are USA & Canada (32 projects), Europe (21), China & Korea (13) and Australia & New Zealand 5). The GCCSI aims to implement at least 20 fully integrated, large-scale Demonstration Projects by 2020.

It is probably fair to say that, while a market in CCS technology is far from being fully realised, many countries and companies are working hard to commercialise CCS in the hope of sales at a later date. This is in spite of the unwillingness of some important countries (e.g. US, China and India) to accept quantitative targets under the Kyoto Protocol and the withdrawal of Canada and Russia. Interestingly, although Canada withdrew from the Kyoto Protocol in 2012, it has eight ongoing CCS projects in the country, three of them associated with the production of synthetic gaseous fossil fuel or hydrogen from bitumen, non-minable coal and oil sands, and five in which the sequestered CO_2 is used for enhanced oil recovery. In Europe, the EU emissions trading scheme (ETS), which was intended to create a market for carbon reductions, has so far

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199 http://www.ukerc.ac.uk/support/tiki-read_article.php?articleId=1606

200 Ladanai, S. and Vinterbäck, J. (eds.) (2009) *Global Potential of Sustainable Biomass for Energy* Report 013, Uppsala http://pub.epsilon.slu.se/4523/1/ladanai_et_al_100211.pdf

201 www.globalbusinessinsights.com/content/rben0172m.pdf

202 http://www.globalccsinstitute.com/

largely failed to do so perhaps because carbon prices have been much less than expected and have, therefore, failed to create a significant stimulus for carbon reduction and, by extension, CCS development in Europe. In the race to develop commercial CCS plant there will, of course, be winners and losers but it seems that countries and companies tend to see CCS as an important opportunity that they should grasp.

7.7 Economic considerations

7.7.1 Energy cost comparisons

We have seen that in at least one significant study by Mott MacDonald commissioned by DECC [ref. 106], an attempt has been made to compare the costs of the various technologies proposed in our three Pathways in a 'levelised' form – i.e. taking account of the initial investment and the ongoing operational costs by combining these into a single 'levelised' figure for the cost in £/MWh for each technology at a given point in time [see Table 5.3 and ref. 75]. Since that study, DECC has been making a serious analysis of the process by which an estimate can be provided for the complete cost of all the elements in a proposed Pathway. This analysis is based on inputs from a number of consultants, including Mott MacDonald, and incorporates their engineering and commercial judgement, backed up by factual information on cost trends during the past decade. Using this information, they have made their own judgements about 'low', 'point' and 'high' estimates of the cost of each element. The resulting figures inevitably have a certain subjectivity.

In interpreting these figures, the reader should be aware that the results of such calculations depend on the assumptions made with respect to:

- discount rates, which can skew the calculations in favour of existing technology;
- "carbon taxes" (i.e. penalties on GHG emissions) which, intentionally, make fossil fuel generation more expensive; and
- the cost benefits of moving from first-of-a-kind (FOAK) to n^{th}-of-a-kind (NOAK), which tend to favour large-scale generators such as nuclear and CCS.

In DECC's calculations, a single discount rate of 3.5% is used, taken from the Government "Green Book"); no carbon penalties were imposed; and no differentiation is made between FOAK and NOAK. The most significant of these is likely to be the surprisingly low discount rate, which will favour offshore wind, nuclear and, to a lesser extent, CCS. CCS will also have a small benefit from the absence of a carbon tax. In the longer term, nuclear costs will be increased by the absence of a NOAK discount. One positive side of DECC's work is that the results so far have been published within the framework of the Pathways to 2050 software, so that it is possible for us to extract all the information required to provide such estimates for each of our three Pathways on a comparable basis. These are shown in Table 7.5 below. The figures in this table are taken from the 'Cost Absolute' tab of the DECC Excel Calculator, and rounded to the nearest £billion. It will be seen that the spread in estimates between the 'low' and 'high' estimate is in every case quite large, and the 'point' estimate is somewhere between these, but not necessarily at the mid-point. An indication of the source material used by DECC to derive these estimates, and some of their caveats, can be found in the Calculator[203].

[203] http://2050-calculator-tool-wiki.decc.gov.uk/pages/28

Table 7.5 Quinquennial cost estimates for the three Pathways, all at current prices

Quinquennial cost estimates	£B/quinquennium		2010	2015	2020	2025	2030	2035	2040	2045	2050
High Nuclear Pathway	Capital costs	low	91	96	109	129	134	137	138	139	136
	Operating costs	low	90	88	86	94	97	91	81	68	50
	Fuel costs	low	46	43	40	35	29	26	24	21	18
	Total cost	low	227	226	235	258	260	255	243	228	204
	Capital costs	point	103	111	127	161	172	175	182	185	189
	Operating costs	point	98	102	109	125	136	139	138	131	121
	Fuel costs	point	46	50	54	54	51	48	44	38	32
	Total cost	point	247	263	290	340	359	362	363	354	342
	Capital costs	high	137	149	176	247	285	302	337	373	416
	Operating costs	high	110	116	125	152	180	200	220	241	265
	Fuel costs	high	47	59	70	75	75	72	67	58	44
	Total cost	high	294	324	371	474	539	574	624	672	725
			2010	2015	2020	2025	2030	2035	2040	2045	2050
High Renewables Pathway	Capital costs	low	89	95	109	129	137	132	137	144	146
	Operating costs	low	89	86	82	86	86	81	74	69	60
	Fuel costs	low	45	40	34	27	20	16	13	11	8
	Total cost	low	223	221	225	242	242	229	224	223	214
	Capital costs	point	103	112	131	163	178	173	183	195	220
	Operating costs	point	97	101	105	117	123	124	123	122	115
	Fuel costs	point	44	47	47	42	35	26	19	13	9
	Total cost	point	244	259	283	323	336	323	324	331	344
	Capital costs	high	140	153	185	255	298	296	329	384	443
	Operating costs	high	109	115	125	148	168	178	186	195	198
	Fuel costs	high	45	53	57	55	46	29	14	4	-4
	Total cost	high	293	321	367	459	511	503	529	583	637
			2010	2015	2020	2025	2030	2035	2040	2045	2050
Intermediate Pathway	Capital costs	low	91	95	108	127	130	132	134	137	134
	Operating costs	low	90	86	84	87	87	78	68	59	48
	Fuel costs	low	46	43	39	34	29	27	25	23	21
	Total cost	low	227	224	231	248	246	237	227	218	203
	Capital costs	point	103	110	126	158	167	169	177	186	191
	Operating costs	point	98	101	106	118	126	125	123	120	116
	Fuel costs	point	46	49	52	52	50	47	44	41	37
	Total cost	point	247	260	285	327	342	341	344	347	344
	Capital costs	high	137	149	175	240	272	281	309	345	372
	Operating costs	high	110	115	123	142	161	166	171	178	184
	Fuel costs	high	46	57	65	69	70	67	64	60	52
	Total cost	high	293	320	363	452	504	514	544	583	608

Rather than using their data to construct 'levelised' costs (that would ignore the economics of reductions in energy demand), DECC has preferred to present breakdowns of these quinquennial costs in terms of the mean 'Cost per capita per year', calculated over the years 2010-2050. For our three Pathways these are given in the 'Cost per capita' tab in the DECC Excel spreadsheet, from which the figures shown in Table 7.6 below have been extracted.

It will be seen from Table 7.6 that DECC's total annual average point estimates for the three Pathways are very similar, and the differences are well within the band of uncertainty in the estimates. Interestingly, the largest differences between the three Pathways occur in the "Transport" row, with the numbers reflecting the level of ambition chosen by the three Pathways in terms of changes in behaviour (i.e. miles travelled). The total capital costs for the three Pathways are surprisingly similar: this is perhaps because the selected technology has been strongly influenced by market forces in each case, and in all three Pathways, the UK will within a few years be starting almost from scratch – the existing nuclear cohort, and much of the more conventional energy infrastructure, will have been retired, and whatever new system replaces them will have rather similar investment profiles.

Given the importance of these figures in influencing decisions on public and private investment policy, it is perhaps surprising that they have not yet been the subject of much published expert scrutiny or media comment.

Table 7.6 Average Cost per capita per year in £ for the three Pathways 2010-2050

	High Nuclear	**High Renewables**	**Intermediate**
Cost/capita/year av 2010-2050	Point	Point	Point
Thermal (incl CCS)	51.9	18.5	73.1
Nuclear	120.0	3.9	62.7
Wind	47.4	201.1	72.8
Wave, Tidal, Hydro, Geothermal	3.5	52.1	3.8
Solar	34.5	95.4	34.5
Biomatter to fuel, imports	97.1	47.0	66.0
UK bioenergy	179.6	175.0	179.6
Electricity imports	0.0	13.3	5.7
Electricity Exports	-14.5	-77.9	-4.1
Grid, storage,backup	52.2	69.9	61.2
H2 production	7.6	0.0	0.0
Domestic Heat & Insulation	644.1	864.1	644.1
Commercial heat & cooling	110	46.9	109.8
Lighting, appl, cooking	49.2	54.0	49.2
Industrial processes	131.7	131.7	131.7
Transport	2467.6	2171.9	2331.1
Fossil fuel prod & imports	611	506.4	634
District heating	2.9	1.9	2.2
Storage of captured CO2	16.1	4.8	27.4
Total point estimate	4612.0	4378	4485
For information:			
Total low estimate	3404	3257	3286
Total high estimate	7178	6588	6554

7.8 Overall social acceptability, including public opinion and politics

7.8.1 Public attitudes

As regards renewable sources, the most recent national UK DECC surveys[204] found that 77% of those asked supported renewable energy for providing our electricity, fuel and heat, with 26% strongly supporting. Just 4% opposed renewable energy. Highest levels of support were found for solar (82%), offshore wind (73%) and wave and tidal (72%). Onshore wind had the highest level of opposition, though still only 12% opposed this, with 4% strongly opposing compared with 66% supporting.

On nuclear power, the DECC survey mentioned above found:

- 43% agreed that nuclear energy provided a reliable source of affordable energy; 17% disagreed.
- 33% felt that the benefits outweighed the risks; 28% felt that the benefits and risks were about the same; and 28% felt that the risks outweighed the benefits.

An Ipsos-Mori opinion poll in December 2011[205] reported on their annual findings during the period 2005-December 2011. Their key findings were:

- To the question: "How favourable or unfavourable is your opinion or impression of the nuclear energy industry?", the number responding "very/mainly favourable" rose from 33% in 2005 to 40% in December 2011, with a major dip down to 28% in June 2011 (just after the Fukushima disaster).

- To the question: "To what extent would you support or oppose the building of new nuclear power stations in Britain to replace those that are being phased out over the next few years?", the numbers supporting this grew from 20% in 2001 to 50% in December 2011 (at which point 20% were against). There was again a dip down to 36% in June 2011. Men were generally more supportive than women (63% as against 39% in December 2011).

There seems to be little evidence that the public debate about nuclear power is now strongly influenced by its connection with nuclear weapons. There clearly is a link, if only because the civil nuclear industry uses broadly the same fissile material as the military world, and both face similar risks of the diversion of that material for proliferation or terrorist purposes. However that link does not now feature as prominently in debates or polls about civil nuclear power as it did twenty years ago.

7.8.2 Current UK party political positions

In recent years, both the Conservative and Labour parties have become broadly supportive of the idea that nuclear power should form part of the UK energy mix. The Liberal Democrats voiced their opposition to any new build in the 2010 Coalition Agreement document, and were allowed to abstain in any Parliamentary vote relating to new nuclear construction. The Green Party has historically been opposed to any nuclear power, but some influential voices within the party have recently spoken out. The Scottish National Party, which at present governs Scotland under the devolution arrangements, opposes new nuclear build.

[204] www.decc.gov.uk/assets/decc/11/stats/6410-decc-public-att-track-surv-wave2-summary.pdf - see also data tables
[205] http://www.ipsos-mori.com/researchpublications/researcharchive/2903/Nuclear-Energy-Update-Poll.aspx
http://www.slideshare.net/IpsosMORI/ipsos-mori-british-attitudes-to-the-nuclear-industry

8 Comments by devil's advocates on the three presentations

The following is a representative selection of the comments made by champions and independent reviewers on the text of this report as it now stands. We regard such comments as entirely appropriate in the kind of debate which we are seeking to promote, but we do not propose to attempt to answer them here, even though some members of the Working Group regard them as mistaken.

8.1 Methodology of the report

- The report seems to have swallowed the government's target of 80% reduction by 2050 without any critical analysis or discussion. The 80% figure is premised on staying below 450 ppm of atmospheric carbon, and that is likely to carry us well past the 2 degrees temperature rise which is (widely but perhaps erroneously) supposed to be the level beyond which there is a risk of initiating uncontrollable runaway climate change. At least one reputable scientific organisation[206] argues that the critical parameter is the cumulative emission, not the annual figure, and proposes that this should be kept below 1 trillion tons of CO_2 globally.

- It would be helpful if the Executive Summary included a few sentences about why some other plausibly 'possible' Pathways were not considered, e.g. a different 'Intermediate' pathway that went for a mix of nuclear and renewables, rather than nuclear and (primarily) CCS.

- There is a fundamental incompatibility between wind and nuclear energy, because in both cases their economics dictate that they should generate whenever it is feasible to do so, and neither has a capability to increase output substantially to meet peaks in demand. This means that they are in direct competition for the same generating time slots, and they do not really complement each other. The High Nuclear Pathway could have addressed this problem by rejecting wind power in favour of, say, a minimal amount of gas+CCS, but that would have made the eggs-in-one-basket counter-argument even stronger.

8.2 Nuclear technology

- Both the Intermediate and the High Nuclear Pathways would make the UK vulnerable to another nuclear disaster on the scale of Chernobyl or Fukushima, which would undermine public confidence in this technology. Statistically, an accident on this scale occurs somewhere in the world once per decade.

- No account has been taken of the GHG emissions from the process of mining uranium. This could become significant as high grade ores run out, and the industry depends increasingly on the processing of low-grade ores[207].

- Both 'nuclear' Pathways assume that spent fuel and high-level wastes will be held in 'interim' storage until a geological waste repository becomes available. On present UK planning, this will not be earlier than 2040, and even then the space will initially be earmarked for 'legacy' wastes – i.e. waste and spent fuel from past and current plants. So the 'interim' storage' may well be required for ~100 years. The High Nuclear Pathway makes it sound as though reprocessing is somehow an alternative to disposal – it is not. Deep disposal is still needed eventually. It is true that substitution of vitrified high-level waste for spent

[206] http://trillionthtonne.org
[207] Sovacool. B. (2008) 'Valuing the greenhouse gas emissions from nuclear power: A critical survey', *Energy Policy* Vol.36, pp. 2940-2953; Harvey, D (2010) *Carbon Free Energy Supply* Earthscan, London

fuel will make disposal easier but there will always be some spent fuel that will need disposal. Where this is of the mixed oxide type, its higher heat output could make disposal very difficult indeed.

• The large amounts of new nuclear capacity on the grid will cause operational problems. Unless the new plant can be run flexibly, there will be large excesses of output overnight, in summer especially. There would also be an increasing need for extra backup reserve capacity in case some of these plants have unforeseen outages.

• A large increase in the size of the civil nuclear programme will cause a range of security, proliferation and fuel cycle safety issues, such as terrorism and nuclear weapons proliferation. Management of such threats is liable to cause public concerns over security-oppression. None of these issues arise in renewable-energy-based programmes, except in relation to the management of legacy waste. With no new nuclear build, and a rapid phase out of existing plants, the security and proliferation problems will rapidly diminish.

• Nuclear power is well established, but shows no sign of becoming more economically attractive (e.g. the European EPR cost estimate has increased by a factor of four, adjusted for inflation, over the past ten years[208]). Nuclear facilities remain environmentally contentious.

• The disposal of nuclear waste continues to raise problems of social acceptability, even though the technical problems were (arguably) solved long ago. The liabilities that arise from nuclear technology are very long term (at least a hundred years) and very few (if any) countries have shown that their disposal route does not place a significant financial and technical burden on future generations.

8.3 Carbon capture & storage technology

• CCS is a relative newcomer, and although the technology can be expected to improve, it is clear that it will be expensive and also environmentally contentious. There are concerns about toxic environmental emissions from CCS facilities, and also about its propensity to initiate earthquakes, which might in turn lead to catastrophic releases of stored CO_2.

• According to Vaclav Smil[209], "To sequester just 25% of CO_2 emitted in 2005 by large stationary sources of the gas (9.6 Gm^3 at the supercritical density of 0.468 g cm^{-3}), we would have to create a system whose annual throughput (by volume) would be slightly more than twice that of the world's crude-oil industry, an undertaking that would take many decades to accomplish." We do not have the time if we are to avoid catastrophic climate change, and it could prove to be rather expensive.

8.4 The High Renewables Pathway

• This Pathway rejects biomass imports, nuclear and coal+CCS, but retains 1.7 GWn of coal, biomass and gas generation demonstration projects which include CCS. By rejecting CCS beyond these demonstration projects and, with it, the opportunity to achieve negative CO_2 emissions by burning biofuel, the only route to achieving the required 80% reduction in GHG emissions is to maximise renewable generation while minimising the use of fossil fuel. The outcome is a Pathway which is dominated by Level 4 choices. Remembering that Level 4 represents "the extreme upper end of what is thought to be physically plausible by the most optimistic observers", the question of feasibility immediately arises.

[208] http://www.worldnuclearreport.org
[209] *Nature* **453**, 154 (8 May 2008) Long-range energy forecasts are no more than fairy tales

- Unlike the High Nuclear Pathway, the issue here is not too many eggs in one basket but too many baskets – some of the technologies will require a lot of development and, even then, will contribute relatively little; there is a distinct danger of spreading the development resource over so many areas that little progress is made in the time available.

- The Pathway envisages significant overcapacity in electricity production to cover for a shortfall in supply under low wind conditions. When the wind is blowing, on the other hand, there will often be an excess of electricity production. In this case the Calculator assumes that, being surplus to requirements, around 35% of the total electricity production will be exported. This is reflected in Table 7.6 which shows electricity exports making a significant negative contribution to the cost of the Pathway. The difficulty with this argument is that it assumes that the market for these exports would be strong enough to command prices that would adequately reflect the cost of the investment.

- This Pathway has extremely demanding measures for energy saving; so demanding indeed, that they will likely only be achieved by regressive measures. It is assumed, for instance, that notwithstanding improved domestic insulation, people will be content to reduce the average temperature of their homes from the current 17.5°C to 17°C in winter. It seems unlikely that this will happen voluntarily: the most obvious way of achieving such a target would be to make energy less affordable, a measure that could produce societal damage in terms of energy poverty and social cohesion.

8.5 Intermediate Pathway

- With a significant contribution from nuclear power, the Intermediate Pathway is susceptible to all the arguments advanced against the High Nuclear Pathway. In addition, however, it combines nuclear with CCS, which is a relative newcomer.

- While CCS technology can be expected to improve, it is clear that it will be expensive and also environmentally contentious. There are concerns about toxic environmental emissions from CCS facilities, and also about its propensity to initiate earthquakes, which might in turn lead to catastrophic releases of stored CO_2.

- Because CCS will diminish the efficiency of electricity production, fuel utilisation will increase (compared to unabated use of fossil fuels). This increases costs but, more significantly, makes fossil-fuelled electricity generation even less sustainable than it is now. Furthermore, the additional complexities that will arrive when CCS equipment is fitted to electricity generation plant will, almost certainly, make the plant more prone to breakdown and less flexible in terms of adjusting electricity output to match demand.

9 Conclusions and Recommendations

- During the next 40 years, the UK will have to re-build its energy supply infrastructure almost completely, in response to the urgent need to tackle the threat of climate change before it is too late, and the obsolescent nature of so much of our current infrastructure, including particularly our fleet of nuclear reactors. It is difficult not to be overwhelmed by the sheer scale of the required industrial activity, which we estimate to require an expenditure of order £3 trillion between now and 2050.

- During the past decade, the UK government has been collecting together the technical and economic data which would permit the development of an energy policy which would underpin and give direction to this massive industrial activity. But sadly, it has not been providing the leadership required to achieve either a cross-party consensus or public agreement on the right way forward. Instead, much of the parliamentary and public debate has been at a rather superficial level, and has not addressed the numerical and technical constraints on a feasible strategy.

- In this report, we have outlined three 'possible' Pathways to 2050 – possible in the sense that they are based on energy technologies which either exists, or can reasonably be expected to be brought to sufficient commercial maturity in time for them to be rolled out on the scale required if they are to meet both the likely UK energy demands and the target GHG reductions in 2050. We have called these three strategies the 'High Nuclear', 'High Renewables' and 'Intermediate' Pathways. These terms are broadly self-explanatory, but the 'Intermediate' Pathway not only has a combination of nuclear and renewable technology, but it also makes substantial use of the developing technology of Carbon Capture and Storage (CCS). Our three 'Pathways' are by no means the only possible ones, but in our judgement they span the range of possible solutions reasonably well. For each of the Pathways, we have nominated a 'champion' to define its parameters, and to write a chapter of the report making the case for that Pathway.

- Our three Pathways have some similarities to three of the four illustrative pathways set out in the Government's 2011 Carbon Plan, but also some differences, which are discussed in this report.

- All three Pathways meet the over-riding constraint that by 2050 the UK's emissions of Greenhouse Gases (GHG) will have fallen to less than 20% of the 1990 baseline value of 783.1 Mt CO_2e/y. There is an ongoing debate within the climate modelling community over the adequacy of this target, but successive UK governments have made an international commitment to achieving it.

- In order to ensure a common approach to energy accounting and costing, our champions were encouraged to make full use of a computer tool which DECC has made publicly available under the title "Pathways to 2050 Calculator". Using this software, each champion has developed a 'Pathway', and computed its key numerical characteristics, including the mix of technologies proposed, the timetable for their introduction, the progressive reduction in GHG emissions and the overall cost of the programme. The Calculator also offers a 'stress test' – an assessment of the ability of the system to cope with some specified unfavourable climatic conditions without disruption of electricity supply. All three Pathways pass the 'stress test'.

- The outcome of our analysis is that all three Pathways are broadly 'possible' in the above sense. We also find that they all have a broadly similar estimated total cost - approximately £2.8 trillion between now and 2050 - though such estimates are contentious, and naturally have a very wide margin of error.

- Each of our Pathways has a number of technical and/or commercial challenges which might eventually prove to be 'show-stoppers'.
  - As regards Nuclear technology, the two Pathways that involve it accept that the only feasible solution is to engage in serial production of one of the 'third-generation' PWR or BWR designs which are now being constructed worldwide. Several of these construction programmes have encountered delays and cost escalations, and some of the plants which are already operating are not yet achieving their designed load factor.
  - As regards Renewable technology, all three Pathways make significant use of bioenergy and the High Renewables Pathway also has a large wind component. Both bioenergy and onshore wind have constraints relating to the public acceptability of the required land use. Offshore wind is still a rather expensive technology, and the feasibility of achieving the cost reduction required for it to become competitive remains to be proved.
  - As regards CCS, there is as yet no full-scale plant operating anywhere in the world, although components of the technology are well-established at pilot plant scale. Deployment on the scale envisaged in the Intermediate Pathway would require a pipe infrastructure capable of handling some 100 Mt per year – i.e. handling a mass of CO_2 comparable to the amount of oil extracted annually by the UK at the time of the peak of North Sea oil production.

- Given the technical/commercial risks involved, it is understandable that the government has in recent years taken the view that the private sector should carry this risk, and that the government should simply create a level playing field and then stand back and let the market determine the eventual outcome. We recognise that its recent 2012 Energy Bill, which is designed to create an 'Electricity Market' is aiming to do just that. However, in our view, that is an unreal position, given the scale and urgency of the task. The UK does not currently have an industrial infrastructure capable of rolling out any of the proposed technologies on the scale and at the speed required to meet the 2050 emissions target. Twenty years ago it might have claimed that it had the required nuclear industry infrastructure, but it certainly does not today. It is slowly building up a Renewables technology infrastructure, but (for example) almost all of its wind turbines are currently imported, and UK turbine manufacturers do not feature in the list of the 10 top suppliers world-wide. As regards CCS, the UK government has been seeking bids for a £1bn CCS Demonstration Project since 2007: the most recent announcement (Oct 2012) is that it has short-listed four bids and expects to announce a decision early in 2013.

- What is missing – and is sorely needed - is a plan with named technologies, with target dates for the construction of full-scale commercial plants of the chosen types, a management team capable of implementing that plan, and a set of government-funded incentives to induce the private sector to play its part in implementing it, and to establish training schemes for the cadres of skilled staff required to make it all happen.

Annex 1 Pugwash Users Guide to DECC Pathways Software

As we have seen in Sections 1.3 and 3.6 above, the DECC Pathways Calculator provides a very powerful and straightforward means of exploring possible pathways, by inviting users to specify the values of 43 parameters in their proposed pathways, and then computing the implications of those choices. The selections of these 43 Headings made in the three Pathways presented in this report are as shown in Table 3.2 above. As noted, we have chosen non-integral values for some of the headings. This is permitted by the software, but non-integral values are interpreted in a slightly idiosyncratic manner, and we have had to engage in some experimentation to achieve the required Pathways.

Perceptive readers may have noticed that the list of 43 Headings does not include certain highly significant primary energy sources – for example, coal, oil, gas, pumped heat from underground. This is because the DECC software computes the energy which must implicitly be supplied from these sources, once the values of certain listed headings have been specified. These implicit assumptions require some detective work to identify. Some comments on the limitations of the DECC software assumptions will be found in Chapter 5.

The chosen values of these 43 Headings can be fed into one or other of two alternative versions of the DECC Pathways software. The simpler of these is the 'web' version, which can be initiated by following the link[210] and entering the user choices offered on the home page, or by running the url for the chosen Pugwash Pathway, as specified below[211] for the High Nuclear, High Renewables and Intermediate Pathways respectively (the url incorporates the values chosen by the user for the first 43 Headings, unfortunately using a code which is opaque to us). We can make available to interested readers a copy of the Excel Calculator in which the three Pugwash Pathways are stored in columns AB, AC and AD, from which they can easily be copied into column E. An irritating problem is that the Web version does not enable the user to specify a choice for the 43rd Heading (Indigenous fossil-fuel production), but automatically takes the 'default' setting 1. In all the Pugwash Pathways, we have preferred setting 3, so we have had to set this manually within the Excel version. .Having done so, it is possible to copy the whole column of Heading values (including the chosen value for Heading 43) across to the web version (using its 'share' facility), and the web software then calculates the url for that Pathway correctly, and generates a Sankey diagram reflecting those choices.

When the Excel version is run, the user is invited to update links to other spreadsheets, and then to 'continue' even though some links cannot be updated. Both requests should be agreed. The user is also invited to press the key F9 after each change to column E, and this is good practice, though not normally necessary.

Until very recently, the only version of the Excel software which could be downloaded from the DECC website was Version 2.1. This was described as the 'canonical' version, and only DECC staff were allowed access to more recent versions[212]. In our view this was unfortunate, since Version 2.1 had a considerable number of minor software errors which impeded our use of the software. Some of these are reported below. In December 2012, DECC released a new version of both the Excel- and web-based Calculators, described as version 3.4.1. This was unfortunately too close to our planned date of publication for us to make full use

[210] http://2050-calculator-tool.decc.gov.uk/
[211] http://2050-calculator-tool.decc.gov.uk/pathways/s1f3cc1111121f1102231230023222023330220230233022012 3
[211] http://2050-calculator-tool.decc.gov.uk/pathways/1011ot2wr1frz41303441210044144403423041023042304 10133
[211] http://2050-calculator-tool.decc.gov.uk/pathways/2023d2111112121202231220023132202333022023024302 20133
[212] We are aware that a new version (3.4.1) has just been released as we are going to press: so far as we can ascertain, it does not affect any of the numbers in this report, or eliminate any of the problems identified in this Annex.

of the new version, but we have established that for our three chosen Pathways, the new version generates exactly the same Flows (as given in the Flows Tab) as the earlier version, and the Sankey diagrams are also based on the same numbers. Unfortunately these numbers have the same errors as previously.

A regrettable feature of the current version of the DECC software is that neither the Web nor the Excel version can generate all of the useful outputs of the DECC model on its own: they need to be used in conjunction. Both versions present some of the most significant outputs of the model (UK energy demand, UK primary energy supply and GHG emissions) in graphical form. Unfortunately the graphs from the two versions are not identical. The differences are due to different energy accounting conventions. A more significant difference is that only the web version gives access to the 'Sankey diagram' for the Pathway, accessed by following a drop-down menu called 'See implications' and taking the 'Energy flows' option. These diagrams are printed in Annex 2 below for our three Pathways, and we have used them extensively in tracking down the explanations for discrepancies which we have found in the numerical outputs from the Excel version. Unfortunately there seems to be no way to print the Sankey diagrams with all the numerical annotations included. These can only be read on screen, using the mouse to pick them up.

The home page of the web version reproduces the selected values of 42 out of the 43 Headings in convenient tabular form (see above for the problem over the 43rd), and presents a lot of other useful summary information. However there is no obvious way to access information about how its output numerical values are obtained. It seems that it generally incorporates a lot of the Excel version assumptions and calculation algorithms, but not all.

We regard the Excel version as providing the definitive numerical information on the final outputs from the model, and on some of the intermediate steps in calculating those outputs. As explained in Section 3.6.1above, it consists of 73 spreadsheets, each identified by a rather un-informative tab label. The most important of these are the 'Control' spreadsheet, which can be used to input the selected 43 Headings, and the 'Intermediate Output' and 'Flows' spreadsheets, which contain most of the numbers which we present in this report. In addition, we use the 'Land Use', 'Cost per capita', 'Cost Absolute', and (occasionally) the 48 'Module' Tabs, which are helpfully indexed in the Tab entitled 'Structure of the model'.

Unfortunately the numbers in these various Tabs are not always mutually consistent, and the lists of contributions to the overall energy system are not always equally complete, so we have had to take a view on which sources to choose. After much debate, we have chosen to use the information contained in the 'Flows' Tab as being the most complete and accurate, and we have tried to ensure that all the numbers presented above are consistent with that. Our reasons for doing so are:

1. We believe that the Sankey diagrams provide the most complete statement of all the energy flows considered in the model, and the list of flows given in lines 6-94 of the Flows Tab is consistent with that.
2. The magnitudes of the energy flows given there agree with those which can be read off the Sankey diagram in most cases. Differences are due (so far as we can see) to the inability of the web version (which alone presents the Sankey diagram) to represent the choice of Heading 43 correctly. Apart from these, the figures are identical.
3. The 'Intermediate Output' Tab presents a list of flows in lines 370-460. If these and the Flows Tab lists are copied onto a single spreadsheet, and aligned appropriately, it is found that most of the numbers are identical. In the few cases where they differ, it is easy to check where the 'Intermediate Output' figures come from, and in each case there seems to be an addressing error. We have not been able to trace the source of the Flows Tab figures in these cases, because of the opaque formulae used to construct them.

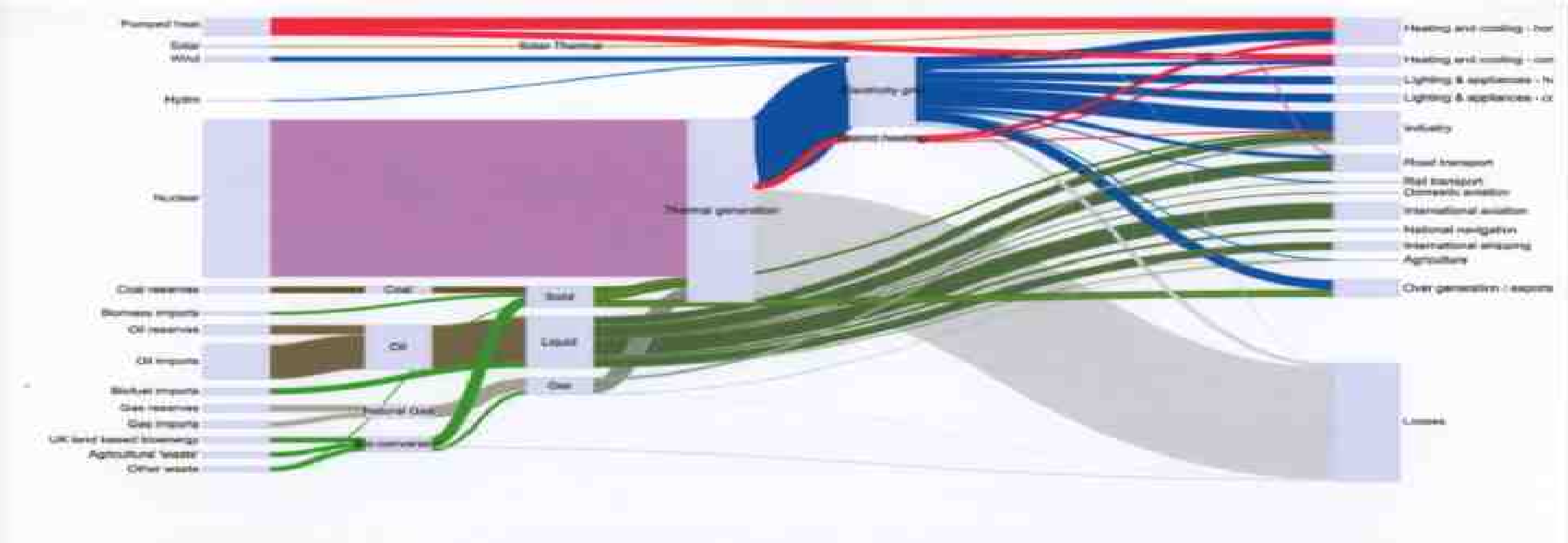
However the agreement of the Flows Tab and Sankey figures in these cases gives us confidence that in most cases they are correct.

It is unfortunately not a straightforward matter to convert the Flows Tab figures into an easily understandable format. The raw figures are presented in a rather arbitrary order, and without any helpful sub-totals. For this reason, we have sought to perform some Excel manipulations, leading to the summary presentations given in the various tables in Chapter 7. In each case we have used check-sum totals constructed from the raw data to ensure that no errors have been introduced by these manipulations. A particular problem which arose during this work was that the calculations within the Flows Tab reported in columns R to AY, with a heading entitled “Cross check of flows through the energy system (based on the idea that energy is transformed, but not destroyed)” purport to show that energy is conserved during the transformations between the primary energy input and the end user output. When it fails to do so, the discrepancy is highlighted in red, but no attempt is made to correct this obvious deficiency. We have encountered red entries in this Tab for both the High Renewable and the Intermediate Pathways. In the former case, the discrepancy amounts to 48.2 TWh/y (i.e. 5.5 GWav) and can be traced back (via Tab Va line 316) to “bioenergy available but not actually supplied, and therefore available for export”. For some unexplained reason this energy is not included in the flow figure for “solid to over-generation/exports”. In the latter case the discrepancy is only 3.2 TWh/y and is not so readily traced.

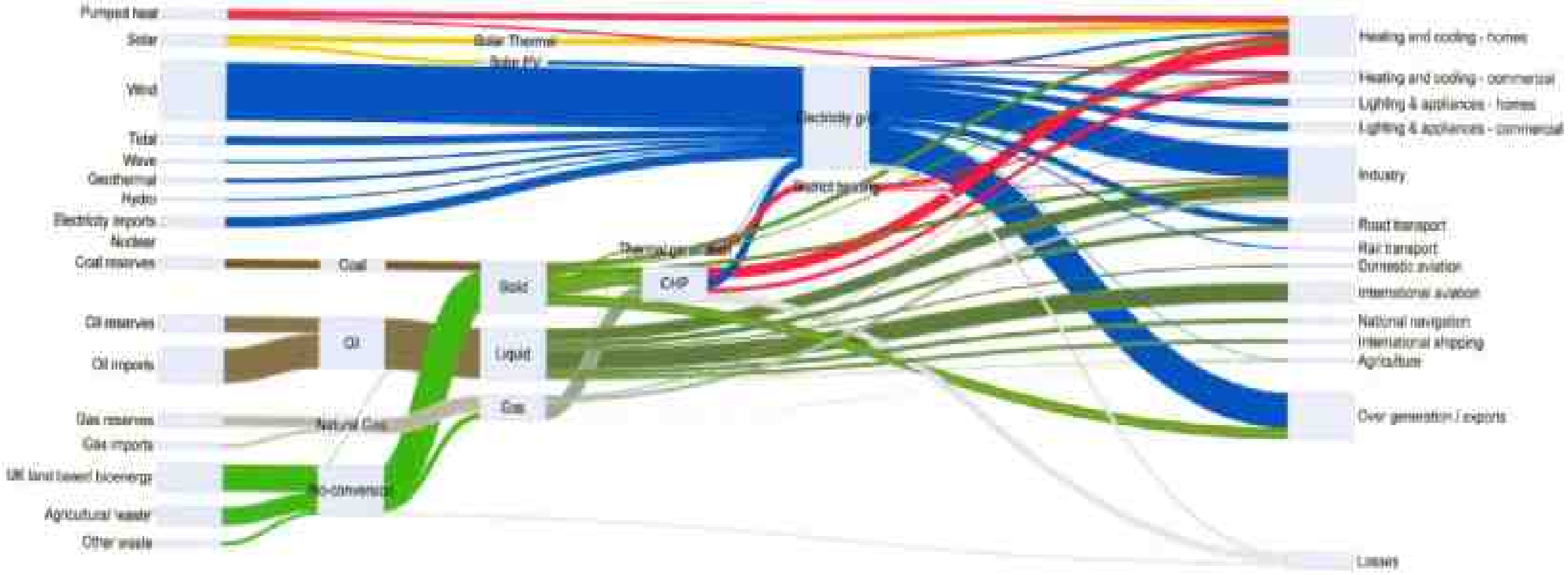
We have not attempted to present all the flow figures in the Flow Tab or Sankey diagram, but we have given a partial summary in the central block of Table 7.2. There, we seek to summarise all the flows crossing a vertical line drawn just to the left of the node entitled “Electricity grid”. This exercise has highlighted how difficult it is to make a clean distinction between flows relating to electrical end use and those relating to other (thermal, mechanical etc) end uses which are not electrically powered.

Annex 2 Sankey diagrams for our three Pathways

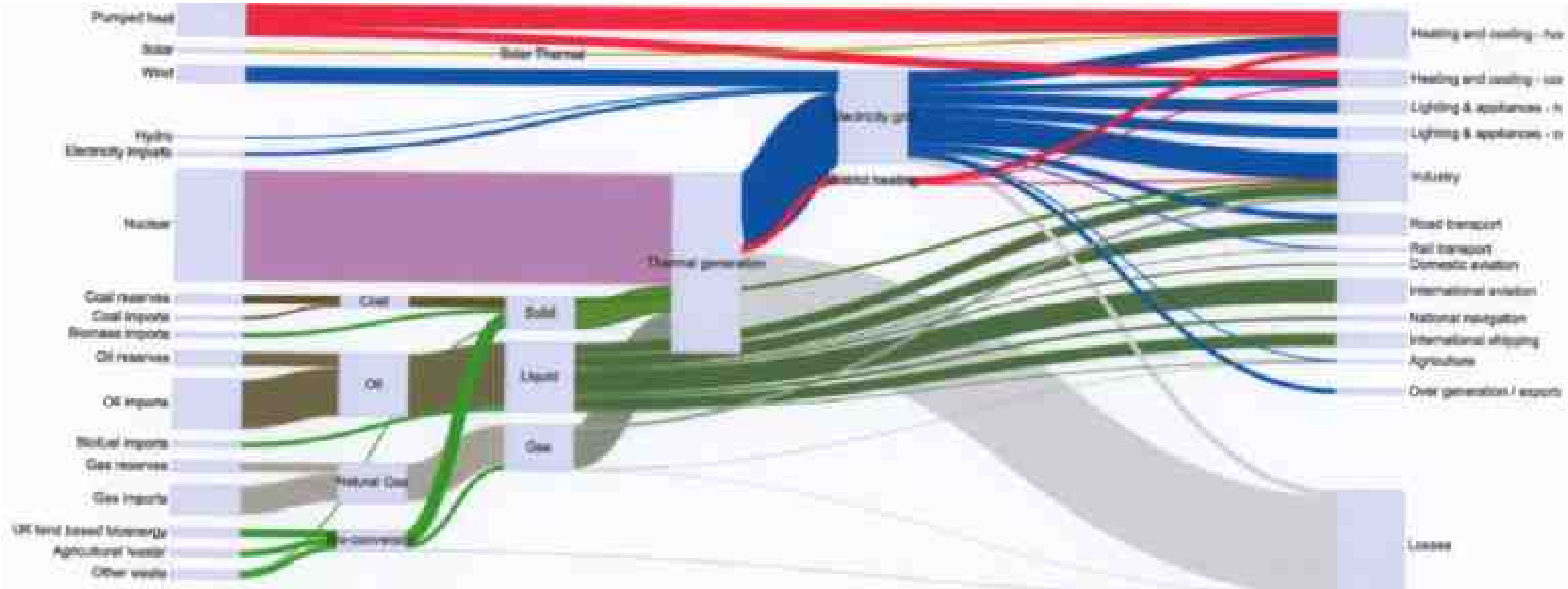
Note that the three Sankey diagrams in this Annex do not exactly correspond to the parameters of the chosen Pathways, because the Web version of the DECC Calculator does not permit the user to specify the value of Heading 43, and omits to print out some of the calculated flows (see Annex 1 for the details)



Sankey diagram for High Nuclear Pathway



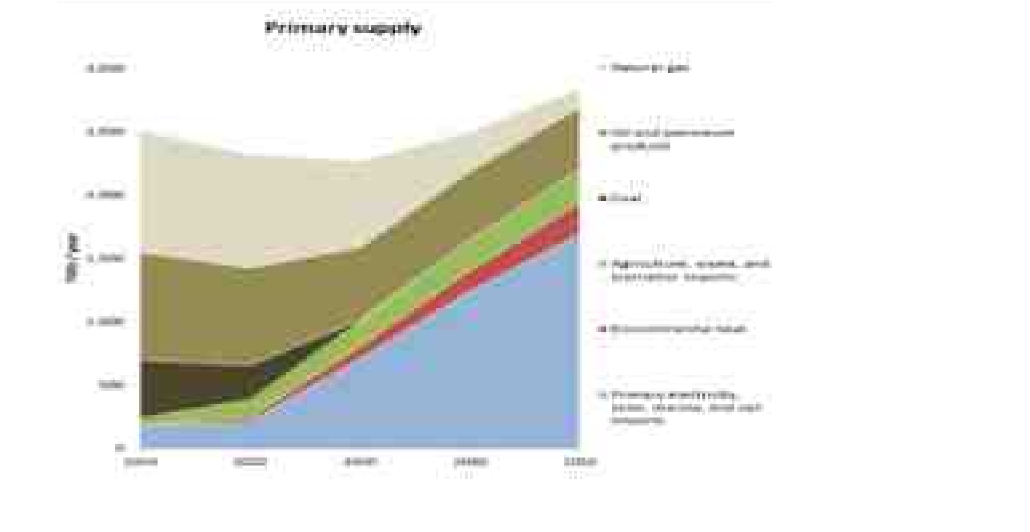
Sankey diagram for High Renewables Pathway

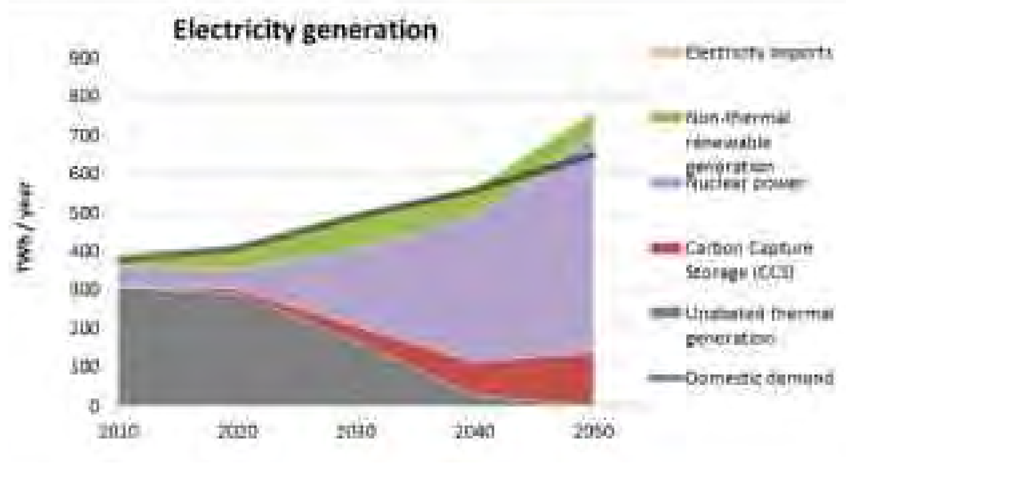


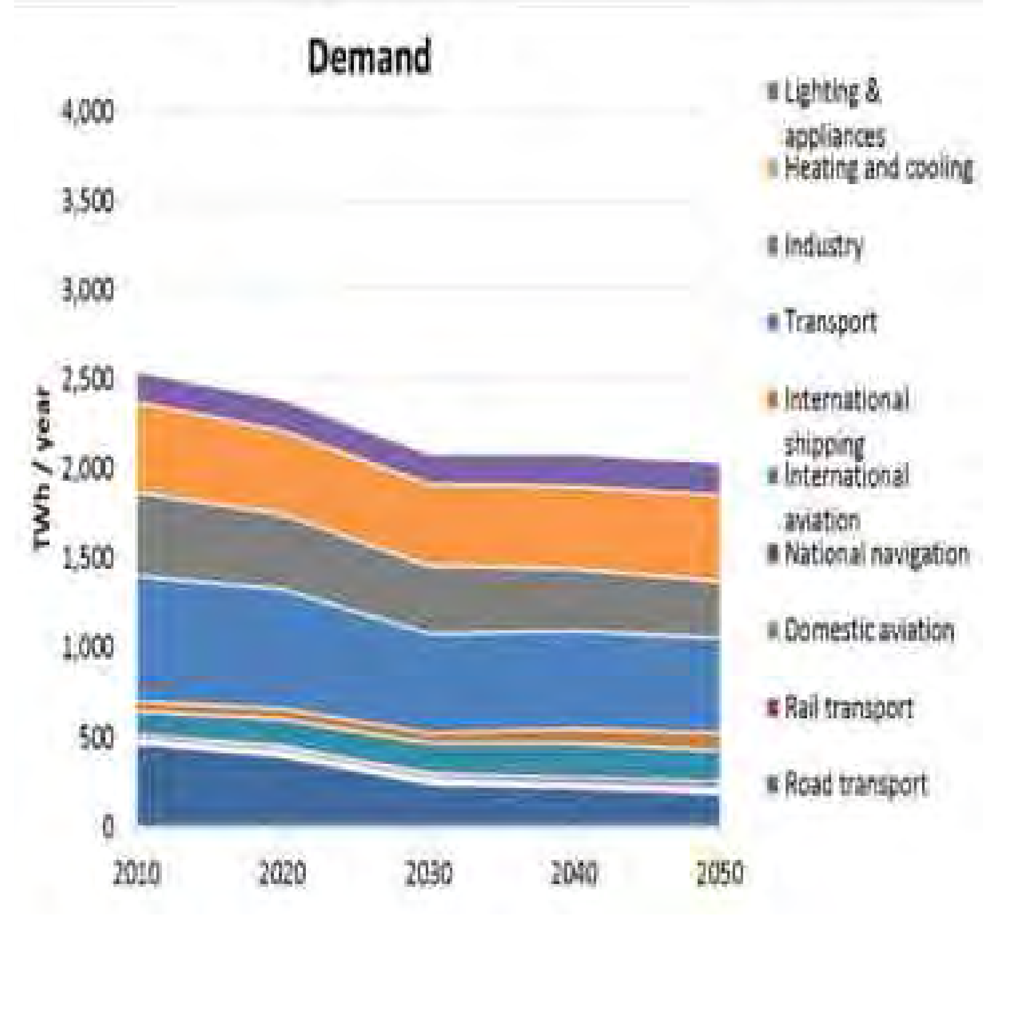
Sankey diagram for Intermediate Pathway

Annex 3 Graphical presentations of development of Primary energy supply, electricity generation and demand

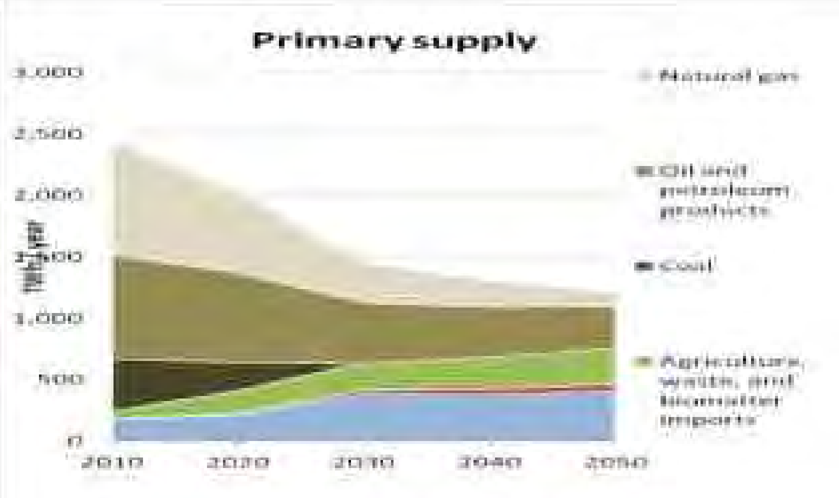
High Nuclear

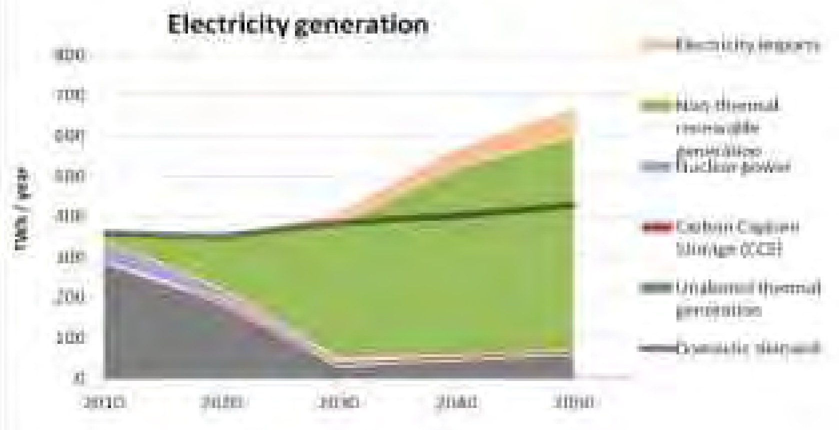


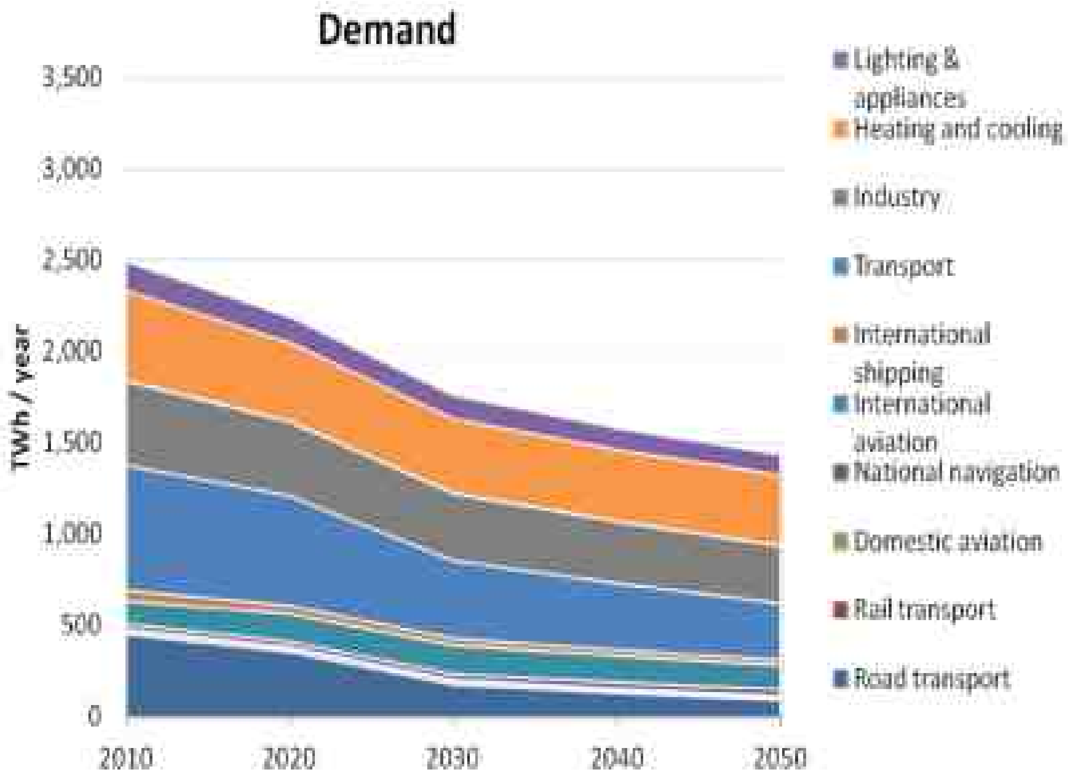




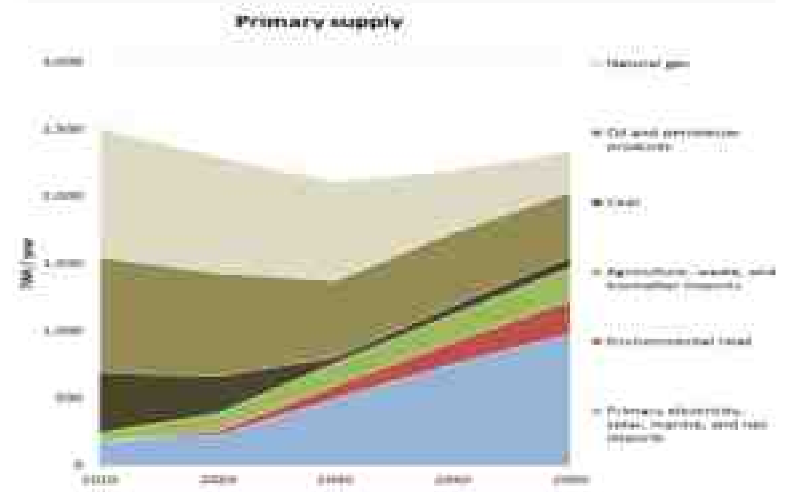
High Renewables

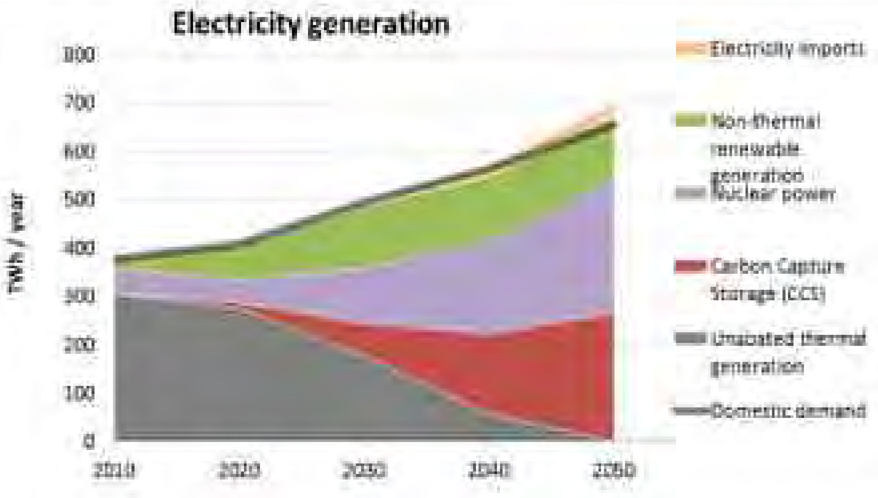


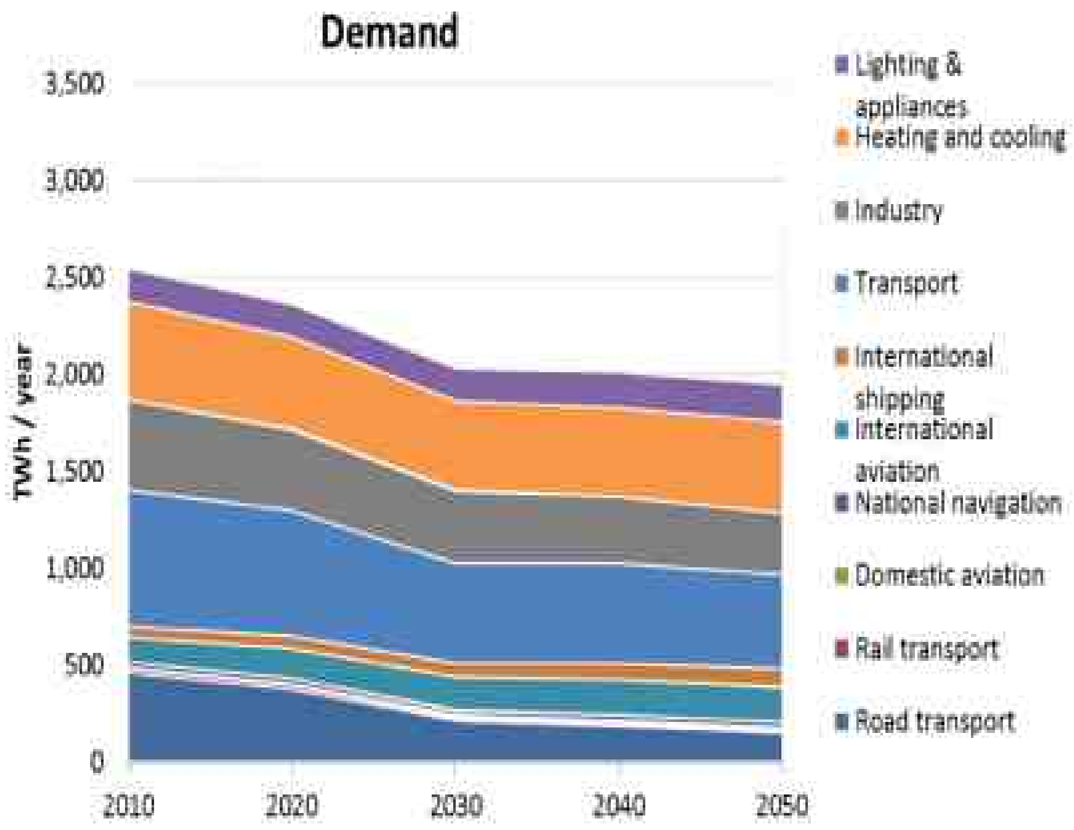




Intermediate







Biographies of members of the Working Group

Dr Christine Brown began her professional career with the United Kingdom Atomic Energy Authority, where her work included the use of plutonium containing fuels in fast reactors. By the late 1980s, she led the UK contribution to the European Fast Reactor Fuels and Materials programme. In 1995, she joined the British Nuclear Fuels Ltd (BNFL) Thermal MOX team at Sellafield to lead the technical development work required to support this part of BNFL's business. In 2002, she joined the US Department of Energy Blue Ribbon Panel formed to advise its Nuclear Energy Research Advisory Committee on the Proliferation Resistant Characteristics of Recycle Fuels. Since retiring in 2006, she has been a consultant on variety of nuclear energy issues. During 2010-11 she was a member of the Royal Society's Working Group of Experts on "Fuel Cycle stewardship in a nuclear renaissance".

Dr David Finney graduated in physics and subsequently obtained a PhD in Ultrasonics at Imperial College London, then taught physics, becoming Head of Science at Tulse Hill School, and then moved to become a Science and Mathematics adviser to Dyfed and then Science and Technology Inspector for Shropshire LEA. Since 1973 he has been increasingly involved in Alternative Technology, and has developed links with the Intermediate Technology Association, the Centre for Appropriate Technology Machynlleth, the Solar Energy Society, the Network for Alternative Technology & Technical Assessment, Scientists for Global Responsibility and Friends of the Earth,. He has always had a 'hands-on' approach, and has designed, built single-handedly, lived in and monitored two passive solar homes. The second was completed in September 1997 and had PV panels installed in November 2002. He has published articles on the monitoring of and lessons learnt from the energy consumption of his self-built properties, and on the principles of sustainable, energy-saving design.

Professor David Elliott graduated in physics with a BSc Hons degree in Applied Physics and a PhD in Solid State Electronics. He initially worked for the UK Atomic Energy Authority at Harwell and then for the CEGB, Bristol, before joining the Open University as a Lecturer in the Technology Faculty in 1971. From then until he retired in 2009, he was involved in developing a range of OU courses in Design and Innovation, with an emphasis on how the design and innovation process can be steered towards the development of socially and environmentally appropriate technologies. His main research interests related to the development of sustainable energy technologies, and in particular renewable energy based systems. His recent publications have covered such topics as 'Energy Regime Choices: Nuclear or Not?', 'Marine renewables', 'Windpower: opportunities, limits and challenges', 'The Emergence of European Supergrids' and 'Fukushima: Impacts and Implications'.

Dr Ian Crossland has worked in the UK nuclear industry for more than 40 years. Until 1990 he worked on the in-reactor behaviour of fuel. Since that time he has specialised in decommissioning and radioactive waste management. Since 2003 he has worked as an independent consultant to IAEA and several national radioactive waste management organisations in Europe. He has a particular interest in developing disposal solutions for disused sealed radioactive sources (e.g. old radium sources) in countries with minimal nuclear infrastructure. For the past few years, he has been involved with the ongoing cleanup and decommissioning at Chernobyl. He is a member of the Executive Committee of the British Pugwash Group and was an author of the 2009 British Pugwash report on "The Management of Separated Plutonium in the UK".

Dr Christopher Watson obtained a DPhil at Oxford University in Plasma physics in 1964, and spent 18 years on Controlled Fusion research at Culham, culminating in a management job in the team that constructed JET. He then spent 13 years at Harwell, managing teams of engineers working on offshore technology and nuclear telerobotics. He then moved to become a Business Development Manager, helping the newly-formed AEA Technology to win work in Russia on the management of spent nuclear fuel and radwaste. Since retirement he has continued to work in Russia and Eastern Europe. He has been a member of British Pugwash since 1969, and became its Chairman in 2011. He has been a co-author of several of its recent publications, including "The Management of Separated Plutonium in the UK" and "Verification of Nuclear Weapon Dismantlement" and has been Convenor of the present report.