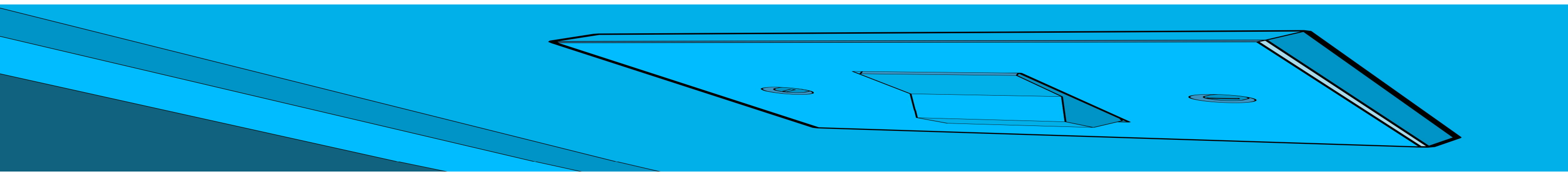


UKERC
UK ENERGY RESEARCH CENTRE

Decarbonising the UK Energy System:

Accelerated Development of Low Carbon Energy Supply Technologies

UKERC Energy 2050 Research Report No. 2

Version 2

March 2009

Draft Report
(subject to peer review)

Mark Winskel, Nils Markusson, Brighid Moran and Henry Jeffrey
(Edinburgh University)

Gabrial Anandarajah and Nick Hughes (Kings College, London), Chiara Candelise (Imperial College, London), Donna Clarke and Gail Taylor (Southampton), Hannah Chalmers (Surrey University), Geoff Dutton (Rutherford Appleton Laboratories), Paul Howarth (Manchester University), Sophie Jablonski (Imperial College), Christos Kalyvas (Imperial College, London) and David Ward (UKAEA Culham)

The research for this Research Report was conducted under the auspices of the UK Energy Research Centre (UKERC) which is funded by the Natural Environment Research Council, the Engineering and Physical Sciences Research Council and the Economic and Social Research Council.

THE UK ENERGY RESEARCH CENTRE

Operating at the cusp of research and policy-making, the UK Energy Research Centre's mission is to be the UK's pre-eminent centre of research, and source of authoritative information and leadership, on sustainable energy systems. The Centre takes a whole systems approach to energy research, incorporating economics, engineering and the physical, environmental and social sciences while developing and maintaining the means to enable cohesive research in energy.

To achieve this we have developed the Energy Research Atlas, a comprehensive database of energy research, development and demonstration competences in the UK. We also act as the portal for the UK energy research community to and from both UK stakeholders and the international energy research community.
www.ukerc.ac.uk

UKERC ENERGY 2050

The UKERC Energy 2050 project is exploring how the UK can move towards a resilient low-carbon energy system over the next forty years. The project focuses on the two primary goals of UK energy policy – achieving a 80 per cent reduction in carbon emissions by 2050, and ensuring that energy is delivered reliably. It acknowledges that the UK will be pursuing these goals in a deeply uncertain world and in a global context.

Together, UKERC researchers and associates are developing a set of "back-casting" scenarios describing possible future energy systems that are both low-carbon, and resilient to external and internal shocks. These will define desirable features of the UK energy system, and identify ways of achieving the transformations needed to get there. Understanding these scenarios in all their dimensions is engaging the full range of skills across UKERC.

ABOUT THIS REPORT

This is the second in a series of reports from UKERC's Energy 2050 project. It investigates the prospects for accelerated development of a range of low carbon energy supply technologies, and the impact of this acceleration on the decarbonisation of the UK energy system. The technologies analysed include a number of renewables (marine, bioenergy, wind and solar PV) and also other low carbon options (carbon capture and storage, nuclear power and fuel cells). Technology acceleration is analysed firstly by devising detailed technology-by-technology accounts of accelerated development, and then system-level modelling of the potential impacts of this acceleration on the UK energy system from now to 2050. The report highlights the potentially important role for low carbon supply technology acceleration in the transition to a low carbon energy system in the UK, especially over longer timescales.

Executive Summary

This is the second in a series of reports arising from UKERC's Energy 2050 project. The report considers the prospects for accelerated development of a range of emerging low carbon energy supply technologies – and the possible impact of this acceleration on decarbonisation of the UK energy system. The technologies analysed here include a number of renewables (wind power, marine energy, solar PV and bioenergy) and other emerging low carbon technologies (advanced designs of nuclear power, carbon capture and storage (CCS) and hydrogen / fuel cells). The report presents a set of scenarios devised by UKERC to illustrate how accelerated development of these technologies could contribute to decarbonisation of the UK energy system from now to 2050. The results suggest that technology acceleration could have a major influence on UK decarbonisation pathways, especially in the longer term.

Background

The broad acceptance that carbon dioxide (CO_2) and other greenhouse gas (GHG) emissions are responsible for climate change has made decarbonisation an international policy priority. As part of wider international efforts, the UK Government recently set out a legally binding framework for decarbonisation of the UK economy from now to 2050, with substantial progress being made over the next decade to 2020.

Decarbonisation is a profound challenge. Economies and societies have developed around carbon-based fuels over decades and centuries, so that carbon emissions are embedded into established patterns of work, leisure, travel and heating. This also means that there are multiple *possible* ways to decarbonise – changing lifestyles, improving energy efficiency and finding different ways to produce energy. Assessing and comparing these different opportunities – and taking account of how they might change over time – means dealing with many uncertainties, and no firm forecasts of the best routes for decarbonisation can be offered.

As part of a wider study of some of the main uncertainties carried out by UKERC, this report focuses on one particular issue: the prospects for accelerated development of a range of emerging low carbon energy supply technologies – and the possible impact of this acceleration on decarbonising the UK energy system. The research has involved bringing together detailed understandings of specific energy supply technologies, with insights on energy system change provided by system modelling and innovation studies. More specifically, the research presented here has involved devising *accelerated technology development scenarios* of UK energy system decarbonisation (which assume high levels of technological progress over time), and then comparing these with non-accelerated equivalent scenarios. Given the uncertainties involved, the results should be seen as illustrating the possible impact of supply side technology progress over the longer term, rather than a detailed mapping out of system change over the next decade and beyond.

Overall Impact of Accelerated Technology Development

Accelerated development opens up alternative pathways for achieving UK energy system decarbonisation, especially over the longer term. The pace of technology development means that, in the short term (to 2020), accelerated development has little impact on the cost and performance of energy supply options in the UK energy mix. Over the medium term, to 2035, more diverse supply portfolios emerge in accelerated scenarios, and in the longer term, to 2050, accelerated technology development makes a very significant impact, with some accelerated technologies playing a much greater role. In attempting to map out desirable decarbonisation pathways for the UK, it is important that the potential for accelerated technology development be taken into account.

Different technologies contribute at different times in the scenarios presented here. In many of the scenarios, coal-fired generation using carbon capture and storage (CCS) plays a major part in the UK energy supply mix after 2020. Bioenergy technologies have an important role across power, heating and transport in the medium and longer terms, after 2020. Offshore wind and marine renewables are also deployed to a much greater extent in accelerated development scenarios, although this impacts mostly after 2030 (and after 2040 for solar PV). Accelerated fuel cells development has a key long term impact on transport sector decarbonisation after 2030. Accelerated development of nuclear power allows for a more sustained nuclear contribution over time than in non-accelerated scenarios. (It is important to note that these results reflect, in-part, assumed progress incorporated in the non-accelerated ‘core’ scenarios. For example, the key role of CCS reflects relatively aggressive assumptions about the pace of CCS development in the core scenarios. Additional scenarios have been produced to illustrate decarbonisation pathways in the absence of CCS, or delayed availability of CCS.)

The overall impacts of accelerated technology development are complex, changing over time as different low carbon supply options are made available, and as overall decarbonisation ambitions increase. For example, accelerated fuel cells development changes the relative attractiveness of decarbonising different energy services, and the supply technologies (and associated research needs) involved. The most attractive supply technologies – and the associated research priorities associated with their commercialisation – are also sensitive to the overall level of decarbonisation ambition. Raising the decarbonisation ambition from 60% to 80% does not simply mean doing 'more of the same' – it introduces new technology preferences and research priorities. For example, the preferred use of bioenergy resources switches between electricity, heating and transport, according to the overall level of decarbonisation ambition and the availability of alternative ways of decarbonising particular energy services.

Overall levels of CO_2 emissions associated with the scenarios presented here are imposed as system-level constraints, so that scenarios sharing the same decarbonisation ambition follow the same overall emissions trajectory. In all scenarios, the electricity supply sector decarbonises first and most thoroughly, and, in 80% scenarios, is substantially decarbonised by 2030, with or without accelerated technology development. Other carbon intensive energy services (especially transport, but also residential demand) decarbonise in the medium and longer terms, with both undergoing much more thorough decarbonisation in 80% scenarios than in 60% scenarios. Accelerated development makes some difference to this broad pattern. For example, the introduction of fuel cells acceleration is associated with greater decarbonisation of transport (and reduced decarbonisation of the residential sector) over the longer term.

Costs and Benefits of Acceleration

The modelling results offer some indication of the overall advantages of supply side technology acceleration in energy system decarbonisation. These advantages accrue mostly in the long term, as accelerated development enables more affordable ways to achieve more extensive decarbonisation. Two parameters – the marginal cost of CO_2 abatement, and the overall 'welfare cost' of decarbonisation – provide some quantification of this benefit. Given the high levels of uncertainty embedded in the scenarios, especially over the longer term, these figures can only offer a broad illustration of the possible benefits of accelerated development (for selected technologies and under assumptions of high levels of progress), rather than any more reliable cost benefit analysis.

The marginal cost of carbon abatement increases over the longer term as progressively more expensive carbon abatement options are deployed. In the accelerated development scenarios, however, this increase is considerably less than in non-accelerated equivalent scenarios – accelerated technology development significantly reduces the long term marginal cost of CO_2 abatement. By 2050, the marginal cost of CO_2 abatement is around £130/tonne in the accelerated development scenario, compared to £170/tonne in the non-accelerated scenario.

Technology acceleration may also substantially reduce the overall social cost of decarbonisation. Over the forty years 2010-2050, accelerated development is associated with a total saving in the 'welfare costs' of achieving 80% decarbonisation of £36bn. Most of this benefit accrues in the longer term, after 2030. This 'saving' should be benchmarked against the added investment costs of accelerated development, in terms of additional spend on RD&D to realise the assumed performance and cost improvements. In practice, this comparison is far from straightforwards, given that the investments associated with technology acceleration will be made internationally. However, there is some evidence that the overall benefits to the UK of accelerated development considerably outweigh the investment costs. From a purely UK perspective, the suggested savings associated with low carbon technology acceleration could be translated into an annual budget for additional UK RD&D investment in low carbon technology development of around £1bn per annum – although much of this investment would need to be committed well before significant 'returns' start appearing after 2030.

Electricity Supply Sector

For all scenarios in which the overall decarbonisation ambition in 2050 is 80%, the electricity supply sector undergoes near complete decarbonisation over the period 2010-2030. After 2030, low carbon electricity is used to decarbonise transport and residential sectors. Accelerated technology development introduces alternative pathways for decarbonising the UK power system in the longer term, and is associated with significantly increased contributions from renewable technologies such as marine, solar PV and especially offshore wind power. The results also suggest that achieving 80% decarbonisation ambition may involve the development a much larger UK power supply industry over the long term. While this expansion is seen with or without accelerated development, it is much more pronounced in accelerated development scenarios, with installed capacity doubling in the long term between 2030 and 2050. This growth is associated with the much greater deployment of renewables (especially offshore wind power) and hydrogen / fuel cells technologies under accelerated development assumptions.

Because low carbon electricity may be an important enabler of system-wide decarbonisation, the absence of an important potential source of low carbon power such as CCS has significant effects across the energy system. The overall pattern of energy service demands and associated carbon emission reductions are significantly altered if CCS is assumed to be unavailable. Decarbonisation scenarios without CCS feature less overall demand for electricity, reduced take-up of hydrogen fuel cells, and a switching of bioenergy resources from residential heating to transport.

Overall Messages

The scenarios presented here allow a structured exploration and illustration of the potential of emerging supply technologies to contribute to UK energy system decarbonisation. The results suggest that emerging technologies could contribute significantly to decarbonisation over the longer term. In attempting to map out desirable decarbonisation pathways for the UK, it is important that this potential be taken into account. In driving energy system change, there is a danger of locking-in to known technologies and infrastructures, and failing to develop and deploy emergent technologies over the longer term. As the scenarios presented here illustrate, these more advanced technologies have the potential to help deliver deeper decarbonisation more affordably in the long term.

Although it carries shorter term implications for system planning and innovation support, supply side technology acceleration only changes deployment patterns over the longer term. This future promise does not imply delaying action to combat climate change until more affordable and better performing supply side options become available: there is increasing evidence of the need for significant decarbonisation over the next decade. Investing in longer-term supply options is a complement rather than replacement for shorter-term action. Indeed, the results suggest that over the shorter term, decarbonisation requires responses from other system drivers and opportunities, such as demand reduction, improved energy efficiency, greater focus on renewable heat, and making best use of more mature supply technologies (by investing in supply chain and installation capacity, and institutional reforms regarding planning and regulation).

The scenarios suggest some disparity between the availability, performance and cost of low carbon power supply technologies, and policy targets for renewables deployment, especially in the short term to 2020. Realising very high levels of renewables deployment by 2020 will require policy support measures and market interventions that go well beyond those embedded in the scenarios presented here. At the same time, the 'learning potential' of emerging technologies over longer timescales imply that highly ambitious short term targets for technology deployment may be inconsistent with the most economically desirable long term decarbonisation pathways – and may direct the energy system into less attractive pathways, seen from a longer term perspective. In the accelerated development scenarios, sustained RD&D investment makes a substantial difference to the cost and performance of renewables and other low carbon supply options, so that their longer term deployment become much less dependent on market subsidies.

Energy system decarbonisation involves a complex interaction between changing patterns of production, distribution and consumption. Within this, supply side technological innovation has the potential to play a key role over the longer term. As energy policy shifts increasingly from target setting to delivery mechanisms, there is a need to systematically analyse different opportunities for decarbonisation across the energy system, to consider how these may change over time, and identify the research needs associated with different decarbonisation pathways.

The research presented here suggests that accelerating the development of emerging low carbon energy supply technologies may offer significant long term benefit, in enabling alternative – and more affordable – decarbonisation pathways. It may well also offer wider benefits in terms of diversity, security and sustainability. Realising this potential will require the UK to participate fully in global efforts at low carbon technology innovation – this investment promises significant reward in the longer term. There are many uncertainties involved here, and no simple messages in terms of 'picking winners' – many of the technologies analysed here, and many others not included – have a significant potential role in UK energy system decarbonisation. Rather than a premature selection of 'silver bullets', the need is for sustained international support of a broad range of emerging low carbon technologies, with the UK playing a committed role as a developer and deployer in the wider international context.

TABLE OF CONTENTS

FIGURES

TABLES

ACRONYMS

AFC	Alkaline FC
AGR	Advanced Gas-cooled Reactor
APU	Auxiliary Power Unit
a-Si	Amorphous Silicon
ATD	Accelerated Technology Development
BERR	UK Department for Business, Enterprise and Regulatory Reform
BGS	British Geological Survey
BIPV	Buildings Integrated PV
BoS	Balance of System
BTL	Biomass-to-liquid
BVkm	Billion Vehicle Kilometres
BWEA	British Wind Energy Association
CCC	UK Climate Change Committee
CCS	Carbon Capture and Storage
CdTe	Cadmium Telluride
CEC	Commission of the European Communities
CHP	Combined Heat and Power
CIGS	Copper Indium Gallium Telluride
CIS	Copper Indium Telluride
CPV	Concentrating PV
c-Si	Crystalline Silicon
DC-AC	Direct Current - Alternating Current
DCLG	UK Department for Communities and Local Government
DECC	UK Department of Energy and Climate Change
DEFRA	UK Department of Energy, Food and Rural Affairs
DEMO	Demonstration Power Station (fusion)
DOE	US Department of Energy
DSC	Dye Sensitised Cells
DTI	UK Department of Trade and Industry
EDC	Energy Data Centre
E-DEMO	Early Demonstration Power Station (fusion)
EGR	Enhanced Gas Recovery
EIA	Environmental Impact Analysis
EMEC	European Marine Energy Centre
EOR	Enhanced Oil Recovery
EPSRC	UK Engineering and Physical Sciences Research Council
ESI	Energy Supply Industry
ETI	UK Energy Technologies Institute
ETP	Energy Technology Perspectives
EU ETS	EU Emissions Trading Scheme
EURATOM	European Atomic Energy Community
FC	Fuel Cell
FIT	Feed-in-tariffs
FOAK	First-of-a-kind
GaAs	Gallium Arsenide
GT	Gigaton
GTCC	Gas Turbine Combined Cycle
GW	Gigawatt
GWEC	Global Wind Energy Council
GWp	Gigawatt Peak
HFC	Hydrogen FC
HFP	European Hydrogen and Fuel Cell Technology Platform
HGV	Heavy Goods Vehicle

ICE	Internal Combustion Engine
ICEPT	Imperial College Centre for Energy Policy & Technology, London
ICOE	International Conference on Ocean Energy
IEA	International Energy Agency
IFMIF	International Fusion Material Irradiation Facility
IGCC	Integrated Gasification Combined Cycle
IPCC	Intergovernmental Panel on Climate Change
IRIS	International Reactor Innovative and Secure
ITER	International Thermonuclear Experimental Reactor
JET	Joint European Torus
kW	Kilowatt
kWe	Kilowatt electrical
kWh	Kilowatt Hour
LC	Low Carbon
LCA	Life Cycle Analysis
LGV	Large Goods Vehicle
LWR	Light-water Reactor
MAST	Mega-Ampere Spherical Tokamak
MCFC	Molten Carbonate FC
MCT	Marine Current Turbines Ltd
MED	Markal Elastic Demand Model
MJ	Megajoule
MOX	Mixed Oxide Fuels
MW	Megawatt
NOAK	Next-of-a-kind
NREL	US National Renewables Energy Laboratory
O&M	Operation and Maintenance
OECD	Organisation for Economic Co-operation and Development
OPV	Organic PV
PC	Pulverised Coal
PEM	Polymer Electrolyte Membrane
PEMFC	Polymer Electrolyte Membrane Fuel Cell
PJ	Petajoule
PV	Photovoltaics
PWP	Pelamis Wave Power Ltd
PWR	Pressurized Water Reactor
R&D	Research and Development
R,D&D	Research, Development and Demonstration
RAB	UK Renewables Advisory Board
RDA	UK Regional Development Agency
RO	UK Renewables Obligation
RO(S)	Renewables Obligation (Scotland)
SKM	Sinclair Knight Merz, consultancy
SME	Small and Medium-sized Enterprise
SOFC	Solid Oxide Fuel Cell
SRC	Short Rotation Coppice
TF	Thin Film
TWh	Terawatt Hours
UKAEA	UK Atomic Energy Authority
UKERC	UK Energy Research Centre
UNEP	United Nations Environment Programme
UNFCC	United Nations Framework Convention on Climate Change
Wp	Peak Watt

Chapter 1: Introduction

1.1 Research Themes and Background

This is the second in a series of reports arising from UKERC's Energy 2050 project. The first report (Anandarajah et al., 2008) presented a number of scenarios of UK energy system decarbonisation, and within these, explored the impact of different levels of overall CO_2 reduction ambition for the UK to 2050, different intermediate targets (to represent earlier or later action), and different discount rates (to represent different weightings of current and future costs, and private or social returns on investment).

As this first report pointed out, analysing the future development of the UK energy system – and the prospects for system decarbonisation – involves dealing with a large number of uncertainties across energy production, distribution and consumption. These uncertainties include resource availability and cost, changing patterns of energy consumption (and efficiency of consumption), the design and impact of policy, and the direction and pace of technology development.

Drawing on a range of different expertise and disciplines within UKERC and beyond, the Energy 2050 project is addressing many of these uncertainties. As part of this, the present report focuses on the prospects for accelerated development of a range of emerging low carbon energy supply technologies – and the possible impact of this acceleration on the decarbonisation of the UK energy system.

The report, and supporting analysis, has been carried out by a multi-disciplinary team working together in UKERC's Energy 2050 *Supply Working Group*. The Group includes researchers with detailed understanding of specific supply-side technologies, and also researchers with expertise in energy systems modelling and innovation studies. Combining together different bodies of expertise and perspectives on system change has enabled UKERC to develop original insights on the opportunities and challenges associated with developing and deploying low carbon energy supply technologies.

As with other parts of the Energy 2050 project, the research reported here has been supported by energy systems analysis using the UK MARKAL elastic demand

(MED) model. A detailed account of the structure and operation of the UK Markal MED model is provided in the first report (Anandarajah et al., 2008). The present report discusses the model in a more restricted way, in terms of how it was used by UKERC's Supply Working Group to explore the possible impact of accelerated technology development on the UK energy system.

This research contributes to the fulfilment of the 'whole systems' energy research mission of the Energy 2050 project. The focus in this part of the project is on emerging low carbon energy supply technologies. Other issues which will also shape the decarbonisation of the UK energy system, such as changing lifestyles and energy efficiency, are covered in other Energy 2050 reports. An executive summary of the entire Energy 2050 project, to be released in spring 2009, will synthesise these findings into a comprehensive whole systems analysis.

Energy supply technologies are now mostly developed by networks of private and public sector organisations operating on a global stage. In analysing the prospects for accelerated technology development, therefore, the primary focus has been on international 'systems of innovation', rather than deployment at the national level. In practice, of course, development and deployment are interrelated: rather than separate parts of a linear 'innovation chain', as they are sometimes portrayed, technology development (and learning-by-research) and deployment (and learning-by-doing) feed-back into one another.

The pace and direction of technological change is a major uncertainty in studying the development of energy systems over time. The difficulties of assessing technological innovation means that, despite its importance, innovation tends to have rather limited representation in scenario exercises. Addressing this issue here, for a restricted set of technologies, has involved devising *accelerated development scenarios* (which assume high levels of technological progress over time to 2050), and then comparing these with *non-accelerated* equivalent scenarios. Given the uncertainties involved, the results should be seen as indicating the possible impact of supply-side technology progress over the longer term, rather than a detailed mapping out of system change over the next decade or beyond.

Without strong and sustained policy interventions, energy systems tend to 'lock-in' around established technologies, so the opportunities for (and benefits from) technology acceleration may be missed. Capturing these benefits requires UK policymakers, investors and developers to participate in global efforts at commercialising emerging low carbon technologies, and also to allow for their deployment in the future UK energy mix. At the same time, this future promise does not imply delaying action to combat climate change until more affordable and better performing supply-side options become available: investing in longer-term supply options should be seen as a complement rather than a replacement for shorter-term actions to promote decarbonisation.

1.2 The Challenge of Decarbonisation

This is a time of unprecedented attention on energy production and use, certainly since the energy crisis of the 1970s. The broad acceptance that carbon dioxide (CO_2) and other greenhouse gas (GHG) emissions are responsible for climate change has made decarbonisation of the economy an international policy priority (IPCC, 2007). Ambitious targets for economy-wide decarbonisation and low carbon technology deployment have been established in the UK and across the European Union (UK Government, 2008a; CEC, 2008).

The UK has set out a legally binding framework for decarbonisation from now to 2050. Following a recommendation by the UK Committee on Climate Change, the UK's reduction target for all greenhouse gases (GHGs) was recently increased from 60% to 80% below 1990 levels by 2050 (CCC, 2008). This new target is one of the most ambitious legally binding agreements for GHG reductions anywhere in the world (UK Government, 2008a).

Policy targets are also being established for the expansion of renewable energy. A proposed Directive from the European Commission sets an EU-wide target of 20% of all energy consumed to be provided by renewable energy by 2020 (CEC, 2008). Within this, the UK national target is 15%, a highly ambitious figure given the UK's modest track record of renewables deployment to date (the equivalent figure in 2006 was 1.5%) (BERR, 2008a). Because renewable technologies can be more readily introduced into electricity production and use than other energy services (such as transport and heat), meeting the 15% target is likely to require that renewables provide around a third of all electricity produced in the UK by 2020 – requiring an unprecedented programme of renewables build over the next decade (Pöyry, 2008).

Responding to these policy ambitions will involve society-wide and economy-wide changes to energy production and consumption, including significantly improved efficiencies of energy use in homes and businesses, and lifestyle changes to enable reduced energy demand. At the same time, any comprehensive response must also consider how to best support the development and deployment of low carbon energy supply technologies.

For many countries, including the UK, these capacities have been eroded over recent history. Levels of funding for energy RD&D (Research, Development and Demonstration) and support for national research facilities declined sharply after the mid-1980s, associated with a collapse in oil and gas prices and the liberalisation of the energy sector (Figure 1.1, below).

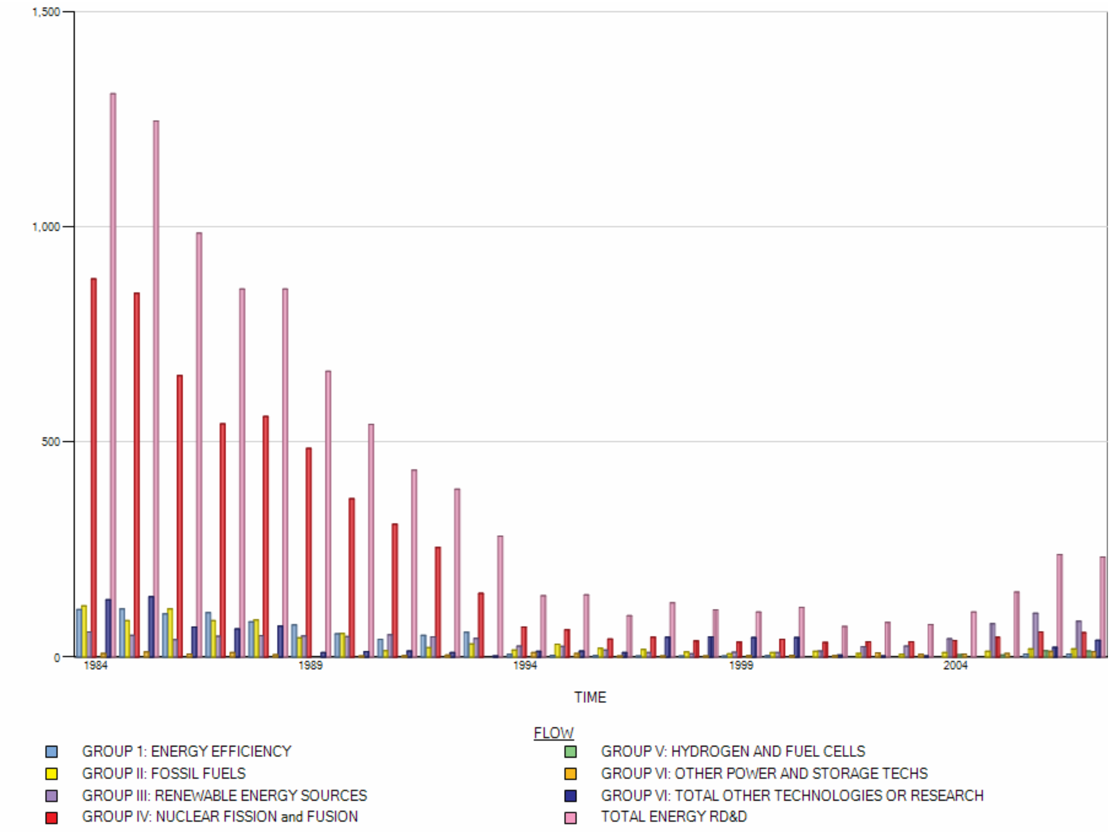


Figure 1.1: UK Public Spending on Energy RD&D (US$m), 1984-2007
(Source: IEA Statistics, 2008 database)

More recently, growing concerns about climate change and energy security have prompted increased spending on energy RD&D, and total global investment in sustainable energy technologies rose by over 50% in 2007 (UNEP, 2008). Although this upward trend is now being affected by oil and gas price fluctuations and the general economic downturn, the challenge of climate change mitigation will provide a long term imperative for investment in low carbon technology development.

Already, the recent resurgence in energy-related innovation activity globally has encouraged the emergence of a large number of prospective low carbon energy supply technologies, supported by particular policy initiatives, investment programmes, developer firms and research institutions. Systematically assessing this activity has become a major research challenge in its own right. This is an inherently multi-disciplinary problem, spanning detailed technology-specific expertise, and also energy system-wide tools and insights. There are many difficulties here: technologies which are routinely compared in debates on energy futures may be at different stages of development, depend on varied natural resources, and have different implications for power storage and distribution.

1.3 The UK Energy System

Compared to other parts of the economy, such as information technology or biotechnology, energy systems tend to inertia and path dependency. This means that responding to the challenge of decarbonisation is conditioned by history, and that without major political or economic interventions, the UK energy system will 'lock-in' around existing technologies.

It is useful, in this context, to consider recent historical patterns of energy production and use. Overall, inland energy consumption in the UK over the past 30 years has been relatively stable, with some fluctuations related to oil and gas prices. Rising levels of GDP have been offset by, for example, improved energy efficiency and a structural shift in the economy away from energy intensive activities (BERR, 2008e).

Energy production and use in the UK have historically been highly dependent on fossil fuels, and this remains the case today. In terms of consumption by final use, while coal and other solid fuels have declined steadily since 1970, gas and electricity consumption have substantially increased, while petroleum remains the single most significant fuel by end use (Figure 1.2).

There have been major changes in the pattern of energy consumption by sector since the 1970s. Between 1970 and 2007, the proportion of energy used in the industrial sector halved, from over 40% to 20%, while the transport sector share doubled, from 19% in 1970 to 39% in 2007. Domestic and service sector shares remained relatively steady, and were 28% and 12% of total final consumption in 2007, respectively.

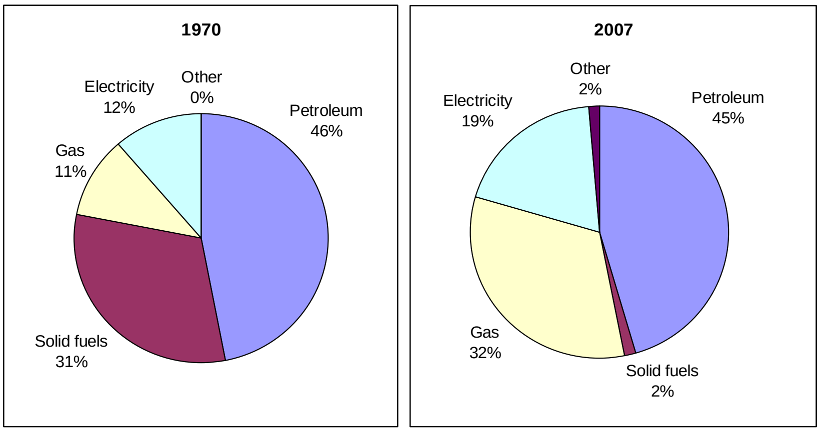


Figure 1.2: Final Energy Consumption in the UK by Type of Fuel (BERR, 2008e)

Historically, coal was the dominant fuel source for electricity; coal-fired generation made up two-thirds of electricity produced in the UK as recently as 1990 (BERR, 2008d). Since 1990 a 'dash-for-gas', associated with the introduction of combined cycle generation technology, has seen natural gas become an important fuel for electricity production, although conventional coal-fired generation plant remains significant despite high levels of associated CO_2 emissions (Figure 1.3, below).

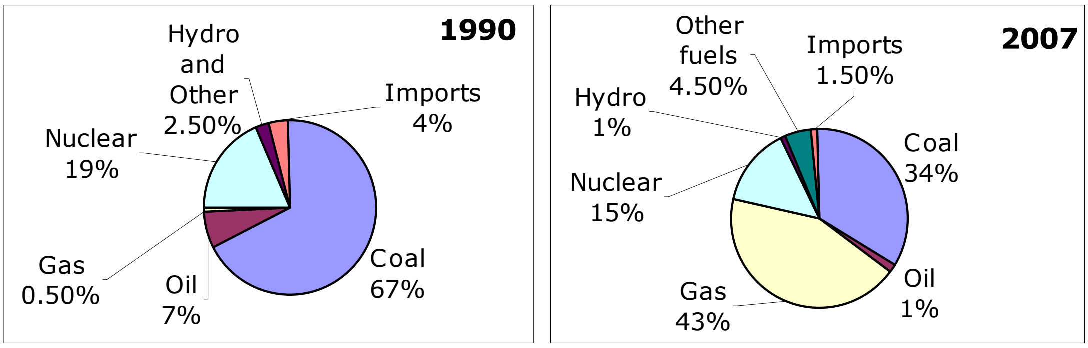


Figure 1.3: Proportion of Electricity Supplied by Fuel Type (BERR, 2008d)

Renewable energy technologies have only ever been a very minor contributor to energy production in the UK: in 1990, 'renewables and waste' accounted for 0.3% of all fuels consumed; by 2007 this had risen to 1.9% (BERR, 2008e). The UK failed to sustain its programmes of renewable energy technology development initiated in the 1970s, and over the past 30-40 years, environmental imperatives have been a relatively intermittent and weak driver of change in the UK energy system. More recently, the introduction of the Renewable Obligation has been associated with a steady growth in renewables deployed, from 2.6% of all electricity generated in the UK in 2000, to 5.0% in 2007 (BERR, 2008d).

1.4 Analysing Accelerated Technology Development

1.4.1 The UKERC Energy 2050 Project

The UKERC Energy 2050 project is examining how the UK can move towards a low-carbon and resilient energy system over the next four decades. In acknowledging that the UK will be pursuing these goals in an uncertain world and in a global context, a range of possible energy system futures (or scenarios) are being described that are both low-carbon and resilient to external and internal shocks. A set of four 'core' scenarios have been devised to provide a starting point for the systematic analysis of the main drivers and uncertainties involved:

- The *Reference* core scenario assumes that current social and economic trends and existing energy policy measures continue. This scenario is a baseline against which the extra costs and other consequences of meeting policy goals can be assessed. The reference scenario is based on 'firm and funded' policies at the time of the 2007 Energy White Paper (DTI, 2007).
- The *Low Carbon* (LC) core scenario assumes that new policy measures emerge that induce investment in low carbon technologies to reduce energy demand and the carbon intensity of supply technologies, consistent with overall UK energy policy targets for decarbonisation by 2050. (Note, however, that the LC Core scenario does not attempt to incorporate specific policies beyond those which were firm and funded at the time of the 2007 Energy White Paper).
- The *Resilient* core scenario assumes that the UK energy system becomes more resistant to external and internal shocks through: a) increasing diversity of supply, in other sectors such as transport as well as electricity; b) reinforcing infrastructure to make it less vulnerable; and c) reducing levels of final energy demand to lessen dependence on gas and oil.
- The *Low Carbon Resilient* (LCR) core scenario addresses how the twin goals of resilience and carbon reduction might work together, and whether trade-offs must be considered in combining these goals together.

With these four core scenarios as a common starting point, different working groups within UKERC have developed a series of 'variant' scenarios to explore specific issues related to decarbonisation and resilience, including, for example, network reconfiguration, environmental sensitivities and behaviour and lifestyles. An Executive Summary of the entire project, to be released in spring 2009, will synthesise these findings into a fuller whole systems analysis.

1.4.2 Accelerated Technology Development (ATD) Scenarios

This report presents the set of variant scenarios devised by UKERC's *Energy Supply Working Group* to represent accelerated technology development (ATD) of a number of emerging low carbon energy supply technologies. Taking the Low Carbon (LC) core scenario as a 'non-accelerated' baseline, a series of technology-specific ATD scenarios have been devised, and then a set of aggregated scenarios were produced to illustrate the accelerated development of multiple technologies in parallel.

The ATD scenarios were created by bringing together technology-specific understandings of the opportunities for accelerated development, and a detailed representation of the UK energy system using the UK MARKAL elastic demand (MED) model. The Markal model selects preferred (least-cost) ways of meeting energy service demands from many different available supply and conversion pathways, while also taking into account investment behaviour and constraints on supply. A more detailed account of the use of the Markal MED model in the Energy 2050 project is provided in Anandarajah et al., 2008; for a wider review of Markal modelling in the UK, see Strachan et al., 2009.

The ATD scenarios represent possible alternative ways of meeting UK decarbonisation ambitions to 2050. Decarbonisation is imposed as a constraint in Markal modelling of the UK energy system. The single-technology ATD scenarios impose a 60% CO_2 reduction (compared to 1990 levels), reflecting the level of UK policy ambition at the time they were constructed in early-2008. Different single-technology scenarios were then aggregated together under both 60% and 80% CO_2 reduction constraints, reflecting the raised policy ambition introduced in late-2008 in the Climate Change Act (UK Government, 2008a). In all the scenarios reported here, there is an additional CO_2 reduction constraint of 26% to 2020. Total cumulative CO_2 emissions between 2000 and 2050 are 22.46GT in 60% scenarios and 20.39GT in 80% scenarios. A general discount rate of 10% is applied to all costs and benefits associated with the different scenarios presented here.[1]

The Climate Change Act also incorporates the Climate Change Committee's recommendation that UK decarbonisation targets should in future be applied to the basket of six greenhouse gases (GHGs) covered by the Kyoto Protocol, and not just CO_2 emissions, as had previously been the case. Non-CO_2 emissions accounted for around 15% of total GHG emissions in 2006 (CCC, 2008), almost 90% of which were from methane and nitrous oxide emissions, mostly associated with agriculture and landfill waste. The Climate Change Committee also noted the uncertainties involved in measuring and assessing achievable reductions in non-CO_2 emissions, and argued that given these difficulties, a CO_2-specific reduction target of 80% by 2050 should be maintained. Given the focus in this report on the UK energy system, the scenarios presented here only consider CO_2 emissions.[2]

The accelerated technology development scenario set modelled for this research are listed in Table 1.1, below.

Non-accelerated Baseline Scenarios (60% and 80%):
- LC Core

Single Technology ATD Scenarios (all 60%):

Renewables
- ATD Wind
- ATD Marine
- ATD Solar PV
- ATD Bioenergy

Other Low Carbon Supply Technologies
- ATD Nuclear Power (Fission and Fusion)
- ATD Carbon Capture and Storage (CCS)
- ATD Hydrogen and Fuel Cells

Aggregated ATD Scenarios (60% and 80%):
- LC Renew (all four renewable technologies accelerated)
- LC Acctech (all seven low carbon technologies accelerated)

Table 1.1: Accelerated Technology Development (ATD) Scenario Set

---

[1] As well as an 80% decarbonisation target to 2050, the UK Committee on Climate Change also recommended an increased interim target of at least 34% reduction by 2020, rising to 42% reduction by 2020 if an international climate change mitigation agreement is reached (CCC, 2008). A range of different decarbonisation ambitions to 2020 and 2050, and also different discount rates, are explored in Anandarajah et al., 2008.

[2] For more information on UK non-GHG emissions, see Chapter 9 of the Committee on Climate Change 2008 report, *Building a Low-Carbon Economy: The UK's Contribution to Tackling Climate Change*. TSO, London.

A number of additional variant scenarios are also discussed in the modelling results. These consider, for example, the failure of some technologies to be developed or deployed, to have delayed availability, or to have differing levels of performance.

Inevitably, this scenario set represents only a limited selection of the many low carbon energy supply options now emerging. Rather than a fully comprehensive technology assessment, the aim here has been to explore the potential of a selected number of the most promising technologies developing internationally, in terms of their potential contribution to UK efforts to decarbonise from now to 2050. Given the limited nature of this assessment, the results inevitably under-represent some opportunities for decarbonisation.[3]

The modelling presented here uses exogenous representations of technology learning, rather than an endogenous learning rate.[4] For each technology, the prospects for accelerated development have been considered by devising narratives of technology development, highlighting potential trends and breakthroughs in availability, performance and cost from now to 2050. These narratives were developed by technology specialists using research landscape and roadmap reports produced for the UKERC Research Atlas[5], and other expert views and reports. For each narrative, a corresponding set of data was then devised to enable representation of technology acceleration in Markal energy system modelling, in terms, for example, of reduced capital or operating costs, improved efficiency, or earlier availability of advanced designs. The differences in input data between non-accelerated and accelerated modelling scenarios are discussed in detail in the later chapters of the report.

The modelling results illustrate the possible impact of accelerated development of low carbon energy supply technologies in terms of changed preferred energy supply mixes and also changed wider system characteristics, compared to the non-accelerated scenario. For each technology, the prospects for accelerated development, and its impacts, are discussed in terms of short (2010-2020), medium (2020-2035) and long (2035-2050) timescales. The scenarios apply the same overall decarbonisation trajectory with or without technology acceleration. In practice, accelerated technology development also offers the prospect of

---

[3] For example, accelerated development of CCS technology has been considered only in terms of its use as a power generation technology, and not its possible use in industrial emissions.

[4] The learning rate of any given technology is the percentage reduction in unit costs associated with each doubling of installed cumulative capacity.

[5] The UKERC Research Atlas is available at http://ukerc.rl.ac.uk/ERA001.html

earlier or deeper carbon reductions (for the same overall cost), but these issues are not formally considered here; the impact of higher and lower decarbonisation ambitions to 2020 and 2050 are explored in Anandarajah et al. (2008).

1.4.3 The Role of Scenarios and Modelling

The scenarios presented here are not forecasts of UK energy system development. There are too many uncertainties and instabilities involved – technological, economic and political (including ongoing changes to the policy framework for low carbon technology development) – to make reliable predications of this kind, even over relatively short timescales. Rather, the aim here is to illustrate the potential role of a number of emerging technologies in meeting UK decarbonisation ambitions, assuming significant progress in their cost and performance. As such, the scenarios explore the possible impact of global innovation trends on UK responses to climate change.

It is important to recognise the purposes and limitations of the scenarios presented here. Markal modelling is used to systematically explore possible energy system responses to the need for system decarbonisation over the next forty years. The modelling results are based on minimising total system costs over the entire period, assuming 'perfect foresight' about future costs.[6] These assumptions are highly simplifying, and the scenarios should be seen as offering 'structured insights into key uncertainties' for policymakers and others, rather than any more prescriptive statements of the future (Strachan et al., 2009).

Given their emphasis on cost minimisation and perfect foresight, the scenarios are based on implicit model of decisionmaking in the energy sector characterised by competitive markets with full understandings of present and future costs. In reality, of course, energy system change is characterised by highly imperfect markets and high levels of uncertainty about technology cost and performance and other factors. While the ATD scenarios explore uncertainties about technology cost and performance over time, many other factors shape investment in energy systems, including, for example, perceived investment risks (Gross et al., 2007). Actual energy system responses to decarbonisation (and other policy imperatives) will also be affected by energy demand and efficiency, changes to the networks used to transfer energy between production and consumption, and many other regulatory, organisational and political interests and pressures.

---

[6] Because of the emphasis on selection by cost, small differences in cost between different technologies may lead to dramatic differences in suggested energy mixes, known as 'penny switching'. In practice, this is ameliorated by introducing tranches of different costs within a technology class.

Despite their simplifications and limitations, the ATD scenarios provide useful insights because they enable structured exploration of an important element of overall energy system change. Long term scenario exercises based on present understandings may under represent the potential of emerging technologies to contribute to system change. In least cost modelling, for example, a small number of relatively well understood, more mature options often compete for market share. Energy supply investments are long lasting and require a host of vested interests to support them, so that energy systems tend to lock-in around these more established technologies and their interests. In this context, it is important that the potential for innovation and learning in emerging technologies be acknowledged and explored, as policymakers and others consider how to respond to the profound and long term challenge of climate change.

1.4.4 The Low Carbon Core Scenario

To an extent, the distinctiveness of the ATD scenarios described in later chapters reflects the amount of technology 'ambition' incorporated in the non-accelerated core scenarios. For example, coal-fired CCS is heavily deployed after 2020 in the low carbon core scenarios, reflecting aggressive assumptions about the future cost and performance of fossil-fuelled power plants and CCS (see Figure 1.4, below). As is discussed in Chapter 7, this means that it is implausible to introduce an accelerated development scenario for CCS which assumes significantly accelerated progress beyond the core scenario, and so a number of additional variant scenario scenarios were created to consider a reduced role for CCS. (The power supply mixes in non-accelerated and accelerated scenarios are discussed in greater detail in Chapter 9).

Alongside this, however, there are discernable differences in the feasibility and desirability of accelerated development for different technologies. For relatively mature and highly capital intensive technologies such as nuclear power, technology acceleration tends to be less attractive, because it is associated with higher technical and economic risk, so incurring higher costs for project developers. This means that, as is discussed in Chapter 6, the focus of the nuclear power community in the UK tends toward supporting current and next generation plant, rather than more challenging designs some decades into the future. For less mature technologies, by contrast, such as advanced forms of solar PV, the emphasis may be much more on research efforts to capture step-changes in cost and performance.

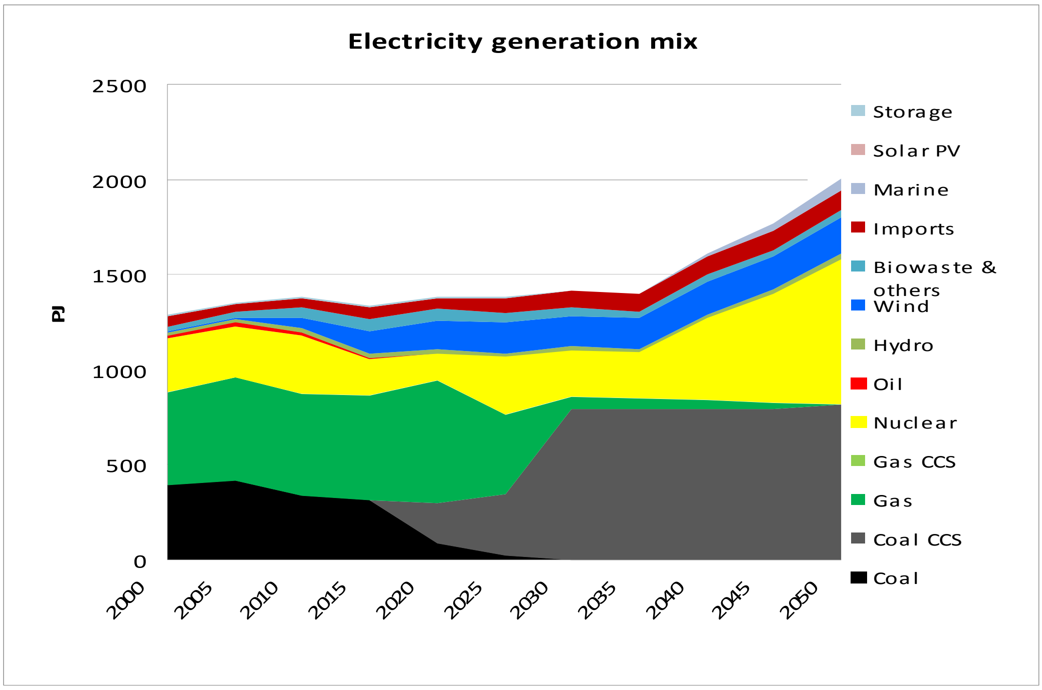


Figure 1.4: Power Generation in LC Core 80 scenario (PJ)

In the LC Core non-accelerated baseline scenario, shown in Figure 1.4 above, nuclear and CCS-abated coal provide the major contributions to power sector decarbonisation, with renewables making a much smaller contribution. Nuclear power delivers virtually all of the expansion of low carbon electricity production after 2035 which is used to help enable decarbonisation of transport and heating. In essence, the power generation mix in this baseline scenario reflects the characterisation of nuclear power as a relatively cost-effective established low carbon supply technology, and also relatively optimistic assumptions regarding the cost and performance of CCS. By contrast, as is discussed in Chapter 9, renewable energy technologies play a much more significant role in the accelerated development scenarios.

The trade-off between technological novelty and financial risk in the case of nuclear energy, discussed above, illustrates a general dilemma for more radical technology development in contemporary energy systems. Meeting relatively short term policy targets for decarbonisation and renewables deployment to 2020 implies concentrating on established technologies which carry reduced technical and economic risk. (This may also mean a focus on institutional rather than technological aspects of system change, such as expedited licensing processes). From a longer term perspective, this risk-averseness and relative short-termism carry a danger of locking the energy system into ultimately less attractive (i.e.

more expensive) decarbonisation trajectories. Certainly, the substantial financial, regulatory and organisational commitments needed to respond to policy imperatives over the next decade will condition the ability of the system to change more fundamentally after 2020.

Understanding the possible trade-offs between shorter and longer term decarbonisation pathways involves many uncertainties, including the interplay between technology *development* (to enable learning-by-research) and technology *deployment* (to enable learning-by-experience). Large-scale deployment of more mature low carbon supply technologies over the next decade offer the prospect of improvements in their cost and performance. However, more mature technologies typically offer less scope for substantial cost reductions or performance improvements than more emergent technologies.

The scenarios presented here suggest that these less well developed emerging technologies could contribute significantly to UK energy system decarbonisation after 2020, and especially in the longer term after 2030. This suggests the need for an overall approach to policy which recognises the interrelatedness of short and long term ambitions, the need to support both technology deployment and development, and to take technological innovation into account in mapping out preferred decarbonisation pathways. These themes are returned to in Chapter 9.

The following Chapters (2 to 8) present a series of detailed technology-by-technology accounts of the prospects for accelerated development, and also the potential impacts of this on UK energy system decarbonisation. Each chapter includes, firstly, a brief overview of the technology field under investigation, an assessment of its prospects for accelerated development (in terms, for example, of research challenges, the status of UK R&D in the international context and the role of policy in supporting acceleration). This is followed by an account of how accelerated development was analysed using the Markal model, including input assumptions and results, both for single technology acceleration and aggregated scenarios. Each chapter concludes with a summary and discussion. The final chapter, Chapter 9, considers the wider effects of accelerated technology development on the UK energy system, the costs and benefits of accelerated development, and highlights some of the overall messages arising from the research.

Chapter 2: Wind Power

2.1 Overview

Wind power has been utilised in various forms for thousands of years. A modern wind turbine utilises aerodynamic lift to power a rotor attached to an electric generator. Applied onshore, this is now a relatively mature technology, with turbines having evolved over years of learning-by-research and learning–by-doing. Turbine availabilities of better than 99% are now typical. The use of wind turbines offshore is a more recent development, and requires adaptation of the technology for a hostile environment. As a relatively mature renewable technology, wind power is likely to be vital in helping decarbonise energy supply systems, and the UK has the potential to play a leading role in the expansion of offshore wind internationally.

Commercial wind energy research began seriously in the 1970s in pioneering countries like Denmark and the United States. Since then, a number of other countries, such as Germany and Spain, have become major players in the development and deployment of wind energy. These established market leaders are being joined by India, China and others, as wind power expansion becomes increasingly globalised. After significant research activity in the early 1980s, the UK fell behind others in developing a wind turbine industry. UK-based wind power project developers are today largely reliant on international markets and supply chains.

In terms of installed capacity, wind energy has become one of the fastest growing energy technologies worldwide; over the last decade the average annual growth of installed capacity has been more than 25%. In 2007, slightly more than 20GW of new capacity was added, taking the total world capacity to 94 GW. The UK share of this is currently about 2.4GW (Figure 2.1, below). The Global Wind Energy Council projects a global wind capacity of 1250GW by 2020. While this seems ambitious, it could be achieved with an annual growth rate of just over 20%, i.e. slightly less than the growth over the last decade (GWEC, 2005).

Onshore wind energy technology systems can be increasingly regarded as mature, with well understood cost components. While there is some scope for accelerated technology development in terms of increased turbine efficiency, much of the scope for increasing the contribution of onshore wind relates to non-technical institutional and wider societal issues, such as planning system and grid access reforms.

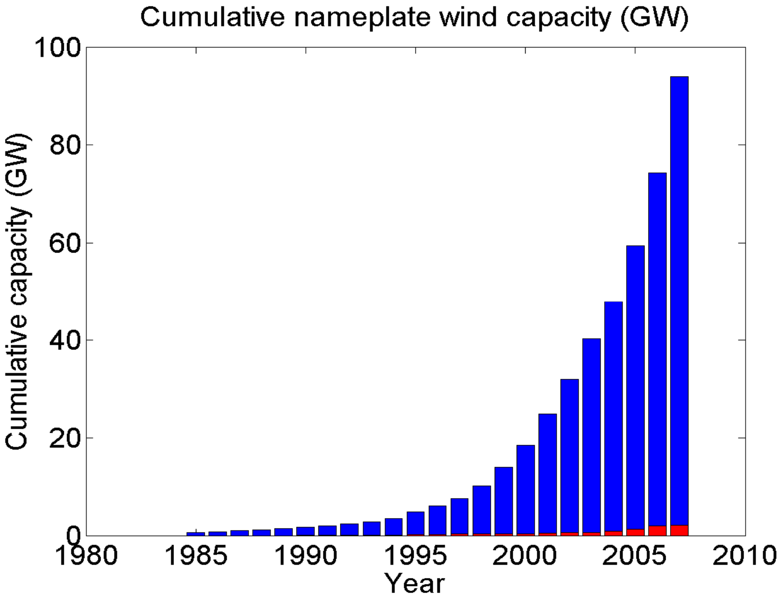


Figure 2.1: Cumulative Global Wind Energy Capacity
UK capacity in red
(Source: UKERC / EDC, 2008)

Offshore wind technology is much less established, and the costs of installation and access for maintenance are highly uncertain. Offshore wind technology is likely to evolve in distinctive directions compared to onshore, given the lower importance of noise and visual impact, the relatively higher cost of installation and grid connection – providing an imperative towards larger unit size – and the generally more severe environment. Offshore turbines are being increasingly designed for this application, for example by favouring more robust designs, possibly reverting back to stall control or to one- or two-bladed designs, with innovative concepts for foundations and/or moorings. Large floating platforms or integrated design with other marine energy devices are among the configurations being considered.

The UK has a huge offshore wind resource, and even though it recently overtook Denmark as the country with the highest operating offshore wind capacity in the world, this resource is still largely untapped. Given this, and despite a relative lack of experience compared to onshore, offshore wind is seen as a key technology for meeting UK and international policy targets for renewable deployment and energy system decarbonisation, especially over the short and medium terms (the policy and technological challenges for wind power expansion are discussed in Section 2.4, below).

2.2 Accelerated Development of Wind Power

2.2.1 Research Challenges and Priorities[7]

Given their different operating environments and stages of development, onshore and offshore technologies have rather distinctive R&D needs. As a relatively mature technology, the key enablers for onshore wind acceleration relate to deployment rather than development, including planning reforms, grid access and promoting indigenous manufacturing and supply chain capabilities (a current barrier to wind farm development in the UK, and beyond). This said, R&D to improve onshore wind devices and system costs also needs to continue.

Offshore wind is a comparatively recently emerged technology with a great deal of scope for learning-by-doing and learning-by-research. Estimates vary as to the realisation of this potential over time, but the Global Wind Energy Council, an association of national wind energy trade associations, has suggested that offshore wind technology could improve and mature rapidly in the future, corresponding to a global learning rate of approximately 10% to 2020 (GWEC, 2005).

In supporting the further development and deployment of both onshore and offshore technology, R&D serves a number of distinctive aims: improved wind turbine efficiency (particularly for low speed onshore locations); improved condition monitoring and enhanced reliability of offshore turbines; improved offshore electricity transmission infrastructure; and improved electricity storage technologies and/or demand-side management. The wind power capacity factor – and therefore generation costs - can be improved by selecting high resource wind speed sites, but also by ensuring turbine reliability is as good as it can be, and improving the aerodynamic efficiency of the rotor and drive train. While this holds true for both onshore and offshore technologies, the added hostility of the offshore environment means turbine reliability and aerodynamic efficiency are particularly important drivers for offshore siting. More specific offshore technology R&D priorities include:

---

[7] The UKERC Research Atlas includes a document summarising the Research Landscape for wind power, including a detailed survey of the UK research capacity, see http://ukerc.rl.ac.uk/ERL001.html

- Improved blade materials technology, leading to lower mass rotor and hub and down-rated drive-train and tower dimensions – this is probably the biggest potential area for accelerated development and cost reduction.
- Improved control algorithms (e.g. fatigue reduction by individual blade pitching) which allows lower rating of components (cost reduction) and a longer lifetime.
- Improved generator design (e.g. increased use of high temperature superconductors).
- Optimised aerodynamic design (how close turbines can get to the theoretical optimum energy extraction). This has limited scope because it is already close to optimum, and is relatively less important than finding a site with better wind regime.
- Better understanding of offshore 'balance of system' costs and resource characterisation. Wind installation costs are highly site-dependent, and there is a need for a finer-grained 'banding' of the available UK offshore wind regime and accessibility.

2.2.2 UK R&D in the International Context

The amount of publicly-funded wind energy R&D carried out in the UK declined substantially after the 1980s. Today, although the UK wind power innovation system is relatively undeveloped compared to countries with more sustained support for the technology over time, the volume of R&D has risen significantly (Figure 2.2, below). Of particular note is the recent £40m joint initiative from the Energy Technologies Institute and the Carbon Trust to accelerate the development of offshore wind power around the UK. The main basic science funding programme is provided by the EPSRC via their Supergen initiative and responsive mode funding. Internationally, UK researchers collaborate within programmes such as the EU Framework Programmes and IEA initiatives.

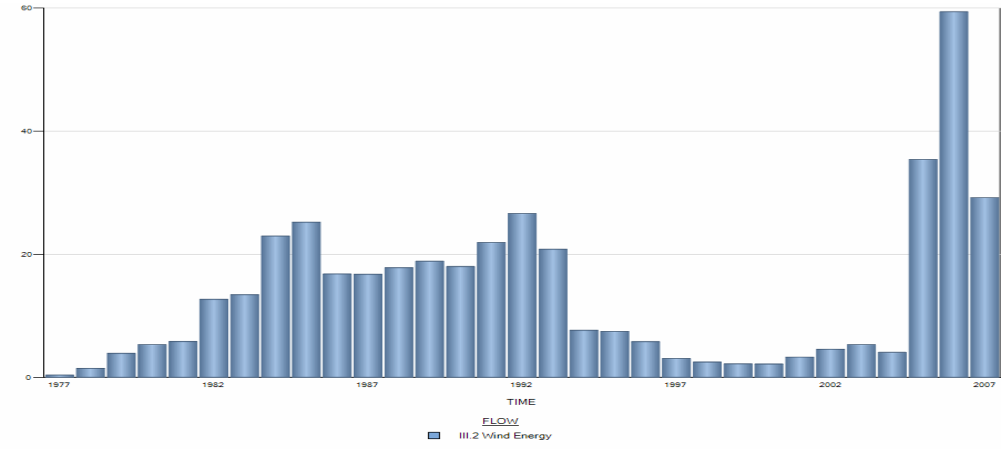


Figure 2.2: UK Public Spending on Wind Energy RD&D (US$m), 1977-2007
(Source: IEA Statistics, 2008 database)

A wide range of disciplines, from science and engineering to the environmental, geological and social sciences participate in wind energy research, providing vital information on the impact of building, operating and decommissioning wind turbines. UK capabilities in wind energy cover the whole range of technologies, from the design and manufacture of generators, blades and towers, to resource prediction, monitoring and control, grid integration, and onshore/offshore wind farm development and construction. With the experience of the oil and gas industry, the UK has strengths in offshore structures and operations that put it in a good position in offshore project development.

2.3 Modelling Wind Power Acceleration

2.3.1 Input Assumptions

Given the different stages of development of onshore and offshore technology, the Accelerated Technological Development (ATD) modelling scenario for wind power was developed in two distinctive ways.

Onshore Wind

The onshore wind input data for ATD-Wind power focussed on essentially non-technical barriers to onshore deployment. Onshore capacity limits in the UKERC Markal reference scenario were compared to an independent assessment by Enviros (2005) of the generation potential for successive wind tranches, under 'low' and 'high' capacity scenarios (reflecting differing levels of planning constraints). The Enviros study involved a bottom-up estimate of onshore wind potential in the UK by region, taking account of land use, excluding National Parks and similarly designated land.[8]

A full re-analysis of the UK onshore wind resource would involve a spatial analysis, identifying attractive sites close to the existing distribution and transmission network for power export. In the absence of such a detailed analysis, the high capacity upper estimates for onshore tranches from Enviros were adopted for the ATD-Wind power scenario. For the UK as a whole, this provides a total deployable onshore wind capacity of 18GW under relaxed planning constraints and improved grid access and capacity (Figure 2.3, below).

---

[8] Generally these reserved areas experience high wind speeds and it can be argued that an accelerated development scenario for onshore wind power penetration should consider (partially) relaxing some of these restrictions, but this was not part of the present study.

Capital cost reductions of 1% per annum (p.a.) to 2020 and 0.5% per annum thereafter are used in the non-accelerated Low Carbon (LC) Core scenario for all onshore wind categories in lieu of learning rates. Given that onshore wind technology is relatively mature, this modest cost improvement trajectory was left unchanged for the ATD scenario.

Offshore Wind

In the non-accelerated (LC Core) reference scenario, offshore wind capital costs, although higher than onshore, are reduced at the same rate (1% per annum until 2020 and 0.5% per annum thereafter). For the ATD-wind scenario, a more aggressive cost reduction profile was devised to represent the greater potential for technology acceleration offshore, as outlined above.

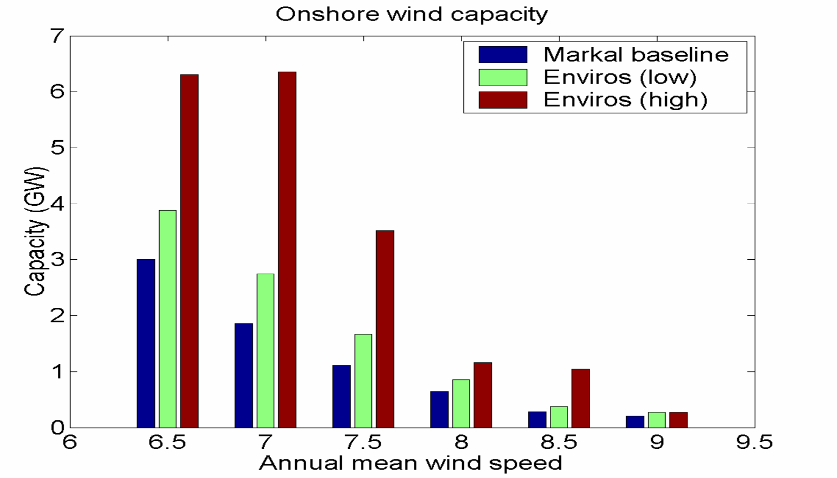


Figure 2.3: Onshore Wind Capacity Limits in UKERC Markal Reference Case and Enviros (2005) [9]

Analysis by the Global Wind Energy Council (GWEC, 2005) suggests that a 10% global learning rate for offshore wind is feasible to 2020; this translates as an 'accelerated' annual cost reduction rate of 3% p.a. to 2020. A study by the Carbon Trust (2008a) has recently suggested a learning rate of up to 15% is feasible for offshore wind, but this figure excludes commodity and material price fluctuations. Indeed, these manufacturing and materials constraints are such that other studies have suggested increased costs for offshore wind internationally over short and medium terms (e.g. IEA, 2008c). After 2020, the offshore industry is assumed to become more mature, although still capable of a faster rate of

---

[9] The Enviros (2005) report specifies generation potential for sites with annual mean wind speeds as low as 5.0 ms^{-1}; such sites are unlikely to be economic and were not used for the Markal modelling study.

improvement and cost reduction than onshore technology. Accordingly, a 1% p.a. rate of offshore capital cost was adopted post 2020(Figure 2.3, below).

2.3.2 Results: Single Technology Scenario

Over the medium and long terms (after 2020 and after 2035, respectively), modelled scenarios which assume accelerated technological development of wind power diverge significantly compared to non-accelerated equivalent scenarios. Over the shorter term to 2020, however, there is very little difference between accelerated and non-accelerated scenarios in terms of the amount of wind power deployed.

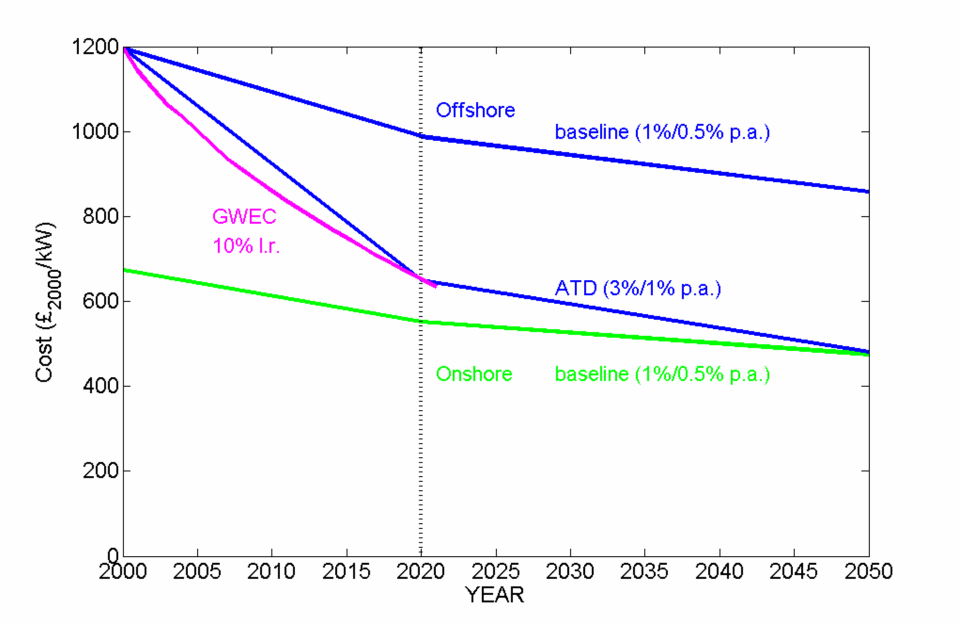


Figure 2.4: Accelerated Technology Development and Reference Scenario Capital Cost Assumptions for Offshore Wind

In the single technology ATD-Wind power scenario (i.e. with wind power accelerated alone) and an overall UK energy system decarbonisation target of 60% to 2050, c.45GW of wind power is installed by 2050, over 30GW more than that achieved in the non-accelerated scenario (LC Core). However, in 2030 the ATD-Scenario deploys only 5GW more wind than the reference case, and in 2020 there is no difference between the two cases. Clearly, wind power technology acceleration – as represented in the ATD-Wind power scenario – manifests over the longer term rather than shorter term (Figure 2.5, below).

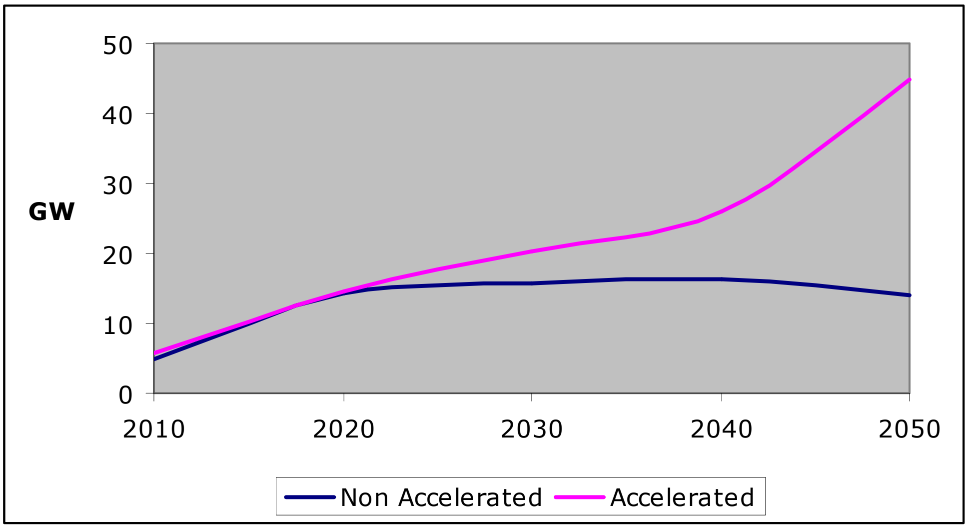


Figure 2.5: Wind power Deployment Accelerated and Non-Accelerated Scenarios (selected data, smoothed)

The ATD-wind power scenario can be interrogated in greater detail to reveal the relative contributions of onshore and offshore technology. In the early period, to 2020, wind power deployment is predominantly onshore, with around 13GW onshore and only 2GW offshore deployed; no additional onshore capacity is installed after 2020.[10] In the 2020s, an additional 6GW offshore wind capacity is installed, but by far the biggest increase in wind capacity occurs after 2030, with around 25GW installed (Figure 2.6, below).

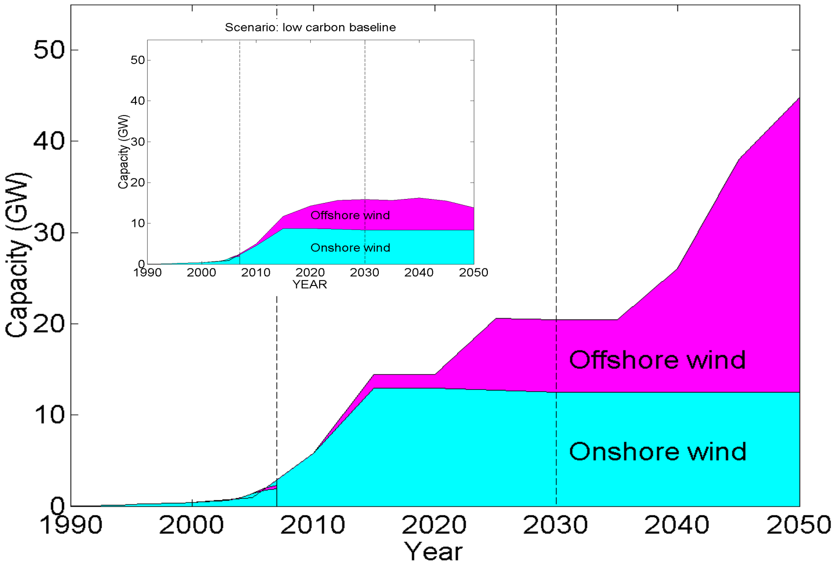


Figure 2.6 cenario
(Inset: non-accelerated scenario)

---

[10] The onshore wind capacity of 18GW is not fully taken up in the ATD-wind power scenario. The lowest onshore wind speed tranches have relatively low seasonal capacity, and under accelerated development assumptions, offshore wind (which has much higher seasonal capacity) becomes a more attractive option.

2.3.3 Results: Aggregated Scenarios

60% Scenarios

Combining together accelerated development assumptions for all renewable technologies analysed here (wind power, marine, solar PV and bioenergy) significantly reduces the amount of wind power deployed compared to the single-technology (ATD-Wind) case. In particular, the dramatic expansion of offshore capacity seen after 2030 in the single technology case is absent, and instead there is only relatively modest – though still highly ambitious in practice – expansion, with around 20GW installed over the period to 2025. A similar pattern is seen in the LC-Acctech scenario (with ATD assumptions for nuclear, CCS and fuel cells also introduced).

80% Scenarios

Increasing the overall decarbonisation ambition from 60% to 80% involves a much expanded long-term role for wind power under accelerated development assumptions. In the non-accelerated reference case (LC-Core 80) wind power deployment levels remain modest, with under 20GW deployed by 2050. In the LC-Acctech 80 case, however, there is a dramatic rise in wind power installed in the longer term, with c.70GW installed by 2050, providing just over 1/3rd of all power supplied in 2050 (Figure 2.7, below).

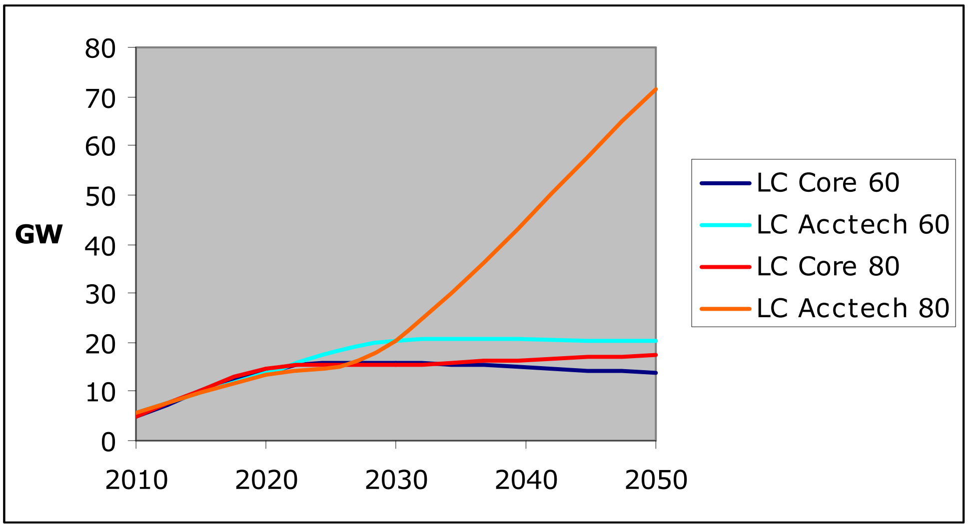


Figure 2.7: Wind power Installed Capacity, Aggregated Scenarios (selected data, smoothed)

2.4 Discussion

Although the modelling results presented above portray a dramatically expanded role for wind power, this only develops in the longer term, and not in a way that would satisfactorily meet the shorter and medium term policy expectations of current UK and European targets.

As discussed in Chapter 1, a proposed EC Directive requires the UK to raise the proportion of all energy consumed that is produced from renewables technologies from 1.5% in 2006 to 15% by 2020 (CEC, 2008). As a relatively mature renewable technology, wind power is expected to deliver much of this expansion, and the UK Government has declared its intention to make 'full use' of the potential for offshore wind power in this effort (BERR, 2008a). The Crown Estate recently launched Round 3 of the offshore wind leasing programme, with bids invited for up to 25GW new offshore wind development rights in UK waters, with 8GW already planned under Rounds 1 and 2.

A number of recent studies have attempted to assess the scope for wind power expansion to 2020, a relatively short-term deadline. An analysis commissioned by the UK Government has suggested that 20-30GW of combined onshore and offshore can be feasibly deployed by 2020 (Pöyry, 2008). Other studies have suggested that up to 34GW of deployed offshore wind may be achievable by 2030 (SKM, 2008a,b), but with only around half that figure (14-18GW) deployable by 2020 (BERR, 2008a; RAB, 2008). More ambitiously, the Carbon Trust has suggested that to meet the EU target the UK must deploy at least 29GW of offshore wind by 2020, a figure it considered technically feasible but 'extremely challenging' (Carbon Trust, 2008a).[11]

Although the majority of installed wind capacity by 2020 is expected to be located offshore, the 2020 policy ambitions also imply a significant expansion of onshore deployment, with estimated deployment in the range of 13-14GW by 2020 (BERR, 2008a; RAB, 2008). Depending on planning and grid capacity issues, much of this is expected to be built in Scotland.

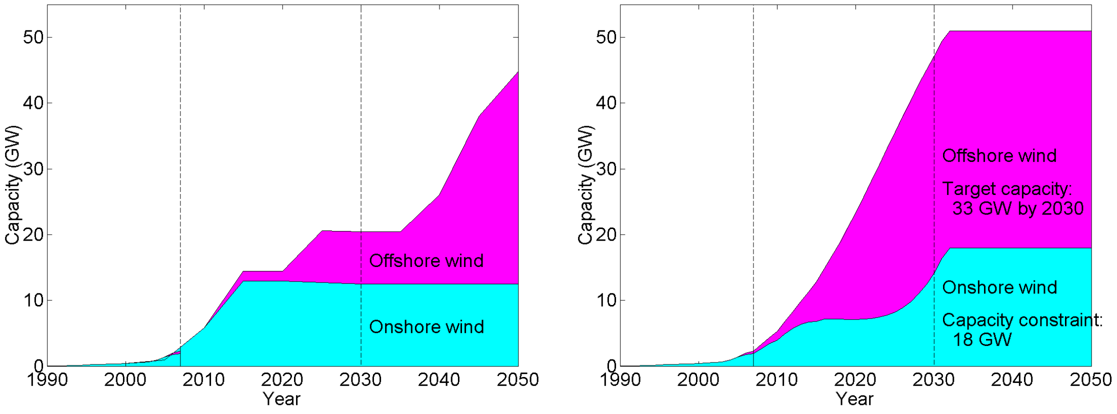
While the anticipated onshore wind contribution is reflected in the ATD-Wind power scenario presented above, the anticipated offshore contribution clearly requires a radical revision of policy drivers for investment and deployment that go

---

[11] The Trust added that delivering this would involve investments of around £2bn to catalyse reductions in technology costs, and around £4-5bn to build up manufacturing capacity (Carbon Trust, 2008a).

well beyond those embedded in the ATD scenarios (Figure 2.8, below). Major offshore wind installations before 2020 will also have to overcome serious supply chain constraints, and additional policy interventions will be needed to drive investment in UK manufacturing, supply chain and installations capacities (SKM, 2008a, b).

Such high levels of projected wind power installations are also associated with electricity network constraints. High levels of wind energy penetration (only partly mitigated by wide geographic distribution and use of sophisticated forecasting software) would need additional electricity storage on the grid and/or extensive load management. Over the longer term, developments such as dispatchable electrolysis for hydrogen production (coupling electricity into the transport energy supply system), or flexible operation of power plants with CCS could potentially support much higher penetrations.



ATD-Wind power Scenario **UK Policy Target Trajectory, derived**

Figure 2.8: Modelled and Targeted Wind Power Deployment Scenarios

2.5 Summary

Over the past thirty years, wind power has developed from a small-scale niche to become a major international power technology, with a mature supply industry dominated by a number of major manufacturers and internationally co-ordinated supply chains. This growth has been possible because of sustained R&D (and associated learning-by-research), but also powerful incentives for project deployment (and associated learning-by-doing). In the UK, although there remains significant scope for further onshore deployment, there is now a strategic opportunity to play a major role in the development and deployment of offshore wind technology.

There are important differences here between onshore and offshore technology, with an emphasis on supported deployment (and removal of institutional barriers) for onshore project development, and a combination of supported deployment but also long-term support for technology development offshore. Offshore system performance and costs are still rather poorly defined, and there is a need for system-level learning beyond core technology components.

For the current modelling exercise, representing the prospects for accelerated development of wind power involved different points of emphasis for onshore and offshore technology, with greater attention on the possibilities for technology-based acceleration offshore and non-technical institutional barriers onshore. The resulting scenarios of UK power system development suggest technology acceleration allows for much greater levels of deployment in the longer term, especially offshore, and under heightened decarbonisation ambitions. However, over short and medium terms, accelerated development was not translated into accelerated deployment.

The results underline the formidable economic and technical challenges associated with the rapid expansion of renewables deployment implied in recent UK and European policy targets. At a technical level, responding to these challenges implies significant investment in construction, condition monitoring, power take-off, and maintenance. However, as the modelling work presented here suggests, much of the benefits of technology development will accrue over longer time periods, after 2020. Over the coming decade it is at least as important to address procurement constraints, and also non-technical institutional issues, such as planning and financing barriers. In their ‘blueprint’ for accelerating the role of wind power to 2020, the Global Wind Energy Council highlighted a series of national and international policy priorities, including legally binding targets for renewable energy, defined and stable returns for investors, risk-return profiles that are competitive with other investment options, and a rapid phase out of support for conventional, polluting energy projects (GWEC, 2005).

At the same time, the substantial expansion of renewables cannot be seen in isolation from wider systems of power production, distribution and consumption. Innovations in power grids, and energy vectors and storage also promise to make high levels of wind power penetration more technically and economically attractive. To the extent that these more radical changes at the system level have not been incorporated into the scenarios modelled here, our work may underplay the potential role of wind power. However, many of these enabling technologies are longer term prospects which will facilitate a gradual transition to renewables-based power systems. Over the shorter term, a more directly interventionist policy framework will be required to rapidly accelerate deployment of onshore and offshore capacity.

Chapter 3: Marine Energy

3.1 Overview

Marine – or ocean – energy (defined here as wave and tidal current technology[12]) is an emerging technology field with considerable promise. For example, it has been estimated that around 15-20% of UK electricity demand could be met by marine energy (Carbon Trust, 2006). This said, marine energy innovation and industrial systems are at a relatively early stage of development as compared, for example, to wind power, and this is reflected in a wide variety of prototype device designs.

There are a number of engineering concepts for capturing wave energy, including oscillating water columns, overtopping devices, point absorbers, terminators, attenuators and flexible structures. Tidal current energy exhibits less variety, with most prototype designs based on horizontal axis turbines, but vertical-axis rotors, reciprocating hydrofoils and Venturi-effect devices are also being developed. Two UK based companies (Pelamis Wave Power and Marine Current Turbines) have recently installed full-scale devices (Figure 3.1, below).

Pelamis Wave Power

Marine Current Turbines Seagen Device

Figure 3.1 Full Scale Marine Energy Devices
(Sources: PWP, MCT)

In the wake of the 1970s energy crisis, a number of wave energy R&D programmes were established internationally, but – in contrast with wind energy – these efforts were not sustained, and there was very limited innovation in the

---

[12] Tidal barrages, lagoons or ocean thermal circulation technologies are not addressed here. (The Severn Barrage, a potentially significant contributor to UK energy system decarbonisation is available as a supply option in the UK Markal MED model; it is not selected in any of the scenarios presented here.

marine sector from the mid-1980s to late 1990s. Renewed policy interest (and public and private funding) over the last decade has provoked a resurgence in innovation activity, and the emergence of multiple device designs. These more recent efforts have been led initially by small and medium enterprises (SMEs) and university consortia, although large power companies and large scale public-private programmes are increasingly involved.

Unlike many other areas of low-carbon innovation, the UK has a leading position in the emerging marine sector, with a significant resource and research base, related skills in offshore engineering, and a relatively strong funding and policy support framework. A significant proportion of all marine energy developer companies and support facilities are based in the UK. At the same time, international interest and development activity has grown rapidly in recent years, and over a dozen countries now have specific support policies for the marine energy sector. Additionally, full scale marine energy test centres have been established in the UK and continental Europe, with new centres being built in the US and Canada. This international interest and growth has lead to the development of international standards specifically for marine energy, and the International Energy Agency (IEA) has formed an implementing agreement to support the sector.

The nascent status of marine energy technology creates considerable scope for its development. Within this, there is a need to address both demonstration trials of the most advanced prototype devices, and also research on more radical but less developed designs and components. For effective accelerated development, the marine sector needs to address new concepts as well as improvements to existing designs. The Carbon Trust have suggested long term learning rates for wave and tidal energy of up to 15% and 10% respectively, but also highlighted the importance of taking advantage of step change improvements (Carbon Trust, 2006).

Development of a full scale device prototype is time consuming and expensive, taking several years. The established route for device development starts by testing at model scale in tank facilities, developing hydrodynamic models to design larger scale models to be tested in larger tanks or offshore, and using results from these tests to verify the modelling before going to a full scale design. As well as specific breakthroughs in devices and components, accelerated development of marine energy aims to speed-up this development cycle, for example, by the development of reliable development protocols and procedures which could reduce the reliance on device-specific tank testing at different scales.

3.2 Accelerated Development of Marine Energy

3.2.1 Research Challenges and Priorities

Both wave and tidal current energy still face a number of significant challenges in order to reach fully commercial status. A representative, but by no means exhaustive, summary of the general challenges for the sector is provided below:

- At present marine energy innovation activity is spread over a wide variety of concepts and components, and at the highest level, wave and tidal current have distinctive innovation needs. This present lack of consensus may have a short term negative effect on the speed of development and learning.
- At the same time, a number of generic technologies and components – such as foundations, moorings, marine operations and resource assessment – offer opportunities for collaborative learning, although the transfer of generic knowledge and components within the developer community is limited by commercial competition (Winskel, 2007).
- Given limited full scale experience in real operating conditions, there is a need for more data on prototype performance and operating experience to feed back into the overall RD&D cycle.
- Across the sector as a whole, there is a need to strike a balance between prototype design variety and consensus, and to manage the selection processes for linking between the two. While resources and effort tend to focus on a few large-scale wave and tidal current prototypes (up to around 1MW), and more conventional designs and components, there is a parallel need to explore more radical options which may offer step-change cost reductions or performance improvements. This can be understood as a balance between early-stage learning-by-research and later-stage learning-by-doing.
- There are significant opportunities for knowledge transfer from other sectors, such as offshore engineering. Enabling this transfer will involve better understanding of the 'adaption costs' of transferring components and methods to the marine environment, and identifying opportunities for collaboration with other industries and supply chain partners.

In the period to 2020 there is likely to be a progressive device design consensus, with a distinct group of wave and tidal designs becoming 'industry standards'. Consolidation in the marketplace is also likely, with mergers and acquisitions allowing hybrids of the best technologies to emerge and reduce overall costs. Up to and beyond 2020, it is conceivable that disruptive technologies, embodying novel approaches to energy extraction, will be introduced allowing for accelerated cost reduction, although the timing of these breakthroughs is difficult to predict. UKERC's Marine Energy Technology Roadmap (UKERC, 2008a) details the technology and commercial challenges involved in establishing a deployment strategy for the marine sector up to 2020.

Beyond 2030, it is implausible to speculate in any detail as to the future direction of the industry; however, given continued publicly and privately funded development programmes, and associated learning effects, device costs are likely to decrease, and performance increase. While an accelerated development trajectory for the marine sector involves some degree of design consensus over the medium term, there is a danger that if this consensus is imposed too early it may lead to 'lock-in' around devices with less scope for development in the longer term.

3.2.2 UK R&D in the International Context

Despite its recent expansion, marine energy R&D is still mostly undertaken by a relatively small international community of research organisations, developer firms and support agencies. The UK, with a favourable resource and research base, and significant policy interest, has been at the centre of much of the recent activity. With a sizeable proportion of all device developers and supporting infrastructure facilities, the UK can presently be said to be world leaders in marine energy technology development, and is seen as offering leadership to other countries entering the sector.

Research capacity in the UK has seen significant expansion recently from publicly- and privately-funded initiatives such as the EPSRC Supergen Marine programme, the European Marine Energy Centre (EMEC) at Orkney, and the involvement of the UK Energy Technologies Institute. At the same time, many other countries are now taking an interest in the technology, both in Europe and beyond, and future development of this sector is becoming increasingly international.[13]

3.2.3 Role of Policy

A number of specific support mechanisms for marine energy development have recently been established by UK and Scottish Governments and other organisations.[14] These measures are starting to facilitate deployment of prototype devices and demonstration arrays; they include:

- The UK Government's Marine Renewable Deployment Fund (25% capital grant for qualifying projects and an enhanced payment of 10p/kWh in addition to the normal ROC payment).
- The Scottish Ministers' Wave and Tidal Energy Support Scheme (40% capital grant for qualifying projects and an enhanced payment of 10p/kWh in addition to the normal ROC payment).
- The Renewables Obligation (RO) and Renewables Obligation (Scotland), and the potential for future RO and RO(S) banding to offer enhanced support of wave and tidal power (BERR, 2008a; Scottish Government, 2008).
- The Scottish Marine Supply Obligation, an obligation placed on suppliers to provide a percentage of generation from marine renewables, towards a proposed 75MW ceiling.
- A range of capital grant support mechanisms and other research initiatives, such as the UK Government's Technology Programme, the EPSRC's Supergen Marine Programme, the Carbon Trust's Marine Energy Accelerator and the UK's Energy Technologies Institute (ETI) marine energy programme; these often involve a mix of public and private funding.

These measures can be seen as mechanisms for promoting technology acceleration and delivering the ambitions of the marine sector, as outlined in a number of marine energy roadmaps. For example, UKERC's Marine Energy Technology Roadmap is targeted towards 2GW of installed marine capacity for the UK by 2020 (UKERC, 2008a), while the British Wind Energy Association (BWEA,

---

[13] The UKERC Research Atlas includes a report detailing the UK Research Landscape for Marine Energy, authored by Dr Markus Mueller of Edinburgh University.

[14] These technology-specific 'niche' support policies are not included in the Energy 2050 Low Carbon Core scenario.

2006) suggested that 3GW of marine capacity could be deployed by 2020 (Figures 3.2 and 3.3, below).

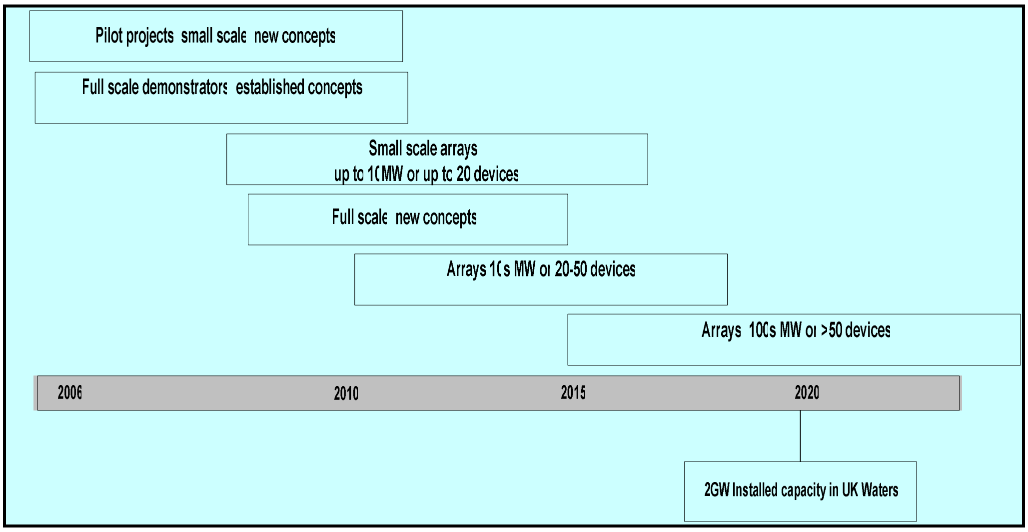


Figure 3.2: Marine Energy Deployment Scenario up to 2020 (Source: UKERC, 2008a)

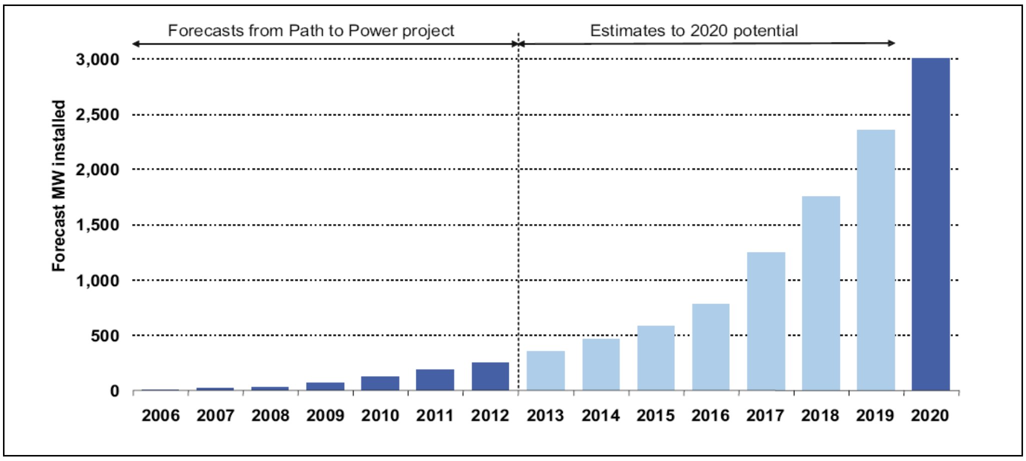


Figure 3.3: Forecasted and Estimated Potential Deployment of Marine Energy in the UK to 2020 (Source: BWEA, 2006)

3.3 Modelling Marine Energy Acceleration

3.3.1 Input Assumptions

Least-cost energy system models, such as Markal, may under-represent the potential for development – and eventual deployment – of emerging technologies such as marine energy. Indeed, in the Low Carbon core scenario for Energy 2050, very little marine energy is deployed in the UK energy mix to 2050. The Accelerated Technology Development scenario for marine (ATD-Marine), in contrast, was devised to represent the impact of recently-established policy support mechanisms that are now beginning to stimulate the development and deployment of marine energy in the UK, as outlined above.

The ATD-scenario involves 'niche learning' of marine by supported deployment. Given the leading position of the UK here, domestic innovation support policies are potentially able to influence the progression of the sector internationally over the short to medium term. Using plausible deployment figures for the period to 2015, and international learning rates and initial capital cost figures derived from the Carbon Trust (Carbon Trust, 2006), 'accelerated' learning curves for wave and tidal were produced (Figure 3.4, below). (Note that this analysis is based on the continuation of tariff and capital support mechanisms in the UK and elsewhere from now to 2015, to support niche deployment and learning).

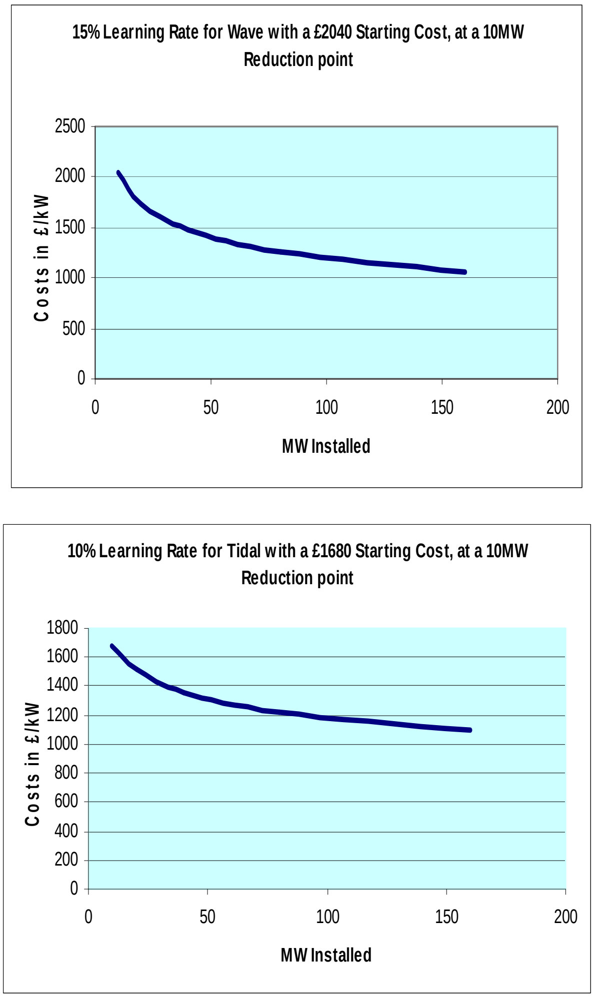


Figure 3.4: Accelerated Learning Curves for Wave and Tidal Energy, as used in the ATD-Marine Scenario(Source: Jeffrey, 2008)

The potential impact of supported niche learning on the cost of marine energy to 2015 was considered in a separate analysis (Jeffrey, 2008). This concluded that an accelerated development programme for marine power could lead to capital costs for wave and tidal current energy of around £1100/kW by 2015, for an undiscounted total investment of over £400m, delivering around 300MW of total installed capacity (150MW each of wave and tidal current). It must be noted that these figures are highly sensitive to starting assumptions regarding initial capital cost and the rate and timing of learning. The costs emerging from the niche learning scenario were used as assumed cost of marine technologies in 2015 for the Markal ATD-Marine scenario. After 2015, annual cost reduction rates are adopted, equivalent to a global learning rate of 10% for both and wave tidal current. The impact of this accelerated development on levels of deployment in the UK is described and discussed in the following section.

3.3.2 Results: Single Technology Scenario

In the ATD-Marine scenario, with marine energy accelerated alone (and all other technologies under non-accelerated 'business as usual' assumptions) and a 60% carbon reduction to 2050, technology acceleration makes a substantial difference to the deployment of marine energy technology in the UK (Figure 3.5, below). In the core scenario, less than 5GW of marine energy is installed, and only after 2040; in the accelerated scenario, over 20GW is installed by 2050, with first deployments between 2010-2015. Under these accelerated development assumptions, marine energy supplies almost 15% of all electricity generated in 2050, over 240PJ (67 TWh).

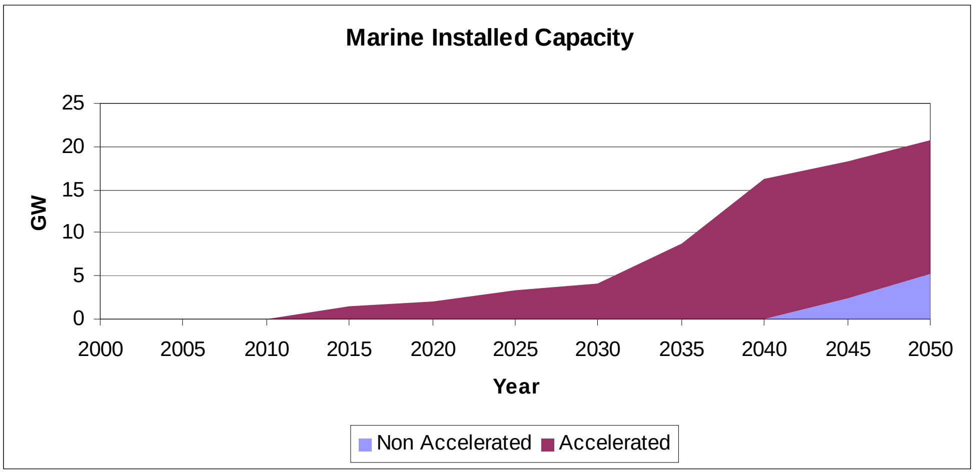


Figure 3.5: Suggested impact of marine energy acceleration on the UK electricity generation mix (2000-2050)

As Figure 3.6 below shows, the accelerated scenario involves a gradual increase in deployed capacity up to 2030, but a step-change increase in the deployment rate thereafter. The first deployments are predominantly tidal current devices, but with wave energy (which has a larger UK resource) dominating after 2030.

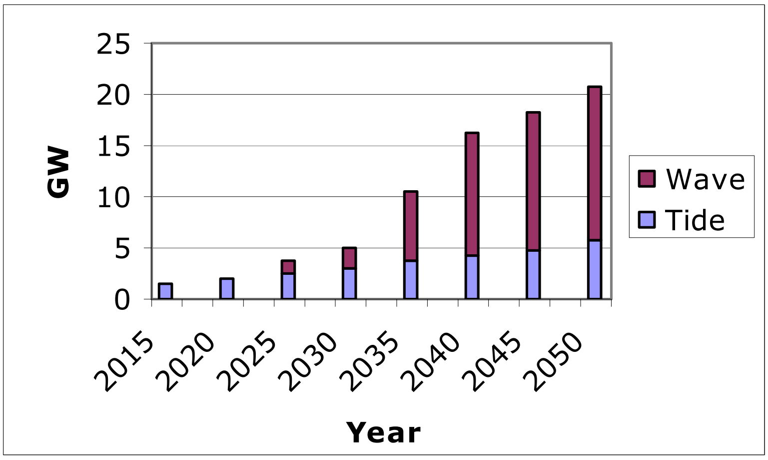


Figure 3.6: Marine Energy Deployed Capacity for ATD-Marine Scenario (2015-2050)

3.3.2 Results: Aggregated Scenario

In the LC-Renew and LC-Acctech scenarios, several energy supply technologies are accelerated in parallel and compete for market share. In both cases marine energy continues to make a much more significant contribution to the supply mix compared to non-accelerated equivalent scenarios, at both 60% and 80% decarbonisation ambition, although early deployment is delayed compared to the single technology ATD-Marine scenario (Figure 3.7, below). After 2030, marine deployment in the aggregated scenarios undergoes rapid expansion, with over 20GW of capacity installed achieved by 2050, matching the marine-only acceleration results. Greater deployment of marine is restricted only by assumed resource constraints, as discussed below.

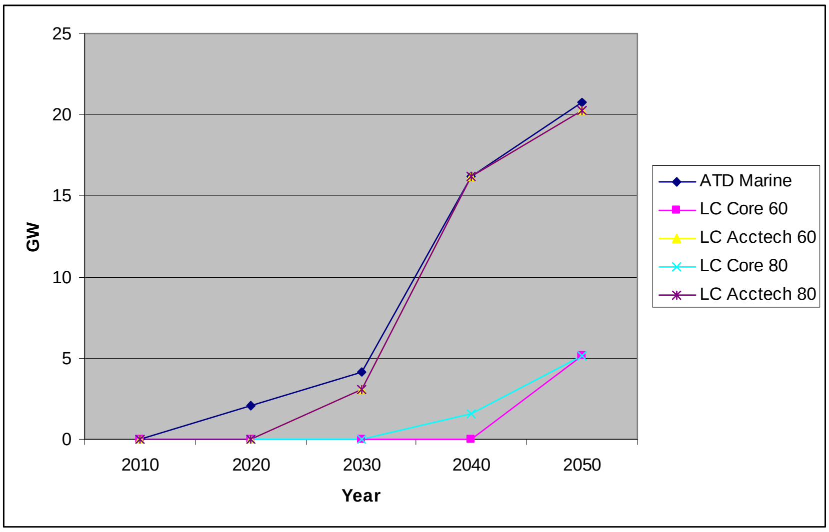


Figure 3.7: Marine Energy Installed Capacity, Single Technology and Aggregated Scenarios

3.4 Discussion

Realising marine accelerated development scenarios will depend on a co-evolution of accelerated *development* and *deployment*, with marine technologies benefiting from learning-by-experience associated with early deployments, in conjunction with learning-by-research to enable step changes in technology performance and cost.

The significant levels of deployment suggested in the ATD scenarios cannot be met with existing supply chain infrastructure, and will require considerable investment in specialised and dedicated installation equipment. Some of this investment is already underway: for example, some technology developers have already taken delivery of dedicated installation vessels. Additionally, technology acceleration will involve measures to address the generic technical challenges highlighted in the UKERC Marine Technology Roadmap (Figure 3.8, below)

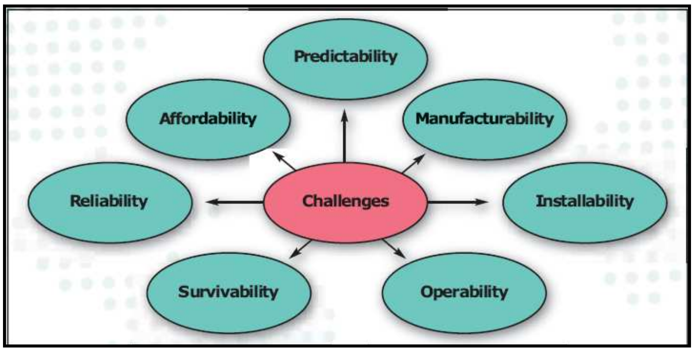


Figure 3.8: Generic Technical Challenges involved in Marine Energy Technology Acceleration

A coherent and adaptive approach to policy, across both UK and international arenas, will be needed to provide an appropriate combination of support mechanisms and ensure effective distribution of investments as the sector matures. In particular, there is a need to strike a balance between technology-push and market-pull mechanisms, to allow for design consensus, but at the same time avoiding 'lock-out' of longer-term breakthrough technologies which may allow for step-change improvements. In addition, significant barriers still affect regulatory, planning and permitting processes.

The level of deployment in the marine acceleration scenario is broadly in line with published medium term targets for the sector. For example, the UKERC Marine Roadmap advances a 2GW deployment target for 2020, which closely matches the ATD modelling result. However, some other longer term ambitions for the sector appear to be predicated on more substantial cost reductions and/or technology performance improvements (and associated policy interventions) than those reflected in the ATD scenario. For example the Energy Technologies Institute has recently identified a long-term ambition of 30GW installed capacity by 2050.

It is important to note here that there is a upper limit of marine capacity of around 21GW in the Energy 2050 scenarios, representing the presently understood technically and economically exploitable resource (e.g. Carbon Trust, 2006). However, this figure may not fully represent the longer term potential of marine energy, as improved resource characterisation and capture device technology advancements may increase the exploitable resource. For example, it has recently been suggested that deeper water tidal current resources may be exploitable in the longer term and that the overall installable capacity of marine may be closer to 30GW rather than 20GW (SKM, 2008a). Given the aggressive assumptions of technological improvement in the ATD-scenarios, this additional capacity is likely to be an attractive longer term option for system decarbonisation, especially for the high levels of low carbon supply technologies needed to achieve 80% decarbonisation. This would enable continued increases in the marine energy contribution over time, beyond the c.20GW seen in the present modelled results.

In terms of build rate, the results imply that the marine energy industry and its enabling infrastructure mature after 2030, so facilitating greater rates of deployment. The split between wave and tidal energy – with tidal energy providing the largest initial contribution, but with wave energy dominating accelerated deployment after 2030 – is broadly representative of the sectors' perception of the present-day maturity and future potential of the technologies.

In the *short term* (up to 2020) there will be considerable deployment challenges for the sector, with planning and legislation, human resource skills shortages, and availability of installation vessels all being significant hurdles. Despite a certain level of existing headroom, grid reinforcement will also be a significant challenge during this period.

In the *medium term* (2020-2035) the challenges of planning and regulation should have been largely addressed. Despite the capacity that will have been built up in the preceding period, skills shortages and availability of vessels will still be a challenge to the sector due to the steep ramp-up in build rate in this period. Given the remote nature of many of the marine resources, major grid reinforcements will be an enormous challenge during this period with the need for an offshore grid being highly likely.

The *long term* (2035 – 2050) appears less challenging for the sector, to the extent that many earlier limitations need to have already been managed (such as supply chain constraints, planning constraints and grid implications). However, additional capacity may be exploitable by this time, so that deployment may continue increasing beyond what is suggested in the ATD scenarios. In addition, competition for resources from other energy and non energy sectors could have significant impacts on their availability to the marine energy sector across all time periods.

3.5 Summary

Marine energy is an emerging technology field with considerable promise over the medium and longer terms. The industry has just started demonstrating full-scale devices and device arrays. The nascent status of marine technology creates considerable scope for accelerated development. In realising this potential, however, there is a need to allow for parallel progress in demonstration trials of the most advanced wave and tidal prototype devices, and also research on more radical but less developed designs and components.

Unlike many other areas of low-carbon innovation, the UK has a leading position in the emerging marine sector, with a significant resource and research base, related skills in offshore engineering, a significant proportion of all developer companies and support facilities – as well as an extensive funding and policy support framework. However, international interest and development activity has also grown rapidly in recent years, and over a dozen countries now have specific support policies for marine energy. This interest and growth has led to the development of international standards and collaborative initiatives to support this sector.

The scenarios devised here suggest that technology acceleration has the potential to make a substantial difference to the deployment of marine energy technology in the UK, with initial deployments starting soon after 2010, and rapid expansion after 2030. Under these accelerated development assumptions, marine energy supplies almost 15% of all electricity generated by 2050, and additional exploitable resource may allow for further increases to this figure.

Accelerating marine energy to achieve these deployment levels will require sustained support for its development over time. A coherent and adaptive approach to policy, in the UK and internationally, will be needed to ensure effective investments as the sector matures. In particular, there is a need to strike an effective balance between technology-push and market-pull mechanisms, to allow for design consensus, but at the same time avoiding 'lock-out' of breakthrough technologies which may allow for step-change improvements. There are also considerable associated investment needs in supply chains, installation capacity, and electricity networks. With these in place, the work here suggests that marine energy can become a significant contributor to low carbon energy supply systems in the UK.

Chapter 4: Solar PV

4.1 Overview[15]

Solar photovoltaic (PV) technology – the direct conversion of sunlight into electricity[16] – is widely expected to provide a significant part of the world's future energy supply (see, for example, IEA, 2008a). For the UK, solar PV has the potential to make a substantial contribution to meeting energy needs in the medium and long-term. To allow this potential to be realised, however, there is a need for a sustained international RD&D programme, and within this, UK expertise to be appropriately targeted. Like other emerging technology systems investigated here, there is no consensus about the expected timeline for development, or the point at which PV may become commercially competitive. This depends on, among other factors, the levels of spending on technology development, and the impact of this spending on PV cost and performance.

Solar PV research activity can be broken down into 4 areas: **first generation** crystalline wafer silicon; **second generation** thin film; **third generation** concepts; and 'balance of systems' (BoS) issues, including buildings integration. First generation PV devices are based on **crystalline silicon**, drawing heavily on the knowledge of that material that developed out of the electronics industry. The first second generation **thin film** device was based on amorphous silicon, but a range of alternative thin film cells have since been developed. Efficiencies for commercial thin film modules can now be up to 12%, compared to up to 18% for commercial mono-crystalline silicon modules. More recent research has opened up the possibility of third generation technologies, including low cost / moderate efficiency molecular based cells (dye sensitised and organic semiconductor devices), high efficiency / high cost devices, and other novel concepts and nanotechnologies (Miles et al., 2005; Kazmerski, 2006)

The international PV market has shown sustained growth of over 30% per annum in recent years, and levels of R,D&D activity worldwide have expanded rapidly alongside this. This research effort has led to a reduction in the cost of PV cells by a factor of more than 20 over the last two decades. Demonstration projects are

---

[15] This section is based on contributions to the UK Energy Research Centre's Research Atlas for solar PV, authored by Professor David Infield (University of Strathclyde). This includes the UKERC Solar PV Landscape, which details the current UK and international research base, and the Solar PV Roadmap which identifies priority research areas for the UK PV R&D community.

[16] The focus here is on solar photovoltaic technologies, rather than solar thermal heating or power technologies.

progressing, dedicated power generation arrays are now being built and integrated building designs are also becoming more widespread. The main drivers for this development have been government incentives – despite the substantial price reductions, PV generation costs are still too high to make PV a commercially attractive investment for the private sector.

Reflecting global interest and growth, the international PV research community is relatively well co-ordinated, with regular conferences and well-established international research roadmaps.[17] The established international leaders in PV R&D are Japan, the US and Germany. Many other countries, including South Korea, Australia and Spain also have strong R&D programmes. The UK PV research community is comparatively small, and although the UK has a strong materials science base and innovative manufacturing research capabilities, these have not been translated into international leadership in PV research. The lack of an aggressive market support programme is perhaps part of the explanation for this alongside the UK's continuing failure to translate strong basic science research into technology applications. The UK also lacks a central laboratory infrastructure of the kind that other European countries, the USA and Japan have used to drive forwards their research.

As a result, UK PV R&D activity tends to concentrate on key areas rather than trying to cover the entire field. UK research groups are among world leaders for advanced third generation PV technologies, particularly molecular based PV (dye sensitised and organic semiconductor devices), quantum well and dots, concentrator cell design and materials. Two EPSRC-funded Supergen consortia focus on competences relating to thin film cells and molecular based PV. Other groups have particular strengths in system-related research.

4.2: Accelerated Development of Solar PV

4.2.1 Research Challenges

The overall aim of PV research is to reduce the costs of PV generated electricity so that it can compete with conventional and other low-carbon sources. The basic research challenge is the design and fabrication of low cost, stable and efficient PV cells. Some improvement in conversion efficiency is also required, particularly

---

[17] Reviews of a number of international roadmaps for solar PV are available from the UKERC Research Atlas.

for the thin film cells, but this must be coupled to dramatically reduced production costs.

The overall impact of innovation is often considered in terms of reduced cost per peak Watt (Wp), but should more accurately be understood as cost per kW hour generated, considering all system and operational costs. Beyond cell performance and cost, there are additional research challenges associated with power conversion, control systems, storage, BoS and production processes.

There is no one approach or technology that stands out in terms of its potential to best respond to these challenges, but it is clear that increased emphasis on the manufacturing process is required, and the bringing together of materials and devices research communities with fabrication plant designers. Materials research on improved PV devices must bear in mind the manufacturability of novel device architectures. Although the biggest research challenge lies with module design and manufacture, PV systems are presently let down by underperforming BoS components. In addition, there is a need for improved performance prediction tools.

4.2.2 R&D Priorities and Opportunities[18]

The main cost component of a PV system is the module, currently accounting for between 50%-70% of overall system costs. The module comprises solar cells, generally fabricated from wafers or thin active layers on a substrate. BoS components include the DC-AC inverter, mounting structures, installation materials, as well as commissioning design and installation costs. PV module technologies are conventionally grouped into wafer based crystalline silicon (*1st generation*); thin films (*2nd generation*); and emerging and novel technologies (*third generation*). Each of these has distinctive R&D priorities, summarised below.

Wafer based crystalline silicon (c-Si)

Crystalline silicon (c-Si) based devices (including mono and polycrystalline silicon) are proven technologies which yield stable solar cells with good efficiencies. C-Si PV is responsible for the impressive growth experienced by the PV sector in recent years, and currently accounts for over 90% of the global PV market. As

---

[18] More detailed discussions of PV research needs and priorities can be found in the UKERC PV Roadmap, and the EU PV Technology Platform's 'Strategic Research Agenda'.

silicon based technologies have matured, costs have become increasingly dominated by material costs, particularly silicon feedstock. The PV industry has recently experienced a silicon feedstock shortage, but this is expected to ease in 2009.

Silicon ingot casting and wafer slicing techniques are capital and energy intensive, and require substantial technical knowledge and skilled labour. Over 40% of the module cost is attributable to the cost of ingot and wafer production, and the most significant opportunities for cost reduction are at wafer and cell production stages; these include:

- Increasing cell efficiency
- Developing cheaper ways to produce feedstock, such as producing less pure 'solar grade' silicon
- Novel manufacturing processes associated with reduced wafer thickness, reduced waste material, high yield processing, and economies of scale
- Product standardization

Thin Film

Thin film cells have a number of advantages over c-Si cells:

- Improved light absorption, allowing for much thinner materials
- Potential to achieve low manufacturing costs by large-scale high-throughput module production
- Production on flexible substrates, increasing the range of potential applications, particularly for buildings integrated PV (BIPV)

TF technologies currently account for around 8% of the total PV market share, but this is expected to grow over time, as they become cost-competitive with c-Si. TF modules are usually of lower average efficiencies than c-Si, although laboratory cells achieve much higher efficiencies than production modules. The broad research challenges are improved cell efficiencies and improved understanding of lifetime performance and product reliability.

There are, in principle, an unlimited number of possible semiconductor materials suitable for use in TF PV cells; in practice, most attention is directed onto amorphous silicon (a-Si) and compound semiconductors based on cadmium telluride (CdTe), copper indium diselenide (CIS) and copper indium gallium diselenide (CIGS). While different technologies are at different stages of development and pose distinctive research challenges, common research concerns include: higher quality component layers, reduction of substrate costs, and improved encapsulation and production processes.

Emerging and novel technologies

Third generation PV holds out the potential for step-change breakthroughs in cost and performance. The term refers to a variety of emerging technologies, including:

1. *High efficiency and high cost devices,* mostly used for space and concentrator devices (generally based on III-V compounds, such as gallium arsenide, GaAs). Concentrating PV (CPV) includes a wide range of technologies, generally suited for sunny climates and for larger scale ground-mounted plants, making them less well suited to UK deployment (although there are world leading CPV design and materials research groups in the UK). [19]
2. *Low efficiency and low cost* molecular based PV, such as polymer cells (organic PV) and dye sensitized cells (DSCs). Such devices are highly promising in terms of cost reduction, particularly for BIPV and applications that do not have space restrictions. Research is focussed on increasing efficiencies and device lifetimes.
3. Other novel concepts and nanotechnologies, such as intermediate band, quantum dots, quantum wells, nanotubes, nanowires and nanocrystals.

Rather than attempting to fully represent third generation technologies, the modelling assessment reported below focuses on organic PV (OPV) as an illustrative case.

Balance of System (BoS) costs and other system issues

PV systems can be implemented in a wide range of applications, traditionally divided into *grid-connected* and *off-grid* systems. Grid-connected systems currently account for around 90% of the global PV market, and are continuing to grow, particularly for BIPV. The variety of applications makes for a wide range of BoS technical requirements, costs and research issues, including:

- Reducing component costs (support structures, inverters, etc.)
- Improving system performance (including reduced losses and lower maintenance costs)
- Improving BIPV technical solutions and aesthetics

---

[19] For further reading on CPV, see NREL (2008).

- Developing new storage technologies

4.2.3 Stages of Accelerated Development

In the short and medium term (up to around 2030) c-Si and TF are likely to dominate the PV market, possibly in competition with each other. TF technologies show greater potential for cost reductions, but this depends on international investments in R&D and production capacity. Estimates vary widely as to when PV may become competitive with other power technologies, according to assumptions about technology cost and performance, future electricity prices and local solar resource potential – break-even is likely to be much earlier in sunnier locations and specific niche markets. The IEA's *Energy Technology Perspectives 2008* report envisages PV becoming competitive around 2020-2030 in its most optimistic scenario (IEA, 2008a). The EU PV Technology Platform estimates PV in southern Europe becoming competitive with retail electricity prices by 2015-2020 and wholesale electricity prices by 2030.

Longer term breakthroughs, in terms of cost reductions and novel applications, are likely to come from third generation technologies. While this is often projected to occur after 2030, recent research and market developments (discussed in more detail later) suggest the possibility of earlier impact.

4.2.4 Role of Policy

The UKERC ATD Solar scenarios implicitly assume that demand-pull incentives will continue for the next 5-10 years in many countries worldwide, to support market expansion and learning-by-deployment. There is a strong body of evidence in favour of feed-in-tariffs (FITs) as the most efficient and effective policy support for PV deployment (see, for example, IEA, 2008b). This form of renewables support has been introduced in many countries – including Germany, Italy, France, Greece and Portugal – often specifically directed at PV.

A provision to implement a system of feed-in tariffs for small renewable energy producers by 2010 was introduced in the 2008 Energy Act (UK Government, 2008b). Current policy support for PV in the UK is mainly offered through the Renewables Obligation and the Low Carbon Building Programme. Alongside market-pull policies, technology-push measures are also needed, particularly for faster progression of 3rd generation technologies from laboratory to demonstration, pilot production and eventually full commercialization. The UK has an opportunity to gain competitive advantage in third generation technologies, building on existing research expertise.

4.3 Modelling Solar PV Acceleration

4.3.1 Input Assumptions

The UK Markal reference scenarios for the Energy 2050 project have a single technology pathway for solar PV. In all reference scenarios, including the LC-Core Scenario, PV technology remains non-deployed out to 2050.

For the ATD-Solar scenario, three technology paths were devised, representing grid-connected PV systems[20] installing 1st generation crystalline silicon, 2nd generation thin film module technologies, and organic PV as a representative third generation technology (Figure 4.1, below).[21] Capital cost and performance data were drawn from a review of academic literature, and also the EU PV Technology Platform and US National Solar Technology Roadmaps.[22] While the figures produced are deemed technically and economically feasible, their achievement will depend on worldwide R&D efforts, policy support and market developments. All three pathways were characterised as distributed (decentralised) technologies in the UK Markal model, i.e. small to medium size PV systems linked to low voltage distribution systems, and so incurring distribution system costs.[23]

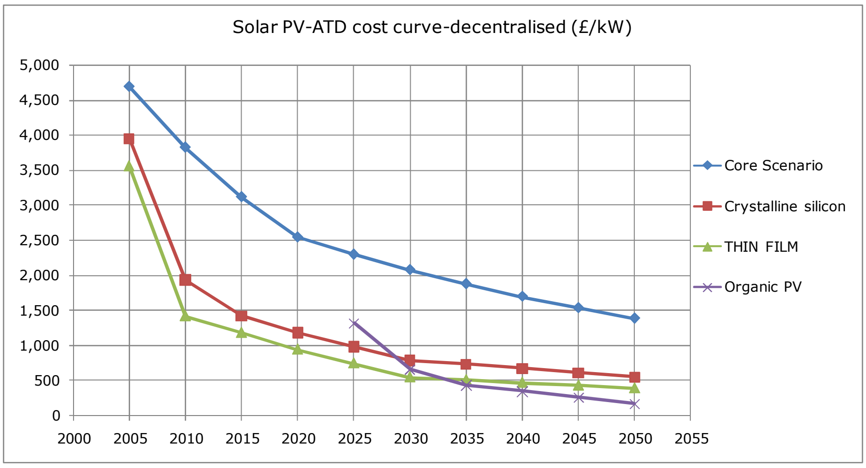


Figure 4.1: Revised Capital Cost Curves for ATD-Solar PV Scenario

---

[20] This includes small to medium size systems, for both residential and commercial applications. Larger ground-mounted PV systems of MWs capacity are not considered in the present analysis, as it is unlikely that such applications will have a role in the UK.

[21] The choice of organic PV was mainly based on data availability.

[22] Organic PV data was drawn from an elaboration of a model presented in Brabec *et al*. (2008).

[23] Larger ground-mounted PV systems (not included in the analysis) would incur additional transmission costs.

PV costs have declined significantly over time as a result of learning-by-research and learning-by-doing, and there are credible projections that OPV module costs will decline very significantly in the future, associated with R,D&D breakthroughs and production process improvements. While there are relatively few studies of PV BoS costs, substantial reductions in BoS costs are also possible, assuming product standardisation and an improved installation process. At the same time, BoS cost reductions are likely to be offset by increasing variety of application and regional/national differences. Finally, it should be noted that the organic case is used here to illustrate the potential of many different emerging third generation PV technologies. While it has not been possible to fully capture these developments, the assumptions devised for organic PV can be seen as reasonable representations of the long term potential of the PV field.

4.3.2 Results: Single Technology Scenario

In the single technology ATD-Solar PV scenario (with solar PV accelerated alone) and 60% carbon ambition to 2050, PV is deployed after 2035. Installed capacity reaches 40GWp in 2050, generating 35TWh, or 7% of total UK generation. Of the three PV pathways, only organic PV is selected: c-Si and thin film technologies remain non-deployed in the ATD-Solar scenario.

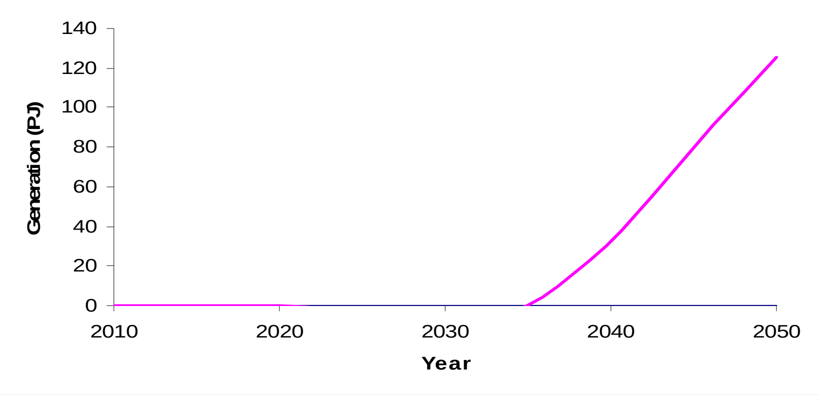


Figure 4.2: ATD-Solar PV Deployment Scenario (selected data, smoothed)

4.3.3 Results: Aggregated Scenarios

60% Scenarios

Combining together accelerated development for the four renewables technologies (wind, marine, bioenergy and solar PV) analysed in the LC-Renew 60 scenario, 23GWp of organic solar PV is deployed in 2050, providing around 5% of total power generated. In the LC-Acctech (excluding fuel cells acceleration) scenario solar PV deployment in 2050 falls to 15GWp, around 3% of power supplied. With accelerated fuel cell assumptions also included in LC Acctech, however, added electricity demand increases solar PV deployment to almost 30GWp and over 5% of generation.

80% Scenarios

In the LC-Renew 80 scenario, solar PV deployment in 2050 is significantly higher than in the LC-Renew 60 scenario, with over 40GWp deployed and around 6.5% of power supplied by 2050. In the LC-Acctech (no fuel cell acceleration) 80 scenario, solar PV is not deployed[24]; in the LC-Acctech 80 scenario including fuel cells acceleration, around 16GWp of solar is deployed in 2050, providing around 2% of power supplied. In all cases, organic PV is the only form of PV selected.

4.4 Discussion

Solar PV is a diverse and dynamic technology field, and there is considerable scope, internationally, for accelerated development of a number of PV technologies. In the present UK modelling exercise, this diversity and potential has been captured by introducing three distinctive pathways for emerging PV cell technologies, each of which reflects much greater cost reduction potential than represented in the pre-existing single PV pathway.

These substantial revisions have led to the introduction of PV into future low carbon UK energy mixes, as modelled in UK Markal. While this is a relatively modest long-term contribution, it can be seen as an indication of a far greater (and considerably earlier) potential role. Recognising this 'untapped potential' is important given the limitations of the present modelling exercise in terms of PV-specific and wider energy system issues.

For example, while the revised cost curves for the different PV technologies reflect the possibility for dramatic cost reductions and performance improvements arising from sustained international research efforts, they have not attempted to represent the potential for much earlier UK-based *supported deployment* (and associated learning and cost reduction) particularly for 1st and 2nd generation c-Si and TF technologies.

Learning-by-research and learning-by-doing are intertwined for emerging technologies such as solar PV. Internationally, PV deployment to date has

---

[24] In the LC-Acctech 80 scenario, large numbers of plug-in electric vehicles are selected, requiring night time power to charge their batteries; as there is no night time supply from solar PV, it is not selected.

occurred mainly through strong market support policies. These measures have allowed for increase in production capacity, further technology development and learning-by-doing for PV systems, especially for BoS components. Alongside these market support measures, PV cell performance and cost reductions have also been driven by sizeable R&D programmes conducted in Germany, Japan, the USA, and increasingly, China, India and elsewhere.

In the future, continuing these parallel efforts at technology-push and market creation promises to allow for more affordable PV systems globally, including in the UK. However, as well as buying and deploying technology developed on an international stage (and contributing to international research efforts in areas of particular expertise), the UK also has a role as an active promoter of learning through supported deployment.

Solar PV is already being deployed in the UK (albeit to a very limited extent), and it is possible that c-Si and TF technologies will be deployed much more substantially in the short and medium terms, through emerging policy mechanisms such as the UK Government's *Zero Carbon Homes* policy, which aims to make all new homes zero carbon by 2016 (DCLG, 2007), and UK commitments to meeting European Union targets for renewable energy deployment by 2020 (CEC, 2008). The modularity and ease of buildings integrated systems may make them an attractive option here, despite their relatively high initial capital costs. The UKERC Solar PV Roadmap provides 'conservative' targets for UK PV installed capacity of 16 GWp by 2030, providing 13 TWh (3%) of generated electricity.

Policy support for niche deployment of 1st and 2nd generation PV technologies in the UK is important because it will facilitate site-specific, local learning on systems integration and BoS costs – areas where international R,D&D has a limited role. BoS costs are affected by application specific and country specific factors, and are mainly driven by experience and learning through deployment. Stronger demand-pull policies to stimulate higher deployment of PV in the short and medium terms may initiate a 'virtuous circle' of learning, cost reduction and market growth.

Even for third generation technologies, the ATD results presented here may be conservative: there are recent suggestions that third generation technologies may be commercialised significantly earlier than previously thought. In its 2008 report on *Energy Technology Perspectives*, for example, the IEA highlights the possibility of niche deployment for third generation technologies around 2020, and strong market uptake after 2030, provided necessary supporting measures are put in place (IEA, 2008a). Overall, the IEA's accelerated deployment scenario presents successive 'technology shifts' between 1st, 2nd and 3rd generation technologies from now to 2050. As Figure 4.3 indicates, this gradual phasing-in of more advanced PV technologies requires recognition of distinctive types of innovation and policy, with an emphasis on learning-by-deployment (and market-support policies) for closer-to-market technologies, but also parallel investments in learning-by-research for longer term technologies. An overall approach to managing the multiple emerging PV technologies offers the opportunity for a sustained contribution to low carbon energy systems.

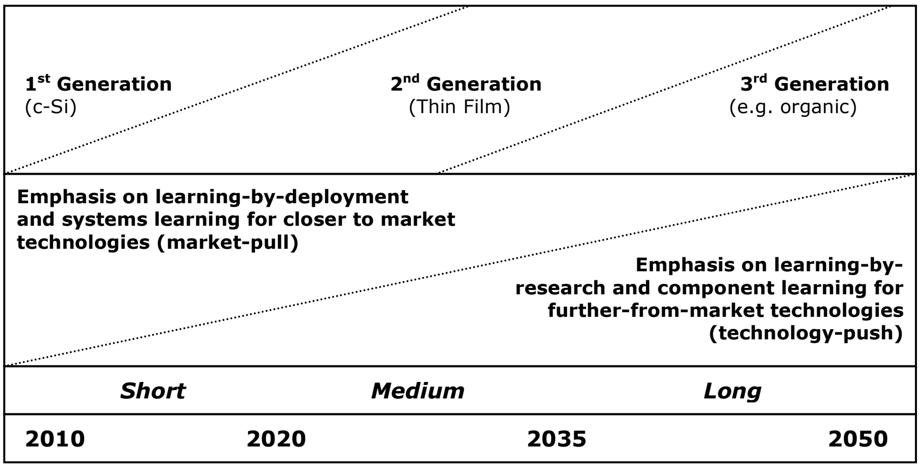


Figure 4.3: Schematic Timelines for PV Technology Transitions, Learning Effects and Associated Policy Support

As well as these technology-specific issues, another reason why the potential contribution of solar PV may be underestimated here is the limited treatment of future electricity networks and storage technologies. For example, in the long term (after 2035), there are possibilities for substantially reconfigured electricity networks, such as distributed generation and 'smart grids', and also major innovations in storage technologies. Together, these promise to allow for high levels of PV generation to be accommodated for much lower system costs (in terms of back-up capacity and/or intermittency penalties) than is currently estimated. Even in the shorter term, research in countries where high level of PV penetration have been achieved, such as Germany, suggests that relatively high PV penetration can be achieved without major system consequences.[25]

---

[25] Cramer (2008)

4.5 Summary

Solar PV has major global prospects for contributing to future low carbon energy systems. Internationally, established industrial and innovation communities are developing a number of distinctive technologies for commercialising PV over short, medium and longer timescales, and there are suggestions that these efforts may deliver cost effective PV systems over shorter time periods than is often forecasted. The UK plays only a relatively modest role as a developer of PV technology, and has deployed very low levels of PV systems compared to many other countries. Within this, however, there are significant areas of UK-based research strength, and also (a largely untapped) role as a niche deployer of PV technologies in the shorter term.

To represent some of this potential, an accelerated development scenario for Solar PV was devised here, and incorporated into a wider energy systems modelling exercise. The ATD-Solar PV scenario, by incorporating data to represent the international prospects for PV innovation, has allowed for some of the technology's untapped potential to be manifested, in terms of future deployment in the UK energy mix. However, even under accelerated development assumptions, PV is portrayed as having a rather marginal long-term contribution in the UK, and the ATD scenario may well underestimate the potential role of the technology. In part, this reflects the emphasis here on international trends in technology specific innovation systems, rather than the possibilities for more radically reconfigured energy networks, carriers and storage.

In addition, the ATD scenario fails to take account of opportunities for nearer-term and more direct UK policy interventions to promote PV deployment and development. These include both stronger *demand-pull* policies (to facilitate application specific Balance-of-Systems learning), and also stronger *technology-push* policies in areas where the UK could gain a significant competitive advantage by building on existing research expertise (e.g. promoting faster progression of third generation technologies from laboratory to demonstration, pilot production and full commercialization). UK and European renewables policies are now under review; this presents an opportunity for a more consolidated attempt to develop and deploy solar PV technology in the UK.

Chapter 5: Bioenergy

5.1 Overview

Bioenergy – the energy that comes from the conversion of biological resources – is a highly flexible option for decarbonising the economy, spanning a wide range of fuel feedstocks, conversion technologies and end-use applications. This makes for multiple development possibilities, and means that there is no overall consensus on the scale and timing of the 'bioenergy opportunity'.

International research and innovation efforts are spread across a vast range of research opportunities and challenges. Bioenergy feedstocks include wood, 'first generation' food crops such as sugar cane, maize, and wheat, and also 'second generation' dedicated energy crops such as willow, miscanthus and other woody shrubs, trees and grasses. Other feedstocks include waste products such as sewage and agricultural residues like straw and wood. Conversion techniques include simple combustion, fast pyrolysis, gasification and fermentation; and end uses include bio heat, power and fuels for transport (Figure 5.1, below).

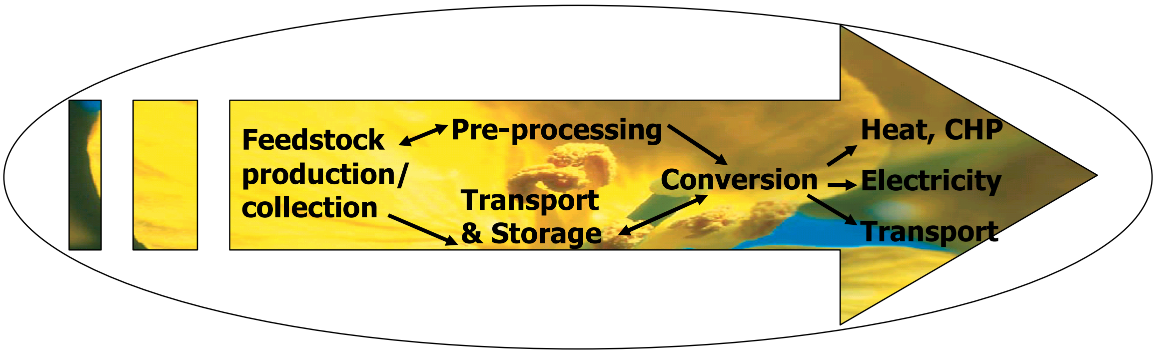


Figure 5.1: Bioenergy production chains (Source: Panoutsou, 2008)

There are numerous strands of research in each of these areas, and also integrative research on, for example, whole system energy balance and life cycle assessment (LCA). This research effort is highly internationalised; some of the largest efforts are taking place in the US and Europe, but many other countries are also important developers and deployers of bioenergy technologies. Research priorities may vary significantly by country; for example, the US and Brazil both support much research on bioethanol, but this is produced from maize in the US and sugar cane in Brazil (in the UK, ethanol is being produced from wheat).

Although the UK is involved in some of these areas, UK businesses are often adopters rather than developers of bioenergy technologies, though there are particular areas where the UK has strong capabilities (UKERC, 2008b). The UK bioenergy research community is small compared to those within the United States and other EU members. UK research has focussed on crop science, feedstock supply, technological innovations for combustion and conversion and whole-chain developments with some consideration of the environmental impacts of deployment. New funding initiatives are facilitating the coming together of multi-disciplinary teams to work on bioenergy research.

Controversies surround direct and indirect land use changes, lifecycle carbon reduction potential and other environmental impacts of bioenergy technologies. There are particular concerns about the use of first generation food crops for bioenergy due to the potential impact on food prices and competition for land, including deforestation. A great deal of research is seeking to develop second generation dedicated energy crops that aim not to compete with food crops or negatively shift patterns of land use. The recently published Gallagher Review explores the indirect effects of biofuels production to inform future biofuel targets (Renewable Fuels Agency, 2008).

It is impossible to characterise the maturity of the bioenergy field as a whole; technologies are found at all levels of maturity, from well established proven technologies (such as wood combustion) to newly emerging technologies in the research and development phase (such as algae based biofuels). There are several large-scale commercial deployments already in progress, including bioethanol production and the use of biomass in co-firing and dedicated combustion. It is important that a mixed portfolio of bioenergy supply is maintained at this time, ensuring the development of competitive and secure bioenergy and a firm research base for future large-scale deployments.

5.2 Accelerated Development of Bioenergy

Accelerated development of bioenergy involves both research-based technology development and more applied learning-by-doing. There is great scope for further development for many bioenergy technologies; even mature technologies such as woodfuel combustion have the potential to become more efficient, or to be adapted for new uses. Other resources, such as second generation energy crops, or emerging conversion technologies such as fast pyrolysis, have a great deal of scope for accelerated development. Furthermore, innovation in one part of the bioenergy supply chain can have significant impacts on the rest of the supply chain. For example, newly developed second generation crops carry a need for improved conversion technologies for their best use.

5.2.1 Research Challenges and Priorities

Within the diversity and complexity of the bioenergy chain, two critical overarching research priorities can be identified: crop feedstocks and conversion technologies. Concerns about the potential environmental costs and poor energy balance of first generation food crops are prompting an emphasis on second generation dedicated energy crops. Sustained R&D efforts are needed to deliver high yielding second generation biomass with minimal land and water requirements, and to verify that these dedicated bioenergy crops are more environmentally sustainable and socially acceptable. Research is also examining potentially more sustainable and productive ‘third generation’ novel feedstocks such as algae and artificial photosynthetic systems.

The development of more advanced conversion technologies is also essential. This includes improving existing conversion technologies, such as gasification, by making them more efficient, reducing their cost and/or increasing their fuel flexibility so that a variety of new energy crops can be utilised. At the same time, novel conversion technologies such as fast pyrolysis must also be studied and developed.

More applied support is needed to facilitate the development of standards for biomass trade and use, and to address wider socio-economic issues. There is also a need for ‘system-level’ research on the best ways to utilise limited biomass resources across the many different possible pathways and end uses.

It is impossible to offer detailed predications of how the bioenergy field will develop between now and 2050. However, the shift from first generation food crops to second generation energy crops has already begun and there is increasing pressure for the use of more sustainable second generation crops in the future. Research into third generation energy crops has also begun, and these could become prominent feedstocks in the medium to longer term. The timing of the transitions between first, second and third generation bioenergy technologies is highly uncertain given the range of technical, institutional and wider societal uncertainties involved, and the early stage of research of many technological possibilities.

While accelerated development may enable technologies to become commercially available at lower cost or at an earlier time, there are also costs and risks associated with acceleration. These include additional financial costs for new investment in research, development and deployment, but also wider risks such as potentially negative impacts on the environment. Environmental impact analysis (EIA) of the sustainability credentials of established and emerging technologies is a key response here. Another risk for emerging technologies is lock-in to 'sub-optimal' designs. While this is perhaps less of a risk for bioenergy, given the variety of technologies being developed and deployed, the possibility of system lock-in to particular feedstocks remains an issue.

5.2.2 Role of Policy[26]

Basic bioscience research has the potential to provide substantial improvements in the efficiency of biomass production and conversion technologies, but mobilising this research effort requires the setting-up and maintenance of a long-term policy support framework. Policy development in the bioenergy area is complex, but political and wider societal support for bioenergy is an important precondition for development and deployment.

The UK has a considerable biomass resource that may be used for renewable energy production in different ways:

- small-scale heat and power production, using dedicated energy crops and forest residues
- large scale power production and co-firing with coal, using dedicated crops
- the production of liquid biofuels such as bioethanol and biodiesel, from current food plants such as sugar beet, oil seed rape and wheat grain

The UK has seen significant increases in bioenergy research, development and demonstration funding and activity since 2000. There are now influential multilateral interests behind bioenergy in the UK, including government

---

[26] This section draws on UKERC's Research Landscape for Bioenergy, authored by Professor Gail Taylor, University of Southampton.

departments and the UK Research Councils. The prospect of further development of the sector has led to the coalescence of research funders' interests and greater collaboration between different research groups. At the same time, although strong in many areas, the UK lags behind international leaders in the field. A clearer strategic vision in some other European countries and the US is reflected in more coherent investment in bioscience R&D.

The UK bioenergy research base ranks high in basic bioscience competencies (plant biology, microbiology, biocatalysts); mid-range in the deployment of existing technologies, and relatively low in developing integrated supply chains and the biorefinery concept. The UK Research Councils and government departments now support a number of dedicated research programmes in bioenergy. These include the whole-systems 'Biosys' Project, the Energy Crops Genetic Improvement Programme, the Supergen Biomass and Biofuels consortium and a new BBSRC-funded Bioenergy Research Centre.

There have been a number of other policies and schemes to encourage the development and deployment of bioenergy technologies in the UK, including schemes to encourage farmers to grow energy crops, funding for R&D, demonstration and commercialisation. For example, the DTI Technology Programme specifically supported improvement of bioenergy crops through a number of demonstration projects and the deployment of agro-machinery for growing and harvesting bioenergy crops. Funding for applied bioenergy research is currently provided by the Carbon Trust's Applied Research / Carbon Vision Programmes, the Environment Agency, Forestry Commission, and also the regional development agencies (RDAs) and devolved administrations. There is an increasing number of commercial or supported-commercial bioenergy power plant projects operating or under development in the UK, covering a range of feedstocks, including straw, wood, miscanthus grass, SRC willow, sawmill waste and co-firing with fossil fuels, as well as production of bioethanol (from sugar cane and wheat grain) and biodiesel (from vegetable oils).

5.3 Modelling Bioenergy Acceleration

5.3.1 Input Assumptions

Given the multiplicity of bioenergy technology pathways, the modelling of accelerated development for this exercise was necessarily selective. Five technology areas with particular potential for accelerated development were identified as the focus for this work. For each of these, a literature review and expert consultation was conducted to define the potential for acceleration, both qualitatively and quantitatively (in terms of capital cost, O&M costs, availability, efficiency and plant lifetime). The data for each technology area was then combined into a single accelerated bioenergy scenario for the modelling exercise.

The five focus areas are: *bioengineering (improvements in energy crops), agromachinery, gasification, ligno-cellulosic ethanol,* and *fast pyrolysis*. For each of these, an accelerated development scenario was devised to represent progress in particular directions:

- For *bioengineering*, improvements in the yield of energy crops are assumed to accelerate the development of energy crops. Future domestic energy crop costs were calculated based on a doubling of average energy crop yield by 2050 from the present. Improvements in *agromachinery* are also assumed to contribute to the increasing yield of energy crops.[27]
- Reduced capital costs and improved availability of *gasification* technology.
- For *ligno-cellulosic ethanol*, improved feedstock quality and conversion technologies are manifested as reduced capital costs and O&M costs, and increased efficiency.
- For *fast pyrolysis*, process and quality improvements in the production of bio-oil are reflected in reduced capital and O&M costs. [28]

5.3.2 Results: Single Technology Scenario

Acceleration of the selected bioenergy technologies has a significant impact on the deployment of bioenergy in the UK as modelled by Markal. The Accelerated Technology Development (ATD) Bioenergy scenario (with bioenergy accelerated alone) shows marked differences from the non-accelerated LC core scenario, particularly for electricity production in the middle term, and biomass heating in the longer term.

Biomass only ever provides a minor contribution to the power sector in the non-accelerated core scenario (from landfill, sewage gas and gasification). In contrast, gasification is significantly deployed after 2010 in the accelerated scenario,

---

[27] Given concerns about the sustainability of imported feedstocks, these improvements were only applied to domestic energy crops.

[28] Fast pyrolysis technology remains non-deployed under accelerated development assumptions. This non-deployment does not mean that the technology should be abandoned or is without potential. Fast pyrolysis is already a commercial technology in other countries.

reaching a peak of nearly 20% of total generation in 2035, displacing wind and nuclear technologies (Figure 5.2, below).

The increased uptake of gasification technologies is, in part, due to the accelerated development of energy crops (Figure 5.3, below). Potential UK energy crop production is never fully utilized in the non accelerated scenario, but all available domestic land for energy crop production is used by 2030 under accelerated development assumptions. Nevertheless, energy crop production continues to increase after 2030 given increasing crop yields. Accordingly, in 2050, there is approximately six times more energy feedstock produced in the accelerated scenario than the non accelerated scenario.

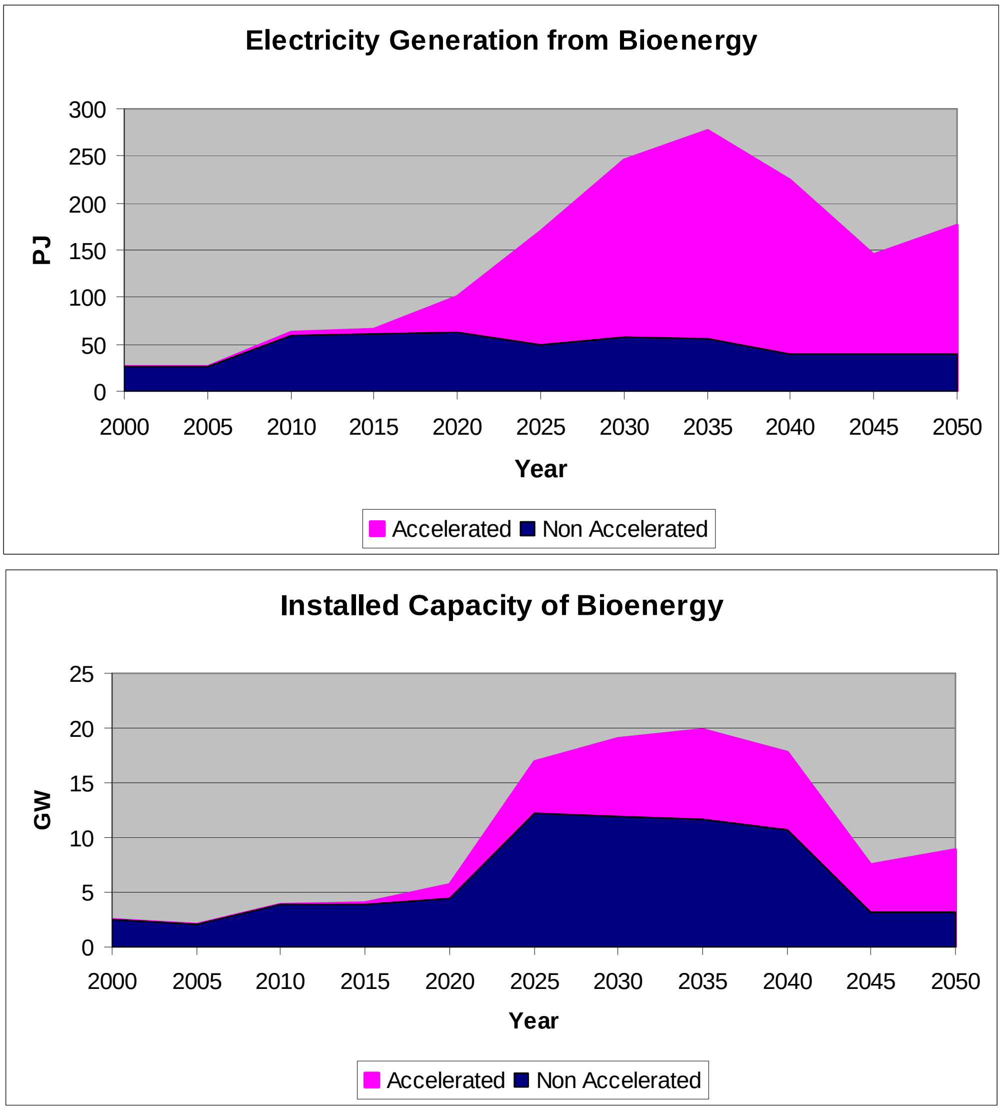


Figure 5.2: Bioenergy Electricity Generation and Installed Capacity

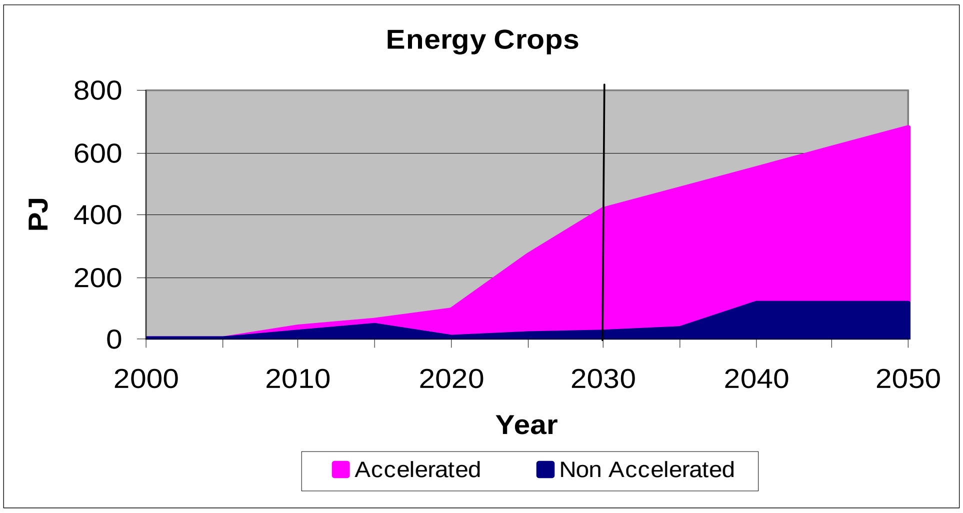


Figure 5.3: Energy Crop Production[29]

Energy crop feedstocks are also used for heating to a far greater extent in the accelerated scenario after 2035 (Figure 5.4). By 2050, over 20% of the total heating demand is supplied by bioenergy in the accelerated scenario. This represents a switch in the use of energy crops from the power sector to the residential heat sector in order to optimally meet overall decarbonisation ambitions.[30]

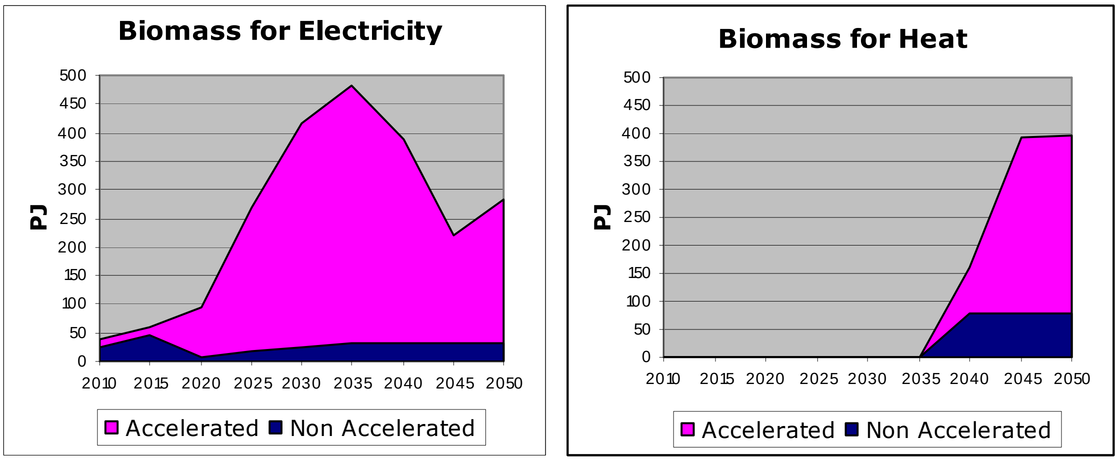


Figure 5.4: Biomass for electricity and heat

The accelerated development assumptions also lead to higher production of ligno-cellulosic ethanol for transport. However, because the production of ethanol

---

[29] The line at 2030 represents when the UK land available is fully utilized in the ATD scenario, further increases are due to yield increases

[30] Energy crops are also deployed much more significantly in the service (i.e. commercial) sector from 2040 onwards in the accelerated scenario. There is, however, less overall biomass deployed in the service sector in the accelerated scenario because woody resources are no longer used.

through fermentation of wheat is lower in the accelerated scenario, there is less overall ethanol production in the accelerated scenario.

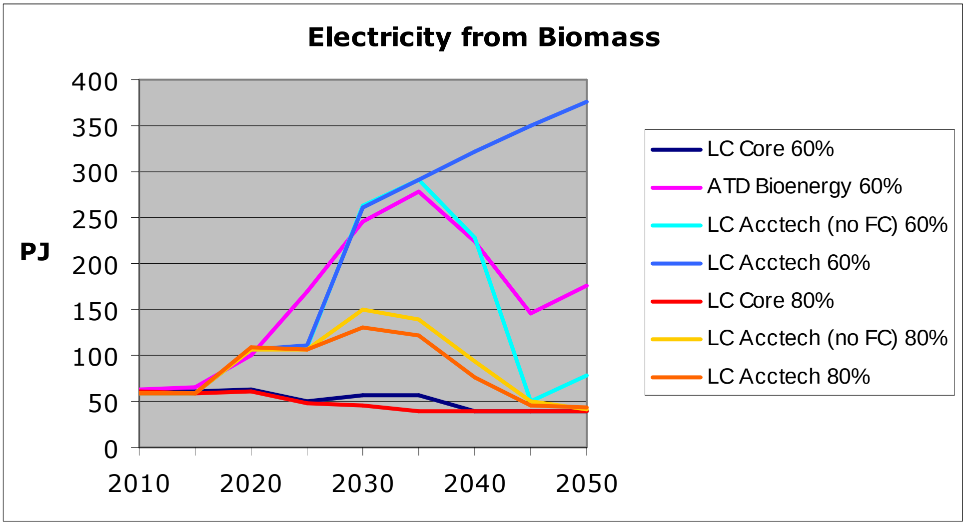
5.3.3 Results: Aggregated Scenarios

60% Scenarios

There are only slight differences in bio-electricity production between single technology ATD-Bioenergy and aggregated 60% scenarios (LC-Renew and LC-Acctech) before 2040 (Figure 5.5). After 2040, however, there is significantly less bio-electricity in the aggregated scenarios, given the availability of other cheap renewables by this time under accelerated development assumptions. Rather, the aggregated scenarios feature more biomass for residential heating and transport, where there are fewer competing low carbon options (Figures 5.6 & 5.7). The introduction of accelerated development of fuel cells has a significant effect here, in raising demands for electricity, and enabling the (resource constrained) bioenergy feedstocks to be diverted to electricity generation and away from heat and transport.

80% Scenarios

While biomass is a significant contributor to decarbonised energy futures in both 60% and 80% scenarios, the higher target diverts the limited biomass feedstock into transport, instead of heat and power (Figures 5.5-5.7). Raising the carbon reduction target to 80% is associated with significantly less bio-electricity and residential heat from biomass, especially in the longer term, but much higher levels of transport biofuels (Figures 5.5–5.7). Adding in accelerated development of fuel cells – an attractive alternative form of low carbon transport – is again significant here, with bioenergy diverted to heating rather than transport in LC-Acctech with accelerated FCs.



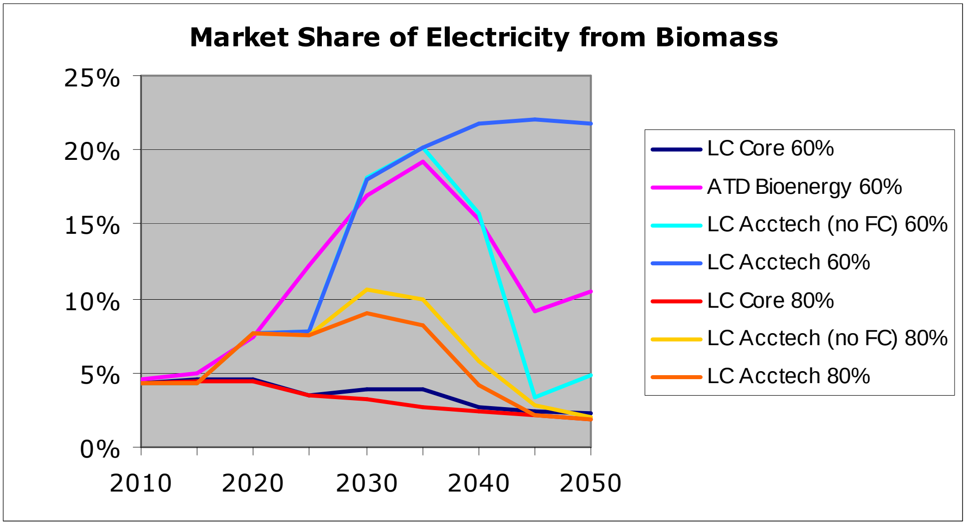


Figure 5.5: Electricity from Biomass (Total & Market Share) in Aggregated Scenarios

Note: LC Acctech (no FC) scenarios have all technologies accelerated except Fuel Cells

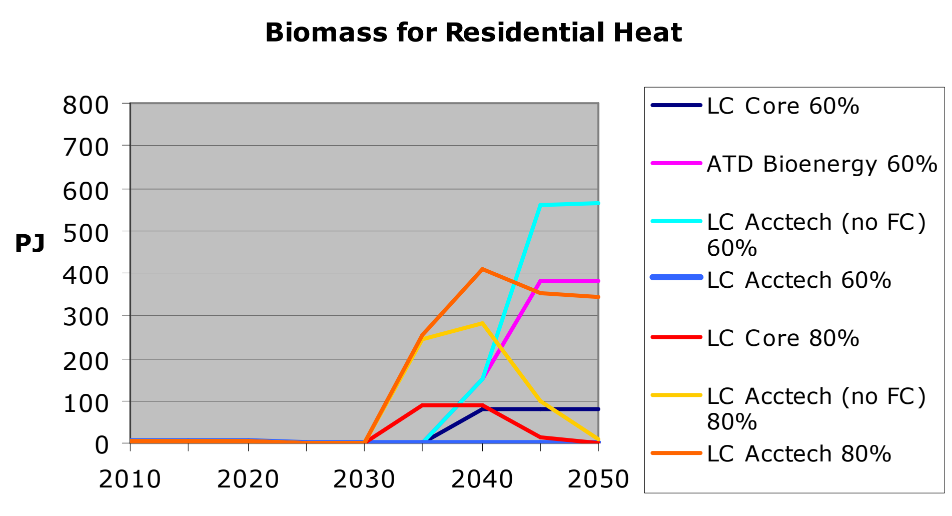


Figure 5.6: Biomass for Residential Heating in Aggregated Scenarios

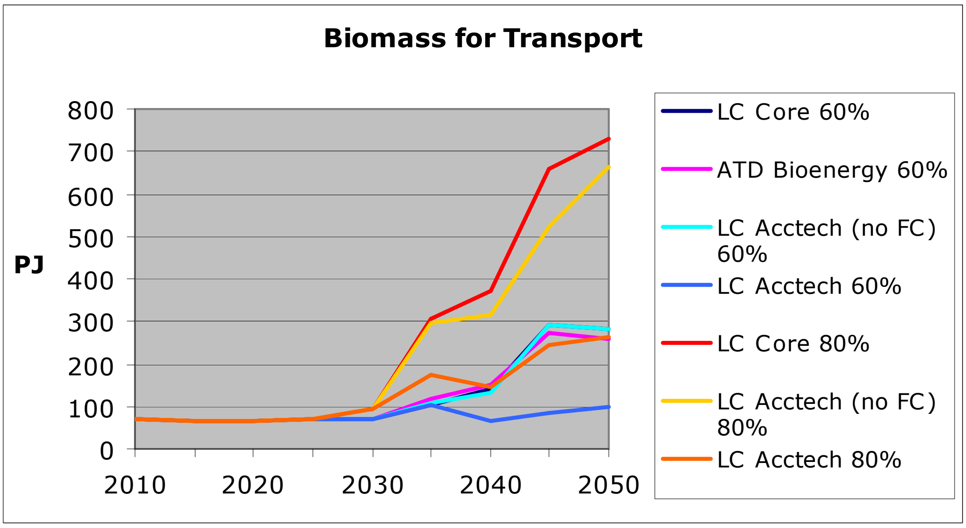


Figure 5.7: Biomass for Transport in Aggregated Scenarios

5.4 Discussion and Summary

Bioenergy is arguably a much more diverse and complex technology field than other technologies analysed here. While this variety means there is perhaps less predictability about the likely pace and direction of change across the 'bioenergy innovation system', the present research exercise has identified a number of opportunities for accelerated development of bioenergy feedstock and conversion technologies, and has translated these into scenarios to allow for consideration of their possible impact in helping the UK energy system decarbonise. (It is important to remember that this is an illustration of the types of accelerated development that could occur in bioenergy, and many other bioenergy chains may play a significant role in the decarbonisation of the UK and elsewhere).

The modelling results illustrate the potential of bioenergy to play an important role in the transition to a low carbon energy system for the UK. The flexibility of bioenergy resources and technologies is particularly valuable here, in facilitating decarbonisation of different energy services: heat, transport and electricity. The versatility of biomass means its optimal role in energy system decarbonisation changes according to different levels of policy ambition – illustrating the interaction between overall climate policy goals and R&D strategy.

The accelerated results highlight non-technical and non-economic constraints facing bioenergy uptake the UK, such as physical land constraints. Energy crops prove an economic way to decarbonise the energy system under accelerated development assumptions, yet by 2030 all of the available land for energy crops in the UK is utilised. In practice, the land available for energy crops could be further limited by social and environmental concerns surrounding the use of large amounts of land to grow energy crops. In the short term, other constraints include a limited supply of planting material and of the machinery for planting and harvesting (SKM, 2008a).

In the accelerated development scenarios, bioenergy resources are first deployed to help decarbonise the electricity sector and then residential heating. This echoes other recent findings; the UK Biomass Strategy Report (DEFRA, 2007) argued that biomass heating is one of the most efficient options for carbon reduction, while using biomass for transport fuels is one of the least efficient. The Gallagher Review (Renewable Fuels Agency, 2008) suggested that deployment of transport biofuels be delayed until more research is done on carbon reduction impacts of biofuel crops, including indirect effects, and suggested setting lower levels for the EU’s Renewable Transport Fuel Obligation.

In the aggregated results, the distribution of biomass to heat, power and transport is clearly sensitive to the relative progress of other low carbon technologies, and also the level of overall decarbonisation ambition. With higher ambition in the 80% scenarios there is a noticeable shift towards using biomass for transport as opposed to heat and power in the lower ambition (60%) scenarios. This could be due to the fact that when moving to an 80% carbon reduction, the transport sector must be highly decarbonised; yet, there are few options to decarbonise the transport sector and thus the limited biomass resource is shifted away from the power sector (with many competitive low carbon options) to the transport sector. However, this Deployment depends not only on progressing the innovation system for bioenergy, but also progress in other technologies and wider forces shaping the development of the UK energy system.

The accelerated results also suggest that improvements at multiple stages of the bioenergy supply chain have the potential to contribute to a decarbonised system. For instance, accelerated development of a resource (energy crops) and accelerated development of a conversion technology (gasification) both allow for higher deployment of biomass. This implies that R&D efforts should be directed across the supply chain, and also that innovation matters for existing (as well as novel) resources and technologies.

Given the multiplicity of bioenergy pathways, the accelerated development scenarios presented here are illustrative rather than exhaustive. In future work, a sensitivity analysis of the accelerated scenario would provide further depth and understanding to the results, and emerging technologies not modelled here, such as algal biofuels, could also be introduced.[31] Despite these limitations, the work here suggests that accelerated progress across the bioenergy supply chain has the potential to contribute significantly to the decarbonisation of the UK energy system.

---

[31] Markal modelling pathways are reviewed in detail in Jablonski et al. (2007).

Chapter 6: Nuclear Power

6.1 Overview[32]

Nuclear power seeks to harness the power of the atom, either by splitting heavy elements apart in fission reactions, or by merging light elements together in fusion reactions. This chapter considers the potential for accelerated technological development of both fission and fusion.

Nuclear fission can be regarded as a well established technology with over 50 years experience, over 400 operating reactors worldwide and cumulative experience of over 11,000 reactor-years. At the same time, the rate of technological change is relatively slow, given that reactor systems have lifetimes of between 30 and 60 years. The vast majority of currently deployed reactor systems are second generation systems (see Table 6.1, below).

Fission has been part of the UK energy mix since the 1950s, and currently contributes just under 20% of electricity generation. However, no new capacity has been ordered in the last two decades, and all of the UK's existing nuclear power stations are scheduled to close over the next few decades. From the mid-1980s onwards, inexpensive oil and gas prices and liberalisation of the electricity supply industry prompted a significant scaling-back of nuclear power technology development capabilities. By the mid-1990s, UK public investment in both fission and fusion R&D had been substantially curtailed (Figure 6.1, below).

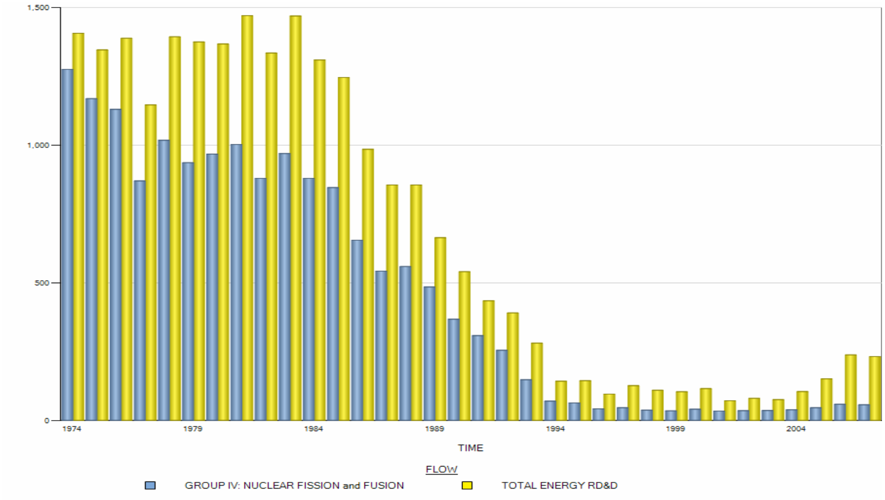


Figure 6.1 UK RD&D Spend on Total Energy and Nuclear Power (US$m) 1974-2007
(Source: IEA Statistics, 2008 database)

---

[32] This section is based on nuclear fission and fusion research landscapes and roadmap reports available from the UKERC Research Atlas, authored by Dr Paul Howarth (Dalton Nuclear Institute) and Dr David Ward (Culham Science Centre).

Since 2000 there has been renewed interest internationally in nuclear power development and deployment, and the technology is expected to play a significant role in many countries' future energy mixes. Fission power plants are currently being constructed in France, Finland and the US, with fleet build programmes in China, India and Brazil.[33] The UK Government recently acknowledged that new nuclear build has a role to play in meeting its wider energy policy goals (BERR, 2008b).

Fission and fusion innovation systems are internationally co-ordinated. Fission development is organised around distinctive generations of reactor technology. Two generations have been built to date, with the first generation, such as the early Magnox stations, now being phased out. Current plans for new build are centred around Generation III technology, and although, technically, these are ready to built, re-establishing nuclear means new Generation III systems will not be deployed until around 2017 to 2020 at the earliest. In the 2020s there are likely to be evolutionary modifications of such Generation III systems. At the same time, more revolutionary Generation III+ systems, including additional safety features, will be considered for deployment. More radical Generation IV designs are expected to become available after 2030 (Table 6.1, below).

Nuclear fusion holds out the long-term promise of electricity production from abundant resources, with intrinsic safety features and very low atmospheric emissions. Fusion technology development made substantial progress following the oil crises in the 1970s. The decline of energy R&D in the 1980s and 1990s reduced the pace of progress, but a more recent emphasis on clean energy has resulted in a renewed impetus. However, making fusion a technologically and economically viable energy source will require a sustained long-term research effort, and it is not expected to be commercially available until the second half of the present century.

Fusion innovation involves the international development of experimental prototype designs. US, Japanese, Russian and EU efforts have dominated the field, with the increasing involvement of China, India and South Korea. UK fusion research is based at the UKAEA's Culham Science Centre in Oxfordshire, with associated researchers at universities throughout the UK and beyond. Culham hosts the main European experimental fusion reactor, the Joint European Torus

---

[33] See World Nuclear Association, http://www.world-nuclear.org/info/inf17.html

(JET), the world's largest and highest performance fusion device. UK-based R&D is an integrated part of European efforts, which are, in turn, increasingly co-ordinated with global developments.

Generation I original demonstration systems, such as UK Magnox reactors from the 1950s, now reaching their end of life and being decommissioned. This process will complete in the UK around 2011.

Generation II technologies continue to be used, either on normal lifetime basis of 40 years or possible lifetime extension. In the UK, Generation II systems are Advanced Gas-Cooled Reactors (AGRs), except for Sizewell B PWR. AGRs will continue through to design lifetimes ending around 2015 to 2025, with limited possibility for lifetime extension. Sizewell B will continue to its design lifetime at 2035 or possible lifetime extension, which is more feasible for light-water reactors.

Generation III technologies such as Westinghouse AP1000, Areva EPR or other such systems are evolutionary LWRs and are ready to be deployed. This process has started in Finland and France and it is envisaged the first Generation III system could be on-line in the UK around 2017. These products are regarded as standard globalised systems, and there is little desire by the vendors to modify such systems.

Generation III+ technologies are more revolutionary; they include the South African Pebble Bed Modular Reactor or the IRIS integrated light water reactor. These systems are less straightforward to deploy commercially, as demonstration is needed. Regulatory authorities will wish to see such systems properly assessed before any demonstration system is deployed, and once this has been achieved, utilities will need to be convinced of reliable operation over a significant period of time. Generation III+ systems could be deployed around 2025, assuming demonstration systems are in place from 2015.

Generation IV systems are more long term and considered for deployment on a 2030+ timescale. These systems attempt to address further improvements on reactor safety, as well as more sustainable use of resources. Some of the technologies have already been demonstrated, such as the sodium-cooled fast reactor, and it is therefore possible that some of these concept systems could be brought forward for earlier deployment. For example, France has committed to building a demonstration sodium-cooled fast reactor by 2020, and this project is now being considered as a central theme of the EU's EURATOM research programmes.

Table 6.1: Nuclear Fission Reactor Technology Development

6.2 Accelerated Development of Nuclear Power

6.2.1 Research Challenges and Priorities

Nuclear fission R&D serves a number of distinctive roles: supporting existing plant operations, enabling deployment of advanced reactor systems, and providing improved solutions for waste management (including legacy waste) and plant decommissioning. This chapter concentrates mainly on reactor systems technology development. Different generations of reactor design have distinctive research needs (Table 6.2, below). From a UK perspective, international collaborations play an important role in keeping abreast of advanced reactor technology being developed overseas, including fast and high temperature gas-cooled reactors for electricity, heat and hydrogen generation.

	R&D Priorities
Generation III	Long term materials irradiation, structural integrity Control, instrumentation, monitoring and lifetime prediction
Generation III+	Heat generation applications High temperature materials Fuel burn-up Long-life fuel cores Demonstrating inherent safety characteristic
Generation IV	Materials Control & Instrumentation Fuel fabrication High burn-up fuel performance Thermal hydraulics Balance of plant Spent fuel reprocessing and recycle

Table 6.2: Nuclear Fission R&D Priorities

To produce energy from fusion reactions, a mixture of deuterium and tritium gases is heated to extremely high temperatures, so that they are ionised and form a plasma. The principal focus of fusion research is the physics of confining plasmas using strong magnetic fields, the engineering required to heat plasmas to the temperatures required, and developing diagnostic devices to refine control of the reactor processes. Current research efforts are directed towards simultaneously achieving high plant availability, high thermodynamic efficiency and high plasma pressure (see Table 6.3, below).

Technology Area	Research Priority
Plasma performance	Disruption avoidance Steady-state operation Divertor performance Start up Power plant plasma performance
Enabling technologies	Superconducting machine Heating, current drive and fuelling Power plant diagnostics & control Tritium inventory control & processing Remote handling
Materials, component performance and lifetime	Materials characterisation Plasma-facing surface First wall blanket/divertor materials & components Tritium self-sufficiency
Final goal	Licensing for power plant Electricity generation at high availability

Table 6.3: Fusion Energy Research Challenges (adapted from UKAEA, 2005)

6.2.2 Phases of Accelerated Development

Fission technology is relatively mature, with current designs able to be deployed at full scale, and a relatively well mapped-out progression to more advanced designs in the future. For the present research exercise, this means that there is less scope to differentiate strongly between accelerated and reference scenarios compared to other, more emergent, technologies, whose development trajectories are less well defined. Nevertheless, an 'accelerated technology development' (ATD) scenario for fission is introduced here, featuring relatively modest revisions to the non-accelerated reference case. Table 6.4, below, characterises Reference and ATD Scenarios for fission over short, medium and long timescales.

	Reference Scenario	**ATD Scenario**
Present	Generation I technology approaching phase out. Generation II technology continued operation.	No significant change, but technology investment to help extend Gen II lifetime.
2020 (short term)	Generation II technology approaching end-of-life, some lifetime extension possible. Generation III systems starting to be deployed. Generation III+ demonstration systems deployed. Generation IV concepts close to research scale pilot plant deployment.	As above, technology development to help lifetime extension. Technology development to help deployment of Gen III systems, not by changing the design, but allowing support and licensing activities to be expedited. Generation III+ could be accelerated, especially heat generation applications. Greater investment in demonstrating Gen IV systems, with demonstration plants developed.
2035 (medium term)	Generation III systems well established, some demonstration. Generation III+ systems in specific markets complimentary to Gen III. Gen IV technologies are feasible.	Generation III technologies well established with further investment in evolutionary improvements. Generation III+ well established alongside Gen III in heat generation applications and countries that lack full nuclear. Commercial deployment of Gen IV systems more likely.
2050 (long term)	Evolutionary Gen III systems offered plus Generation IV systems starting to be deployed.	Generation IV systems in widescale deployment.

Table 6.4: Reference and Accelerated Technology Scenarios for Nuclear Fission

The acceleration of fission development is also restricted because of trade-offs between technology cost, performance, security and safety, and the need to undertake thorough assessments of novel reactor designs before licensing their use. Alongside technology-based RD&D, institutional aspects of innovation are important here, and the ATD-Nuclear scenario identifies some scope to reform licensing and regulatory arrangements for future designs (Table 6.5).

	Generation III	Generation IV
Capital Cost	Some scope for evolutionary reduction, although this would not be evident in the first tranche and benefit would be marginal.	Limited scope for cost reduction. ATD would mainly bring forward the availability of the technology.
Operating Cost	Improved control and instrumentation and materials technology could marginally reduce operational cost.	Limited scope for cost reduction.
Operating Performance	Based on Gen II experiences, load factors of Gen III systems are likely to be very high. Some scope for reducing unscheduled outages.	Limited scope for cost reduction.
Safety	Scope for continued safety improvement through increased knowledge and operational experience. Again, based on Gen II, scope for improvement is limited.	Provide greater certainty to support licensing, enabling earlier deployment and reduced risk/uncertainty.
Sustainability	Advanced fuel cycles (such as MOX and Thorium), requiring supporting R&D.	Innovative fuel cycles to promote more sustainable solutions.
Waste	Reduced waste volumes through increasing fuel burn-up. Research could potentially double burn-up, halving waste volume.	Reduced waste volumes through innovative fuel cycles

Table 6.5 Potential Impact of Accelerated Development of Advanced Fission Reactor Designs

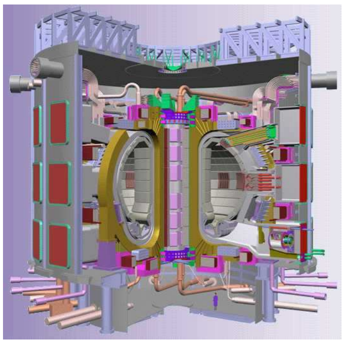
Fusion development is primarily organised around three major facilities being developed by the international research community (Figure 6.2, below). In the shorter term the work is planned to run in parallel on two devices: *ITER*, a large-scale fusion experimental device, currently under construction in France, which could be operational around 2020 and *IFMIF*, a materials testing facility undergoing engineering design in Japan and the EU. In the medium term these two work streams will be brought together to focus on *DEMO*, a demonstration power plant (or several plants), which could be operating in the 2030s. This would allow final deployment of the technology in the longer term.

In addition to this work, there remains activity in developing inertial fusion, in which high power lasers are used to compress pellets of fuel to very high pressures, allowing fusion to take place in a very short time.[34]

Given the research challenges involved, a substantially accelerated development timeline for fusion technology is unlikely, and critical path analysis confirms that significant deployment is not expected until the second half of this century (UKAEA, 2005). Nevertheless, with increased funding, and parallel development of reactor and material technologies, initial deployment of fusion may be feasible before 2050, and an accelerated development scenario was devised on this basis for the present exercise.

---

[34] See http://www.hiper-laser.org



ITER: beginning construction in France

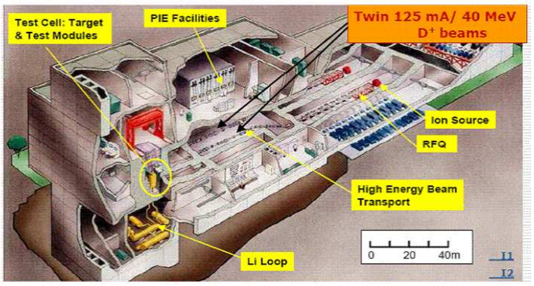
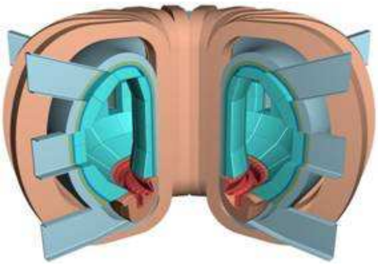


Figure 8.28 *The IFMIF conceptual design*

Materials test facility, IFMIF: Engineering design in Japan



DEMO: demonstration power station, conceptual designs being carried out around the world

Figure 6.2: International Development Pathway for Fusion Power (Source: UKAEA)

6.2.3 UK R&D in the International Context

Both fission and fusion technology development are now highly internationalised. It is rarely possible today for a single country to develop an advanced fission reactor and associated fuel cycle without international engagement. The UK no longer has the capability to indigenously design its own reactor system, and future build in the UK will rely on global vendors offering essentially standardised designs. Fission R&D is organised in a number of international collaborative initiatives, and in contributing to the development of advanced reactor technology, the UK participates in international projects organised by the EU, IAEA and OECD, and initiatives such as the Generation IV consortium and the Global Nuclear Energy Partnership. These allow the UK to leverage much larger R&D investments than those available domestically.

The UK’s fission R&D base across industry and academia covers all aspects of the fuel cycle, including fuel manufacture, reactors, spent fuel treatment, waste management and decommissioning. The UK has strong capabilities in fuel manufacture and legacy waste management and clean-up activities, including fuel reprocessing and refabrication. Funding cutbacks since the 1980s have eroded capabilities in other areas, such as advanced reactor design and environmental and social assessment.

Fusion development is mobilised around a small number of international research initiatives. UK fusion research activity is an integrated part of European efforts, which are, in turn, increasingly co-ordinated with global developments. Outside the EU, the principal countries involved in large-scale fusion research are the US, Russia, Japan, China, India and South Korea. The domestic UK fusion programme is strong in experimental and theoretical fusion plasma physics, and materials modelling, but relatively weak in more applied areas of fusion technology where funding was curtailed after electricity industry privatisation. UK fusion research concentrates on experiments on JET and the UK's-own smaller device (MAST), and on theoretical work on the behaviour of fusion devices, materials, and the design of a future fusion power plant. All this work is carried out in integrated European research teams – much of it would not be possible with UK efforts alone.

6.3 Modelling Nuclear Power Acceleration

6.3.1 Input Assumptions

The ATD-Nuclear scenario features moderately lower costs, higher load factors, improved efficiencies and earlier availabilities for Gen III, III+ and IV fission plant, relative to the Energy 2050 reference scenario. Generation III technology was assumed to become available around 2017 for an initial *first-of-a-kind* (FOAK) plant, with follow-on *next-of-a-kind* (NOAK) plants available from around 2020 (Table 6.6, below[35]).

Plant Type	**Capital Cost (£2000 /kWe)**	**O&M cost (£2000 /kWe)**	**Life (years)**	**Load factor (%)**	**Efficiency (%)**	**Available from**
Gen III FOAK	1000	55	60	0.80	34	2017
Gen III NOAK	900	55	60	0.85	36	2020
Gen III+	800	45	60	0.90	40	2025
Gen IV	750	50	60	0.85	40	2030

Table 6.6: Fission Input Data for ATD-Nuclear Scenario

---

[35] The data revisions for the ATD-Nuclear scenario involved a merging together of previously discrete Generation III reactor designs, and the introduction of a new pathway for Generation IV technology; this means there is no direct correspondence between the available nuclear technology pathways in non-accelerated and accelerated scenarios.

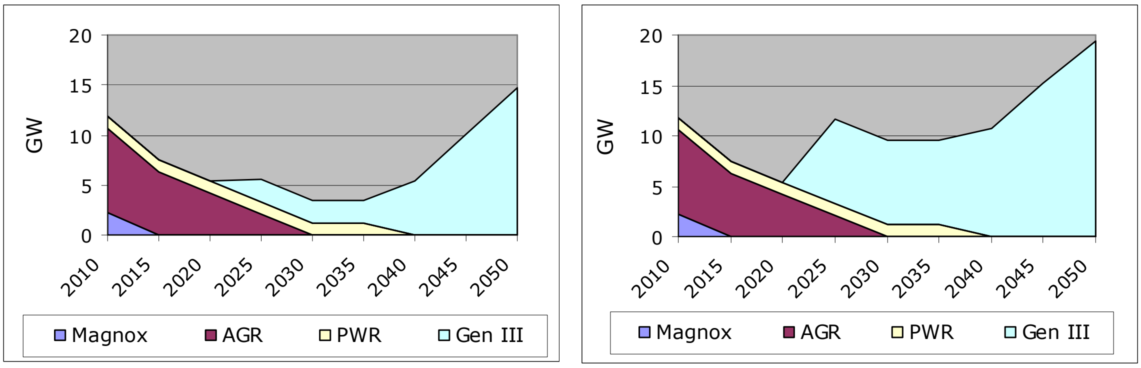
In considering the prospects for accelerated fusion development, a distinction can be drawn between European and US ambitions. The EU has recently analysed the possibility of earlier construction of a demonstration power station, DEMO, before the full exploitation of ITER is completed, with construction of an early-DEMO (EDEMO) enabling fusion development to be accelerated by perhaps 5 years (Maisonnier et al., 2006; CEC, 2007). By comparison, US studies tend to impose more stringent demands for lower fusion costs, and therefore more technologically advanced designs for the first fusion power plants. These two trajectories – earlier availability in the EU and more advanced technology development in the US – were brought together in the ATD-Nuclear scenario, with an EU-style plant assumed to be available in 2040, and a more advanced (and cheaper) US-style plant in 2050. (Note that even under these assumptions, there is little expectation of fusion deployment before 2050- the time horizon in the present modelling exercise).

Date of availability	Capital Cost £/kWe
2040	2,800
2050	1,800

Table 6.7: Fusion Input Data for ATD-Nuclear Scenario

6.3.2 Results: Single Technology Scenario

The ATD-Nuclear Scenario (with nuclear power accelerated alone, and 60% CO_2 carbon reduction ambition to 2050) differs significantly from the LC-Core (non-accelerated) reference scenario. While there is little new nuclear plant deployed before 2035 in the reference scenario, the ATD-Nuclear scenario features substantial new build after 2020 (Figure 6.3, below). By 2050, just under 20GW of new nuclear capacity is installed in the ATD-Nuclear Scenario, generating just over 30% of total electricity supplied. As anticipated, fusion technology has not been selected, even under accelerated development assumptions.



LC-Core (non-accelerated)

ATD-Nuclear (accelerated)

Figure 6.3: Installed Nuclear Capacity, Impact of Nuclear Acceleration

Technology acceleration also means that a significant nuclear contribution to the energy mix is sustained over time, largely filling-in the gap seen in the reference case between phasing out of existing nuclear capacity and new build. In practice, as well as the possibility of significant Gen III build in the 2020s, there is also a likelihood of AGR and PWR lifetime extension into the mid 2020s, enabling a significant nuclear power contribution to be sustained before any new build programme after 2020.[36]

6.3.3 Results: Aggregated Scenarios

Combining accelerated development assumptions for nuclear power with those for other technologies analysed here underlines the relative modesty of the ATD-Nuclear assumptions compared to those for other technologies. This means that the long-term nuclear share of the overall electricity supply mix is generally higher in the non-accelerated (LC-Core) scenarios, compared to equivalent scenarios with all technologies accelerated (LC-Acctech). This is especially pronounced for LC-Acctech 60 (with 60% decarbonisation ambition to 2050) where there is only a very small amount of new nuclear capacity installed in the LC-Acctech scenario.[37] By contrast, under 80% carbon ambition, LC-Acctech features a significant programme of Gen III build after 2020, with almost 20GW installed by 2050 (although this is still significantly lower than the c.30GW installed in the non-accelerated equivalent) (Figure 6.4, below; note that Figure 6.4 assumes no lifetime extension for existing plant; in practice, lifetime extension is likely to increase the overall contribution from nuclear power, especially over the short and medium term).

Although the aggregated scenarios presented in Figure 6.4 suggest there may be only a modest role for nuclear power over the short and medium term, this is predicated on accelerated development of other low carbon power supply technologies, especially carbon capture and storage. For example, in the LC-Acctech (no CCS) scenario, in which CCS is excluded on the basis that it fails to develop or be commercially deployed, suggest a much greater role for nuclear power after 2020. The medium term role for nuclear becomes even greater if

---

[36] While PWR reactors have significant scope for lengthy lifetime extension, AGRs have only limited lifetime extension prospects, of perhaps 5-10 years (Worral and Gregg, 2007).

[37] Fuel cell technology has a significant influence on the diminished role of nuclear power in LC-Acctech 60. The availability of affordable fuel cell vehicles after 2035 (under ATD-Fuel Cell assumptions) means that bioenergy resources are available for use in power generation (rather than for low carbon transport), displacing nuclear power.

renewables technologies fail to progress along accelerated development trajectories, illustrated in the ATD-Nuclear (no CCS) scenario (Figure 6.5, below).

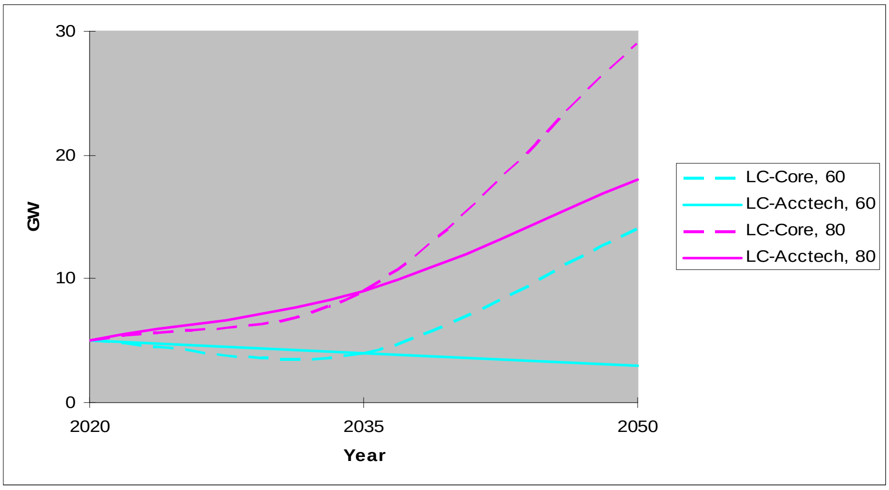


Figure 6.4: Nuclear Power Capacity Expansion after 2020, Aggregated Scenarios (selected data, smoothed)

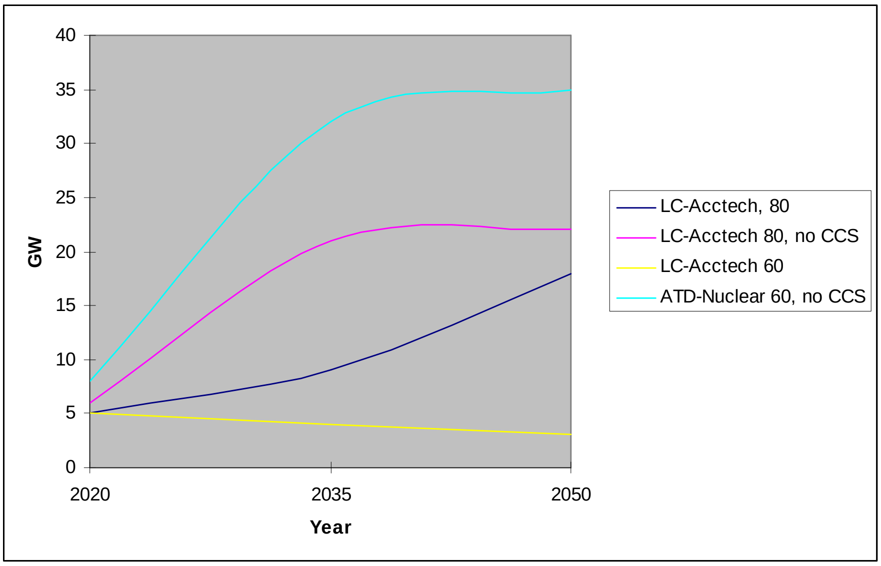


Figure 6.5: Nuclear Power Capacity Expansion, Variant Aggregated Scenarios including 'no-CCS' cases (selected data, smoothed)

6.4 Discussion

The nuclear power technology field is technologically, organisationally and institutionally dissimilar to the other low carbon supply technologies analysed elsewhere in this report, in terms of its historical development and future prospects. Nuclear fission power is relatively mature; it was central to the planning and expectations of the UK electricity supply industry (ESI) for decades under nationalisation, even though it never assumed the dominant role in the supply mix that was envisaged. By comparison, renewable energy technologies have, until very recently, been seen as a marginal option, and CCS has only recently emerged as a low-carbon supply-side prospective technology.

In the two decades since ESI privatisation, the emphasis has been on 'normalising' nuclear power – i.e. making it technologically, economically and politically low risk (MacKerron, 2004). No new nuclear plants have been commissioned in this period, but since 2000, wider policy imperatives for decarbonisation and security of supply have prompted a resurgence of interest in new nuclear build. However, the contemporary institutional context for the power sector requires a different style of technology development and deployment than under nationalisation, emphasising private finance for project development.

Given this, the priorities of the UK nuclear power sector are efficient operation of current plant stock and additional deployment of available technology, rather than developing more futuristic designs likely to carry higher technical and economic uncertainties. This is readily understood given the dominant role of capital financing in the overall (levelised) cost for nuclear electricity (Figure 6.6, below). Given that Generation III technologies are essentially standardised, any change in product specification offering to reduce capital cost may increase overall cost, if it is considered to carry greater risk.

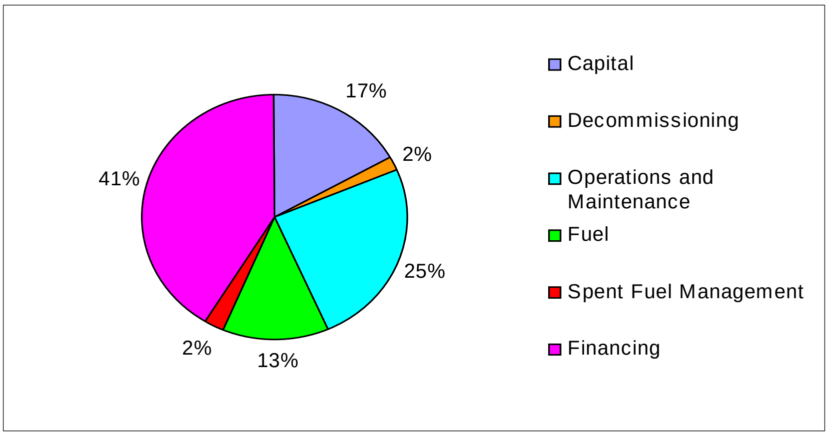


Figure 6.6: Levelised Generation Cost for Nuclear, showing the dominance of capital cost and its associated financing (Source: Dalton Nuclear Institute)

This risk-averseness translates as reduced concern, within the nuclear power community, of mapping out an accelerated development pathway that diverges radically away from a non-accelerated reference case. Fusion energy also offers only limited scope for acceleration away from its established trajectory towards commercialisation over the long term.

These restrictions notwithstanding, an ATD-Nuclear scenario was devised here, with progressive cost reductions, performance improvements and earlier availability across successive generations of nuclear fission plant, and earlier availability of an initial fusion plant design. Despite the relative modesty of these changes, they were seen to make a significant difference to the suggested timing of nuclear deployment, such that a programme of new fission build is initiated significantly earlier in the accelerated scenario.

Allowing for lifetime extension for existing nuclear plant, accelerated technology development suggests that a significant nuclear contribution to the UK energy mix is sustained, with new capacity essentially replacing decommissioned existing plant over the medium term. Over the longer term, the contribution from nuclear grows more rapidly out to 2050. Rather than the intermittent capacity additions seen in the ATD-Nuclear scenario, a more sustained programme of build out to 2050 can be inferred from the modelling results, taking into account likely retiral dates and lifetime extensions of existing plant, and the subsequent introduction of Gen III+ and Gen IV technologies in the 2030s and 2040s (Figure 6.7, below).

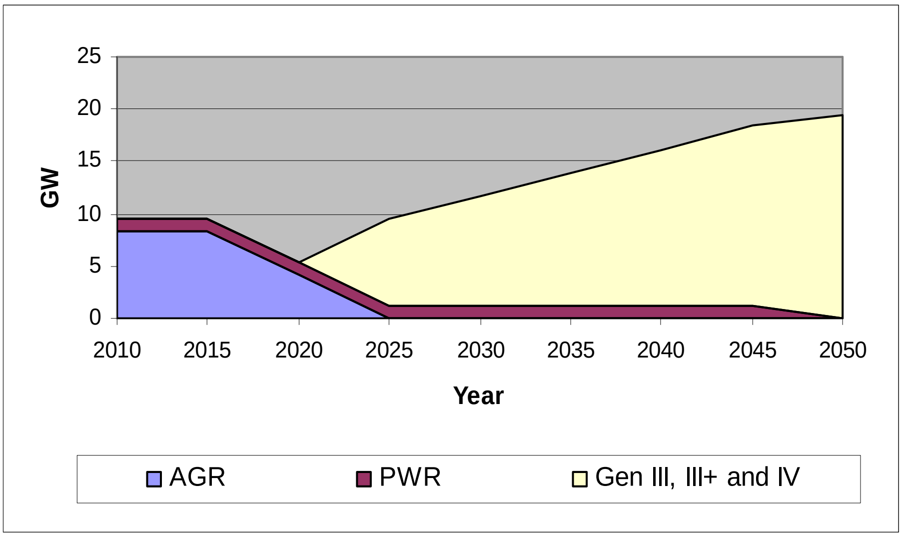


Figure 6.7: Possible Nuclear Fission Capacity Profile, based on ATD-Nuclear results

Aggregating together ATD assumptions for all low carbon supply technologies analysed here, the relatively limited scope for nuclear acceleration results in a generally reduced role for the technology compared to non-accelerated scenarios. However, this depends on the overall level of decarbonisation ambition (while the nuclear contribution is marginal under some 60% scenarios, it remains a significant contributor in most 80% scenarios), and also on the availability and affordability of other low carbon supply technologies. In particular, the results here suggest that in the absence of CCS, nuclear power may play a key role in lower carbon UK power mixes in the 2020s and 2030s, particularly if renewables technologies also fail to develop along accelerated development trajectories.

In common with some other technologies analysed here, such as solar PV, the ATD modelling results fail to represent the intergenerational shifts between different designs envisaged in technology-specific roadmapping exercises. Instead, a more technologically-conservative scenario is suggested, relying wholly on Gen III devices for new nuclear build.[38]

The inferred 'fleet-build' deployment programme in the ATD-Nuclear scenario is relatively modest, with a gradual build-up of capacity over the period 2020-2050 (Figure 6.7, above). Although this is technically feasible, there are policy implications here, so as to enable first deployment of Generation III technology in the UK soon after 2020, and supporting UK capacity to sustain a fleet build programme (crucial to capturing fleet build economies) out to 2050. However, other scenarios here suggest the possibility of a much more ambitious programme of new build in the 2020s and beyond, which would be highly challenging in terms of international supply chains and domestic build capacity.

Policy also has key role in enabling the re-emerging UK-based nuclear fission research community to build up its development capacities, thereby fostering the UK's ability to participate in (and take advantage of) international RD&D efforts over medium and longer terms. For fusion technology development, the policy challenge is to sustain the UK contribution to the development of the technology internationally, so that it can become a deployable low carbon technology after 2050.

---

[38] The non-deployment of GenIII+ and Gen IV in the ATD nulcear scenarios is related to their use of fuel with higher enrichment levels (so incurring higher fuel costs) than Gen III.

Chapter 7: Carbon Capture and Storage (CCS)

7.1 Overview

Many forecasts predict a continued major role for fossil fuels in meeting global energy demand to 2020 or even 2050 and beyond. In this context, Carbon Capture and Storage (CCS) is potentially a key technology for mitigating emissions of CO_2 from these fuel sources.[39] CCS involves abating the emissions from power plants and other industries by chemically capturing – or separating out – the CO_2, transporting it to a storage site, and injecting it for long-term storage in sealed geological formations. Depending on the capture technology, the CO2 is captured from flue gases, from the fuel before combustion, or directly from the combustion process. This chapter will focus on geological storage, as opposed to storage on ocean floors or biological sequestration. Improvements in the underlying power plant technology will also be discussed, but the main focus will lie on CCS abatement technology.

CCS technology is generally understood as consisting of three major steps: capture, transport and storage. Although each step can be realised with technologies proven in other applications, these technologies need to be adapted for use in the CCS application. For each step there are several technology options, with varying maturity and performance profiles (see Tables 7.1 and 7.2, below).

Component	**Technology options, by component**				
Fuel	Coal	Gas	Biomass	…	
Power plant	PC	GTCC	IGCC	…	
Capture	Post-combustion	Pre-combustion	Oxyfuel	…	
Transport	Pipeline (shared)	Pipeline (proprietary)	Ships	…	
Storage	Offshore depleted oil and gas fields	EOR/ EGR	Offshore aquifers	Onshore aquifers	…

Table 7.1: CCS System Technology Options, including fuel and power plant

Notes on table: PC = pulverised coal, GTCC = gas turbine combined cycle, IGCC = integrated gasification combined cycle, EOR = enhanced oil recovery, EGR = enhanced gas recovery.

---

[39] Haszeldine *et al.* (2008)

Currently CCS development is driven mainly by a need for abatement of emissions from coal and gas fuelled power plants. If CCS technology succeeds, it will be possible also to apply it to power plants using biofuels – as co-generation of biomass and fossil fuels, or using only biomass – thus potentially creating a net CO_2 sink. The overall environmental profile can also be improved by using CCS on combined heat and power plants. Depending on innovation in other fields, CCS on power plants could also contribute clean energy – as electricity and/or hydrogen – for transport applications and other energy services.

CCS component	**CCS technology**	**Demonstration phase**	**Economically feasible under specific conditions**	**Mature market**
Capture	Industrial separation (natural gas processing, ammonia production)			X[1]
	Post-combustion		X	
	Pre-combustion		X	
	Oxyfuel	X		
Transportation	Pipeline			X
	Shipping		X	
Geological storage	Enhanced Oil Recovery			X[2]
	Gas or oil fields		X	
	Saline aquifers		X	
	Enhanced Coal Bed Methane recovery	X		
System integration		X		

Table 7.2: The maturity of CCS technologies
(Source: adapted from IPCC, 2005).

Notes on Table:
1) This technology for producing CO_2 is mature, and typically used together with existing storage demonstration projects, but is not the kind of capture technology that would be useful in terms of abating emissions from power production.
2) CO_2 injection for EOR is a mature market technology, but when this technology is used for CO_2 storage, it is only economically feasible under specific conditions.
3) Maturity here indicates the most mature variety of each technology. For each technology there are also more radical (less mature) varieties.

Depending on the configuration of power plant (or other CO_2 source) and capture technology, CCS is a more or less tightly integrated part of the overall system. Post-combustion capture can be added on to existing power plants.[40] In contrast,

---

[40] In practice, depending on the exact configuration, layout and location of a specific plant, this may not be feasible without incurring prohibitively large costs.

other capture technologies, pre-combustion and oxyfuel, are to a greater extent integral parts of power plant designs. Moreover, all three steps of CCS need to be integrated together with a power plant, to form a functioning system, which also entails technical challenges.

To date, two main industrial sectors are involved in developing CCS technology: electricity utilities and oil and gas companies, each with their supporting groups of fuel, equipment and service suppliers. This corresponds to a potential division of the CCS system, with the utilities operating capture equipment, and oil and gas companies operating storage sites. Other industries with a role in a CCS system include pipeline operators. The main actors today are incumbent companies, but with dedicated niche CCS companies emerging.

The world's first integrated CCS system including power generation – Vattenfall's Schwarze Pumpe – recently began operation in Germany at pilot scale. At a larger scale, the Canadian Weyburn-Midale project demonstrates CO_2 storage using CO_2 from a gasification plant producing synfuel. In Norway, CO_2 has been injected into the offshore Sleipner field since 1996. Apart from these examples, there are other storage demonstration sites, as well as pilot scale capture plants.[41] The UK Government has initiated a competition for funding of a full-scale, integrated CCS demonstration plant.

The main development work is being done in developed economies in North America and Europe, as well as Australia and Japan.[42] Increasingly, there is also work being done in industrialising countries like China and Brazil.

From an emissions mitigation point of view, it is important to consider the geographical profile of fossil fuel reserves and, hence, likely locations for fossil fuel use and deployment of CCS. Since a number of developing countries have significant fossil fuel reserves it will be important to consider the possibility of developing the technology mainly in developed economies, with later diffusion of the technology to developing economies. Work is ongoing to adapt international financial instruments, like the Clean Development Mechanism under the Kyoto framework, to stimulate such technology transfer.

---

[41] An interactive map and database of demonstration projects is available from Scottish Centre for Carbon Storage (2008)

[42] Innovation Norway and Gassnova (2008)

7.2 Accelerated Development of CCS

7.2.1 Scope for Acceleration

CCS is currently at demonstration stage, with some steps (but not all demonstrated) at the scale required for a typical fossil-fired power plant, and the integrated CCS system demonstrated only at pilot scale. Nevertheless, there are high hopes for a rapid development and market introduction of the technology, though estimates of this vary.[43]

This said, there are some significant uncertainties around the future of CCS. This is mirrored by a wide range of assessments of the technology in the CCS community, spanning from cautious to more optimistic. According to more optimistic assessments, the technology will be able to contribute significantly to the decarbonisation of energy systems from around 2020.

In the short term, until 2015-2020, no fundamental technological breakthroughs are expected to be ready for large scale deployment. Instead, the main technical challenges will involve demonstrating existing technologies, planning and building transport infrastructure, and optimising the retrofitting of capture technology onto power plants.[44] Parallel R&D for potential future improvements also needs to continue. Non-technical challenges include the development of regulatory frameworks, and putting in place sufficient financial incentives to facilitate the efficient uptake of the technology.

7.2.2 R&D Priorities

In the longer term, there is scope (and need) for technical development. A central challenge is to improve the efficiency of, and reduce the cost of, capture. Moreover, there is a need to better model and understand the integrity and capacity of storage aquifers. By comparison, transport technology is relatively mature.

It should be noted that the underlying power plant technology is also evolving. Designs that have fewer hours in commercial service, such as integrated gasification combined cycle, may have a higher scope for accelerated learning than mature technologies like pulverised coal boilers and steam turbines.

---

[43] IEA (2008a); Gibbins, J, and Chalmers, H (2008); Hansson, A. (2008)
[44] UKERC (2008c) Energy Research Atlas: Carbon capture and storage.

However, whilst higher efficiencies will decrease emissions, CCS is still needed for substantial emissions reductions, and being a novel technology it has a large scope for acceleration. It is therefore the focus of the analysis here.

The technical R&D priorities for CCS relate mainly to the storage and capture steps, with transport a comparatively mature component. Storage R&D needs include:

- how to assess aquifer storage potentials – in terms of both volume and time
- how to evaluate CO_2 sealing vertically by mud rock or faults
- adapting and trialling monitoring and verification technology from existing hydrocarbon and mineral exploration applications
- investigation of natural CO_2 storage and leakage analogue sites, as well as environmental impacts of CO_2 leakage into shallow ocean bed, as well as onshore leakage.

Capture is widely expected to become the dominating cost component of CCS. Reducing the capital costs, running costs and efficiency of capture are among the central aims of capture-related R&D, alongside up-scaling. Other capture-related R&D aims include:

- Post-combustion: advanced amine solvents or alternatives.
- Pre-combustion: improved membrane or pressure swing separation of both CO_2 from H_2 and improved O_2 separation.
- Oxyfuel: lower cost O_2 separation from air, better membranes for CO_2 separation, chemical looping.
- Understanding and, if necessary, improving the performance of capture during plant ramp-up and ramp-down for flexible operation.

There is scope for acceleration of off-shore transport and storage in terms of large – and therefore potentially more cost-effective – storage options in the form of depleted oil & gas fields as well as saline aquifers[45] in the North Sea. Depleted oil and gas fields present likely first generation options, with saline aquifers needing more mapping whilst also potentially having much larger volumes for CO_2 storage capacity for subsequent CCS build.

In terms of capture technology, the first generation of CCS systems to be built will probably draw on technologies such as post-combustion capture with

---

[45] Geological formations impregnated with salty water.

chemical solvents (for example amines), and oxyfuel combustion and pre-combustion capture with physical solvents (for example Selexol or Rectisol). In the longer term, there is greater scope for more radical capture technologies, with potentially substantially improved performance. Examples of such technologies may include chemical looping for oxyfuel systems and new membrane technologies for post- and pre-combustion capture.

7.2.3 Costs and Risks of Acceleration

Current renewed interest in low carbon supply technologies has led to enhanced levels of innovation activity, and it can be difficult to distinguish between accelerated scenarios and 'business as usual'. Acceleration is an especially problematic concept in the case of CCS, since the technology has only recently emerged. There is no clearly defined consensus about what should count as 'first generation' CCS technology options, and expectations about the performances of different technology options vary. The uncertainties as to the prospects of the technology are still very large and any clear distinction between business as usual and acceleration is difficult to sustain.

It is therefore also difficult to calculate any distinct added cost of acceleration. To give an indication of the costs involved in development, the EU Parliament has suggested allocating up to €10bn funding for 10-12 demonstration plants by 2015 (Reuters, 2008).[46] It has been suggested that the EU ETS allowance price will not be enough to cover development and demonstration costs, until the technology has been developed further and costs have been reduced. Additional support measures will therefore be needed. The International Energy Agency have estimated that accelerated development of CCS would cost an extra $16-17bn globally in terms of RD&D expenditure up to 2030, and also additional commercial investment of $590-720bn up to 2050.[47]

CCS acceleration poses 'lock-in' and 'lock-out' problems. On the one hand, post-combustion capture is the easiest form of CCS to use for retrofitting on existing power plants, and so is likely to be needed for fast deployment of the technology. On the other hand, other capture technologies may well be competitive for new

---

[46] The EU Commission has decided to allocate revenue from the selling of allowances to CCS demonstrations. The exact value is not yet known, but may be of this order.

[47] Based on the cost differential between the accelerated low carbon (BLUE) scenario and the baseline low carbon (ACT) scenario in the IEA's 2008 Energy Technology Perspectives scenarios.

build, and it is premature to pick a single 'winning' capture technology. In this sense, accelerated deployment may risk locking-out promising capture technologies over the longer term.

Furthermore, CCS technology needs to work at a high level of performance to reduce CO_2 emissions to very low levels. For example, the CCS capture rate – the fraction of CO_2 produced that is captured – has high importance for achieving deep decarbonisation, as will be discussed in more detail below. If high capture rates cannot be achieved, there is a risk of CCS investments producing generation capacity that has much lower carbon intensity than today's power plants, but still unable to meet very low emission targets. Such investment therefore presents the risk of continued lock-in to carbon emissions from fossil-based generation.

7.2.4 UK R&D in the International Context[48]

World-class research on CCS has been undertaken since the 1990s by the British Geological Survey (BGS), focussing on transport and geological storage. BGS (and other CCS researchers in the UK) is also very strongly involved in EU and worldwide networks.

UK universities have significantly improved the coordination of their CCS activity since 2004, enabled by the UK Carbon Capture and Storage Consortium linking up research across 14 universities and importance of high (Natural Environmental Research Council) institutes.

A large amount of research is undertaken within science and engineering that is relevant for carbon capture or storage but which has not yet been mobilised for this purpose. This is especially true within earth and environmental sciences, as well as general and chemical engineering.

The UK has a long history of making boiler and turbine systems components for power stations with some UK companies and subsidiaries of transnational companies. There is therefore a wide and deep experience base regarding power plant efficiency and clean coal technologies, but presently limited domestic capability to build all parts of a plant.

---

[48] The UKERC Research Atlas (2008) includes a Research Landscape which documents CCS-related research activity in the UK, and also a roadmap of possible future activity.

Membranes and air separation could be developed from a very strong university base of materials and chemical engineering. However, there is, in general, a weak link to the dominant manufacturers, mainly to be found in the USA, France and Germany.

The UK is very strong on subsurface evaluation and geotechnical engineering because of the North Sea oil and gas developments. Likewise, UK expertise in the whole supply chain of design, fabrication and installation of offshore equipment is very strong. There are large companies and SMEs to fill many niches. Financing, design and management of power and offshore projects are also areas where the UK is perceived to be strong.

The UK government is currently in the process of selecting an investment project for the receipt of additional funding to demonstrate CCS technology. This will, together with demonstration projects abroad, generate useful new knowledge about comparatively mature CCS technologies through learning-by-doing as well as R&D.

7.2.5 Role of Policy

Government policy has a key role in funding research, development and demonstration projects. As the technology enters the demonstration era, there is a need for accompanying R&D to learn from demonstration projects (Gibbins and Chalmers 2008) – in other words, the establishment of mutual feedbacks between learning-by-research and learning-by-doing. In the longer term, there are potentially more radical technologies with step-changes in performance. Research is needed to support their development, alongside more short-term concerns and potentially significant improvements in technologies already close to commercial deployment.

In parallel with these R&D policies, enabling CCS also means dealing with non-technical issues. There is a need to engage with public understanding and acceptance, starting from a situation today where most people know nothing or very little about CCS. Another crucial policy challenge is to put financial drivers in place, the required size of which are currently uncertain. There are also challenges with regard to developing regulation. Currently, progress is being made to address the need for enabling regulation, for example regulating ownership of storage sites which is necessary for commercial CCS deployment.

To prepare for wider commercial deployment, there are also policy challenges in terms of, for example, expanded provision of skills and expertise, planning for the construction of pipeline infrastructures, and governing the supply of storage reservoirs.

These policy challenges span international, national and local levels. Research is highly international, with a role also for national research priorities to support capacity building and to explore local conditions, for example the geological prospects for storage. International efforts – such as the EU's Zero Emissions Platform – may be central also for supporting demonstration. Furthermore, in terms of climate mitigation, ensuring the technology is deployed in China and other large industrialising countries is critical. In contrast, for deployment-related policies, there is more scope for effective national level policy-making, although international agreements are likely to be an important driver of action at the national level.

7.3 Modelling CCS Acceleration

This section describes how the potential for CCS acceleration was modelled, and presents the results from the modelling, comparing them with a baseline low-carbon scenario without technology acceleration.

7.3.1 Input Assumptions

Expectations clearly vary as to when CCS technology may become available for commercial deployment. It is however common to discuss a roll-out of the technology in the 2020s (Gibbins and Chalmers 2008; McKinsey & Company 2008), although it is important to note that these are predicated on significant efforts to demonstrate and further develop the technology in the period before that. The IEA (2008a) also assumes that CCS will become available for power plants in 2020, and it plays a role in all of their scenarios. Therefore, for this study, it was assumed that CCS will become available in 2020.

A literature review identified data for storage that indicated that less expensive storage may be available than that deployed in Markal – especially for off-shore depleted oil and gas fields, and saline aquifers. Accordingly, reduced cost data for these storage options were adopted for this project.[49]

There is also scope for acceleration of the development of capture technology. It has, however, proven very difficult to quantify this acceleration potential, since there is as yet no clear consensus on what counts as 'business as usual' for CCS, in terms of technology choice or performance. Cost estimates in the literature are characterised by unclear assumptions, a range of non-compatible metrics, and frequently no indication of the degree of uncertainty in the cost data (Richards 2004; Allinson *et al*. 2006). Indeed, McKinsey & Company (2008) argue against trying to predict the cost of CCS, given the very high uncertainties involved. It is worth noting that the McKinsey study applies learning rates to assess possible cost developments, but only after demonstration and a first generation of commercial plant has been built, reflecting the need for 'cost discovery', i.e. more robust cost data from demonstration and early implementation, and potential price increases during early development.

The data assumptions for capture technology (coal CCS) costs and performance in the UKERC 2050 core modelling are relatively optimistic, and were therefore left unchanged – the same input cost and year of availability assumptions were used for the accelerated scenario and the baseline low-carbon scenario. This data emerged from the UK Government's Carbon Abatement Technology strategy consultation process (DTI, 2005). CCS had a central role here, and the Government drew on industry expertise to generate CCS cost and performance data.[50]

7.3.2 Single Technology Scenario

This section will present modelling results where only CCS technology is accelerated and will compare it to the low carbon core scenario, a non accelerated baseline scenario.

---

[49] Costs of transport to and storage in offshore aquifers and depleted oil and gas fields were lowered to £3.1/tCO_2.

[50] Capital costs for the three main power plant types in 2020 are assumed to be: pulverised fuel costs £698/kW without capture and £833/kW with, IGCC costs £862/kW without capture and £1100/kW with, and GTCC costs £380/kW without capture and £598/kW with. Thereafter, the relative costs of coal CCS improve compared to gas-fired CCS, such that the latter is not selected.

CCS on coal is the dominant energy supply technology in the low carbon core scenario.[51] In the low carbon scenario, CCS on coal is built at a high rate – approaching 4GW per year – between 2015[52] and 2030, but not at all thereafter (see Figure 7.1, below).

Coal CCS ramps up to a high level of capacity (almost 40GW) and generates around 2/3 of all electricity by 2030 (over 1000PJ (278TWh)). Thereafter, other technologies emerge that compete successfully with coal CCS and since no more CCS is built the coal CCS capacity plateaus. The deployment of coal CCS replaces unabated conventional coal and gas fired generation.

Acceleration of CCS through lower storage costs adds slightly more coal CCS capacity and generation.

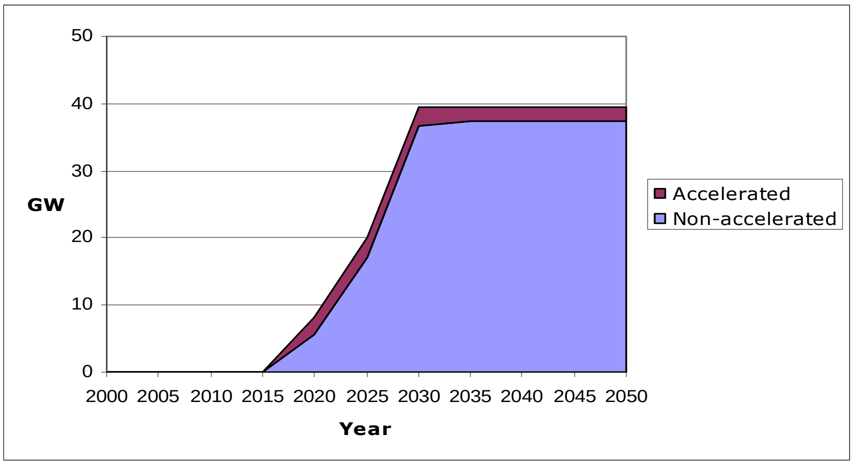


Figure 7.1: CCS Installed Capacity, before and after acceleration, single technology acceleration

7.3.3 Aggregated Scenario

In the previous section only CCS was accelerated; in this section, scenarios with all the technologies studied in this report accelerated are discussed.[53] Furthermore, scenarios with 60% and 80% decarbonisation targets will be compared.

In the scenario with acceleration of all the technologies at the level of 60% emission reduction, CCS deployment is heavily reduced; just over half as much

---

[51] As compared to the reference scenario without any CO_2 reduction ambition, CCS replaces electricity generation using mainly unabated coal plants.

[52] The technology is assumed to become available in 2020. However, "2020" represents a 5 year period in the modelling.

[53] Fuel cells technology is treated as a special case, and scenarios including accelerated fuel cell development are mentioned separately when suitable.

CCS is built and deployed as compared to the Low Carbon core scenario without accelerated technology development. This reduction is readily understood as other technologies having become more competitive.

There is generally less CCS deployed in scenarios with an 80% emissions reduction level, than with 60%. In the 80% scenario, CCS generation also tapers off towards the end of the period to 2050 by around a quarter (see Figure 7.2, below).

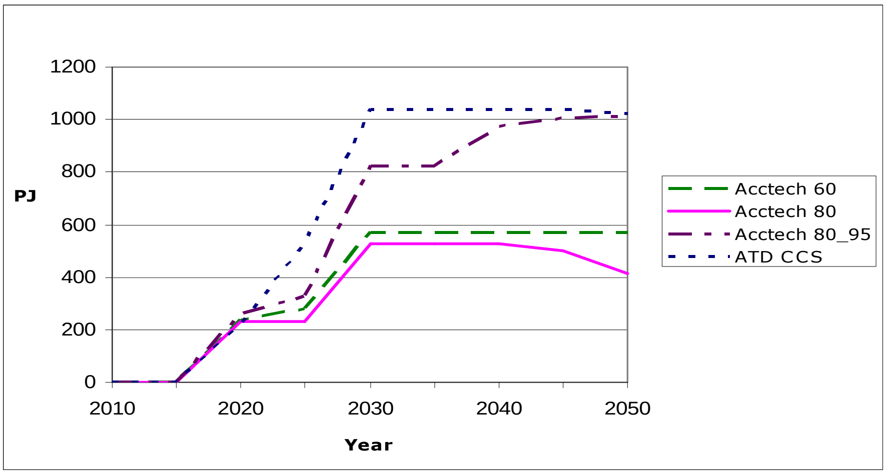


Figure 7.2: CCS Electricity Generation in Different Scenarios (PJ)

Note: 60 and 80 in the legend refers to UK energy decarbonisation constraints by 2050. 95 refers to an enhanced CO_2 capture rate. 'Acctech' refers to scenarios where all technologies have been accelerated, and 'ATD' to single technology acceleration i.e. CCS accelerated alone.

This decline in the long term of the 80% scenarios is due to the residual emissions from the power plants. In this work, the capture rate – the fraction of CO_2 produced that is captured – is generally assumed to be 90%, and is assumed to be constant throughout the period. In a further scenario variant with a constant 95% capture rate, CCS does not taper off, and overall deployment levels increase substantially toward 2050 (Figure 7.2). Residual emissions constrain CCS deployment towards the end of the period modelled, as the 80% target deadline approaches, but also well before that, given the long lifetime of the plants. This illustrates that the capture rate is crucial for the levels of CCS deployment portrayed here, and for its role in the generation mix, especially with higher and more urgent decarbonisation ambitions.

Under an 80% overall decarbonisation ambition, adding in fuel cells acceleration to the LC Acctech scenario substantially increases the amount of CCS deployed.

There is a strong synergy here between CCS and fuel cells, going beyond the role for CCS to decarbonise the transport sector by providing low carbon electricity for electric vehicles.

7.4 Discussion and Summary

The accelerated development scenarios suggest that coal-fired CCS could provide a substantial share of low carbon power supplied in the UK in the 2020s and beyond. In LC Acctech 80, with all technologies analysed here accelerated in parallel, coal-fired CCS provides around a third of all electricity supplied in 2030. Although this proportional contribution declines in some scenarios after 2040, as renewables deployment expands (Figure 7.3, below), it rises to almost half of all power supplied if a higher CO_2 capture rate is assumed.[54] Given that fossil fuels currently contribute more than 2/3rds of current UK electricity generation, these results do not seem unreasonable, in terms of overall electricity generated in 2050.

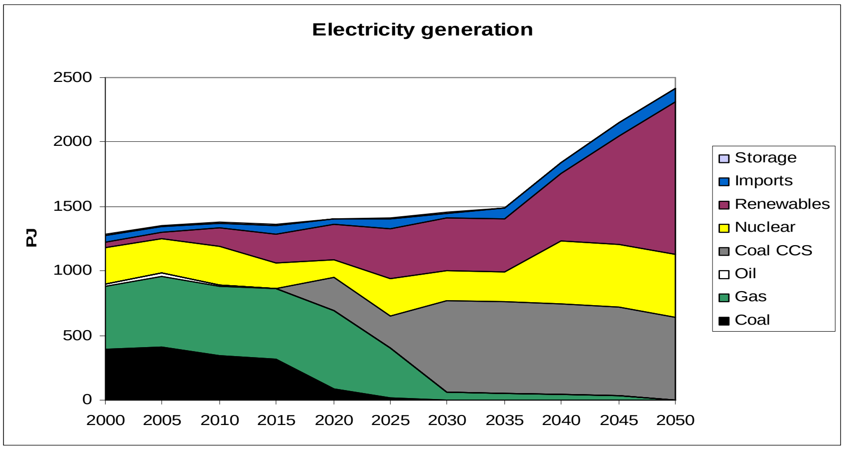


Figure 7.3: Electricity generation in LC Acctech 80 (PJ)

A major challenge in the scenarios presented here lies in the suggested deployment rate of CCS – just under 30GW in between 2015 and 2030. This very significant scale of build can, however, be compared with previous episodes of investment in generation plant, such as the 'dash for gas', which saw an increase in generation capacity from combined cycle gas plant of around 20GW in 10 years (BERR, 2008c), as illustrated in figure 7.4 (below).[55] This indicates that the speed of CCS introduction in the scenarios is optimistic, but of the same order as

---

[54] This compares with the 30% of all electricity generation in 2050 as modelled in the IEA's Energy Technology Perspectives study in their accelerated 'Blue' low carbon scenario (IEA, 2008a). While the IEA report models global deployment of CCS (rather than just for the UK) their results also suggest a significant uptake of CCS from the 2020s onwards.

[55] There are, of course, significant differences between the two technologies, making comparisons like these more complicated than the relative sizes of total capacity indicate.

previous investment cycles. However, it should be stressed that in the case of CCS, there is also the challenge of planning for such rapid introduction, including the building of an infrastructure for CO_2 transport and storage, making such fast build more challenging.

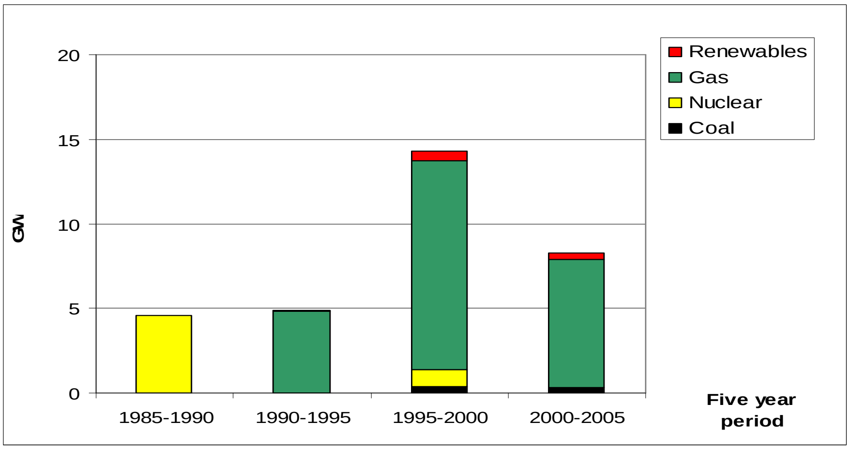


Figure 7.4: Investment in new generating capacity in the UK, 1985-2005
Source: Carbon Trust (2008b)

The modelling results suggest a switch in fossil fuel use away from unabated coal and natural gas, to coal with CCS. The overall use of coal-based power increases, requiring, not just a build up of coal and CCS supply chains, but also reduced gas build capabilities in the UK. Along with new build of power plant with CCS, retro-fitting of CCS onto existing fossil plant is likely to have a central role to play for such rapid introduction, since it significantly reduces the construction effort and capital expenditure required.[56] This rapid introduction of CCS involves many policy challenges, including funding and incentives for demonstration (especially at commercial scale) as well as deployment of the technology, developing a regulatory framework, and addressing the question of how to design and govern the pipeline network.

These results illustrate the critical role that CCS may come to play in the decarbonisation of the UK energy system. There may be scope for a rapid introduction of CCS-abated fossil capacity at very substantial levels. In the short to medium term, this raises challenges in terms of science and technology, but also in terms of economy and regulation. In the longer term, there is scope for more radical capture technology options, and a need for a better understanding of geological storage, particularly in saline aquifers.

---

[56] Given difficulties in representing retrofitting in modelling, the modelling scenarios here include only new build.

It is worth remembering, however, that CCS deployment may happen very differently than as modelled here. These scenarios propose CCS on coal, but with different assumptions about relative fuel prices, CCS on gas plant could be deployed instead of (or in addition to) coal-fired CCS. Also, the model does not select advanced combustion technologies such as IGCC, but such technologies may well be deployed alongside other coal-fuelled plant, depending on a number of factors including technology development and costs. More generally, the UK energy system may see a mix of technologies for fossil-fuelled generation with and without CCS, particularly as the capital and running costs of plant are site-specific. This work has also not studied in any detail the impact of CCS on hydrogen production (as an energy vector for use in transport), the effect of increased use of heat from power plants in CHP schemes, or co-generation with biomass in CCS-abated power plants.

Finally, it is worth remembering that CCS has not yet been demonstrated as an integrated system including a power plant, at full scale, and therefore the technology still carries significant technical as well as economic risk. Figure 7.5 illustrates the expanded need for other supply technologies, especially renewables and nuclear power if CCS is not successfully developed. In an uncertain future, having fewer technology options available means the risks and costs of decarbonising energy supply are likely to be higher.

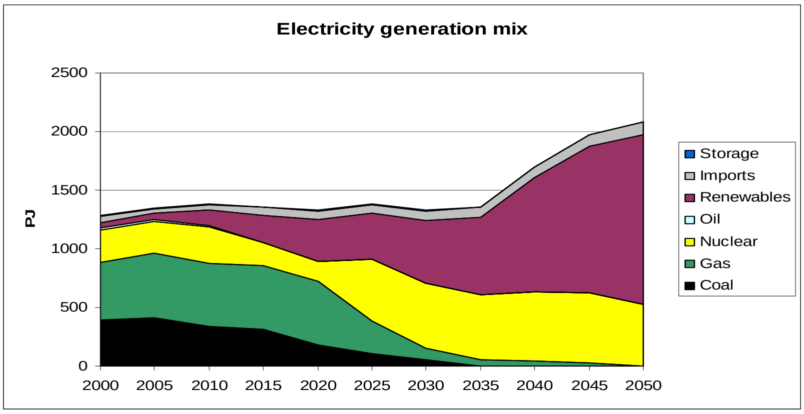


Figure 7.5: ATD scenario variant at 80% decarbonisation, all technologies accelerated, no CCS

Chapter 8: Hydrogen and Fuel Cells

8.1 Overview

Fuel cells (FC) are electrochemical devices that generate electricity and heat using hydrogen and hydrogen-rich fuels, together with oxygen from air. They consist of an electrolyte sandwiched between two electrodes an anode and a cathode (making up a FC stack). Activated by a catalyst on the anode side, H_2 atoms split into electrons and ions. Electrons migrate to the cathode through an external circuit and generate electricity, while ions travel through the electrolyte and reunite with electrons and O_2 on the cathode side, producing heat and water. There are variants of this process, depending on FC types and fuels. H_2-powered fuel cells maximise the benefits of using hydrogen as an energy carrier (efficiency, emission reduction). There are several types of fuel cells, usually categorised according to their operating temperature and electrolyte (Figure 8.1, below).

Type	**AFC**	**PEMFC**	**PAFC**	**MCFC**	**SOFC**
Electrolyte	Concentrated KOH	Nafion	Conc. H_3PO_4	$LiCO_3$/ K_2CO_3	ceramic, solid oxide
Operating Temperature	50-200°C	50-90°C	200°C	650°C	650-1000 °C
Charge carrier	OH^-	H_3O^+	H_3O^+	CO_3^{2-}	O^{2-}
Electrolyte state	Mobile or immobilised liquid	Solid	Im/sed liquid	Im/sed liquid	Solid
Electrode	Doped carbon electrode, Pt, Ag	Doped electrodes Pt	Doped electrodes Pt	Nickel electrodes	Nickel and solid oxide ceramic electrodes
Catalyst	Platinum	Platinum	Platinum	Nickel	Perovskites
Fuel and oxidant	Pure H_2 Air or pure O_2	Pure H_2 Air or pure O_2	H_2, CH_4, CH_3OH	H_2, CH_4, Air	H_2, CH_4, CH_3OH Air

Figure 8.1: Main types of Fuel Cells

The enormous global effort over the past fifteen years to develop fuel cells was initially driven by the prospect of improved electrical efficiency and better air quality in urban environments. Today, fuel cells are considered to be an important option for improving the sustainability of energy use, reducing greenhouse gas emissions and reducing other the emissions related to transport energy use.

Fuel cells can be used for large and small-scale electricity generation, combined heat and power (CHP), transport of all types, and as a battery replacement for portable power applications such as laptop computers and mobile phones. Lower-temperature fuel cells are better suited to mobile and portable applications, while higher-temperature ones can be used for power generation and CHP.

Fuel cell vehicles mostly use polymer electrolyte membrane fuel cells (PEMFC), which also represent some 70-80% of the small scale stationary FC market. Molten carbonate fuel cells (MCFC) and solid oxide fuel cells (SOFC) are expected to dominate the FC large-scale stationary use in the near future (IEA, 2005). SOFCs currently represent 15-20% of this market segment. Global FC production amounts to several thousand units per year, 80% for stationary and portable applications, and the rest for fuel cell vehicles demonstration projects (IEA, 2005).

Fuel cell technology cannot yet be regarded as mature. Fuel cells are currently commercially competitive only in narrow 'premium power' niches where reliability and quality of electricity are of primary concern, or where no other technology is appropriate. Among the more mainstream markets, fuel cells are beginning to make minor inroads into the distributed and CHP sector.

At present, hydrogen and fuel cells are a rather costly option to mitigate CO_2 emissions and improve energy security. There is thus considerable scope for accelerated development of hydrogen and fuel cell technologies with a main aim of reducing fuel cell stack and system costs. Such development will need to address improvements in the existing FC designs that will lead to optimised efficiency and better performance. Government policies and technology learning driven by private investment will hold important synergies and should act in concert in order to promote accelerated market deployment of FC system.

8.2 Accelerated Development of Hydrogen and Fuel Cells

8.2.1 R&D needs and priorities

In order to make fuel cell and hydrogen technologies commercially viable, intense public and private research, development and demonstration efforts (RD&D) and corresponding technology breakthroughs are required. For all types of fuel cells, research is needed to develop and evaluate materials, systems and related components that will offer the prospect of low-cost mass production while meeting demanding targets for commercial competitiveness.

Fuel choice and cost is another technical barrier that will need to be addressed. Hydrogen fuel cells will need a reliable, inexpensive source of hydrogen while hydrogen storage solutions will need to provide enough capability and capacity to enable the same driving range as a conventional gasoline vehicle. A multinational approach covering a wide range of feedstocks, regional constraints and infrastructure related preferences and conditions will have to be considered. Hence, focused R&D will be essential to overcome current obstacles and increase the speed of technological development in the period until hydrogen becomes economically competitive.

Important R&D areas considered for mobile and stationary hydrogen and fuel cell applications and the required infrastructure have been identified and described in the HyWays Roadmap, produced for a major European research project (HyWays, 2008). The following are considered to be the most critical:

1. *Obtain significant cost reduction of the H_2 drivetrain*
    - *a)* Component technology development and improvement of PEM and other types of fuel cells (membrane, catalyst, materials, bi-polar plate,)
    - b) Periphery components (air supply, humidification, valves, power and control electronics)
    - c) Onboard storage (optimisation of currently demonstrated compressed and liquid storage systems, new technologies such as cryo-compressed or chemical metal hydrides or carbon nanotubes)
    - d) Hydrogen ICE integration (including fuel cell APU and hybridisation)
    - e) System optimization (trade-off between the single subsystems to get highest performance at lowest cost)

2. *Obtain significant cost reduction of hydrogen production chains*
    - a) Electrolysers, biomass gasification systems, CCS as well as standard components and instruments such as compressors, valves, sensors

3. *System integration for hydrogen systems*
    - a) Integration of main components (drivetrain, onboard storage) and auxiliary equipment (safety equipment, valves, electronics) for hydrogen transport applications
    - b) Integration of main components (FC and onsite storage) and auxiliary equipment (safety equipment, valves, electronics) for stationary hydrogen applications
    - c) Integration of renewables and hydrogen in 'island / remote' systems, specifically integration aspects (power conversion and power conditioning) and storage (hydrides, porous adsorbents, compression)
    - d) Use of current low pressure grid for transport of pure hydrogen
4. *Assure safe and reliable hydrogen applications*
    - a) Close current gaps in development of harmonized regulations, codes and standards for hydrogen

b) Build consumer confidence in hydrogen end use

5. Comply with long-term sustainability requirements

a) Hydrogen produced from renewable energy sources, fossil fuel with CCS or nuclear pathways, i.e. without CO_2 emissions and with a closed fuel cycle

8.2.2 Interim milestones and potential for step-changes

The successful deployment of fuel cells and hydrogen technologies over a ten-year timeframe involves extensive public-private research and ambitious development and deployment programmes. The HyWays Roadmap and key documents published by the European Hydrogen & Fuel Cell Technology Platform (HFP), such as the HFP Deployment Strategy (HFP, 2005) and Implementation Plan (HFP, 2007), highlight two important milestones on the way to the successful commercialization of hydrogen and fuel cell applications in transport:

Snapshot 2020 characterises the transition to mass market commercialization. It translates to the 'take-off' point where production volumes are increasing substantially and breaking the level of 100,000 units per year per manufacturer due to almost competitive production cost of fuel cell systems.

Snapshot 2030 translates to the growth phase. Hydrogen and FC technologies are fully competitive and hence lead to a booming market where the growth rates reach their maximum.

Beyond 2030 it is impossible to speculate developments in any detail. According to the HyWays Roadmap, by 2050 80% of the light duty vehicles and city busses could be fuelled with CO_2 free hydrogen while in stationary end-use applications, hydrogen could be used in remote locations and island grids.

8.2.3 UK R&D in the International Context[57]

UK industry

The knowledge and expertise of the UK industry spans the full length of the commercial value chain, from R&D to systems integration and from finance to servicing. Over 100 UK companies, including Johnson Matthey Fuel Cells, Rolls Royce Fuel Cell Systems, Ceres Power Ltd, Intelligent Energy Ltd, are contributing to the creation of the global fuel cell industry.

---

[57] UKERC's Research Atlas includes a document detailing the current UK Research Landscape for fuel cells, and summaries of roadmaps of the possible future development of the international fuels cells research community

The UK has particular strengths in key areas of fuel cell research,

- materials and catalyst technology for fuel cells and reformers
- the design of fuel cell stacks
- the ‘balance of plant’ (BoP) for stationary applications

The UK also has strong capabilities in system design, systems integration and production engineering. There are world-class power plant vendors with significant activity and manufacturing in the UK. Important opportunities are therefore likely to exist for UK industry in the design, manufacture, installation and maintenance of fuel cell systems, particularly for stationary power and CHP applications.

Many of these capabilities have been developed in partnership with companies and organisations from across the world. The UK’s engineering capability has a long history of successful innovation creating tangible commercial advantage. The fuel cell industry requires such innovation along its supply chain, and the UK is in a strong position to deliver. Equally important is the fact that many of the global energy companies (e.g. Shell, BP) have significant R&D capabilities in the UK.

UK research community

The UK is home to a number of the world’s top universities and over 35 academic and contract research groups are highly active in hydrogen and fuel cell research with world-class expertise in key areas such as materials and catalysts development. The UK academic base exhibits a high degree of collaboration and there are strong links with Germany, USA, Canada, Japan and China. Academic institutions work closely with industry and several new companies are university spin-outs. A typical example of such spin-outs is Ceres Power which was founded to commercially exploit revolutionary fuel cell technology developed within Imperial College, London, during the preceding 10 years.

EPSRC-funded Supergen is a multidisciplinary initiative that aims to help the UK meet its environmental emissions targets through a radical improvement in the sustainability of power generation and supply. The Supergen Fuel Cells consortium is part of the wider EPSRC Supergen initiative. Areas of investigation include polymer electrolyte fuel cells, fuels, solid oxide fuel cell anodes cathodes and electrolytes, novel routes to powders and components, characterisation techniques, fuel cell modelling, high temperature polymer electrolyte fuel cells, high temperature solid oxide fuel cells and metal supported intermediate temperature solid oxide fuel cells.

There are also a number of initiatives to support networking across the UK fuel cells demonstration and deployment community. The Low Carbon and Fuel Cell Technology (LCFC) Knowledge Transfer Network (KTN), supported by the UK Technology Strategy Board, provides a platform for communication and cooperation between members of the UK fuel cell community and other groups vital for bringing products to market.

8.2.4 Role of Policy

Policy interventions are required to overcome initial barriers and enable the introduction of hydrogen into the energy system and the demonstration and deployment of fuel cell technologies. Significant cost reductions will have to be achieved, initially through R&D-driven improvements, and later through economies of scale and learning-by-doing (IEA, 2005). Substantial and effective policy support is a key factor in achieving these cost reductions. The Hyways European research project outlined the desirable elements of an effective policy framework (HyWays, 2007):

- *A technology specific framework*: including support for both R&D and deployment, tax exemption on hydrogen fuel, and subsidies and tax exemptions for fuel cell vehicles.
- *Planning and financing of infrastructure*: to enable infrastructure build-up in the early phase consistent with long-term higher demand.
- *Level playing field*: In order to better compete with areas outside Europe (e.g. US, Japan), barriers within Europe will have to be removed by harmonisation of regulations, codes and standards, and comparable incentives for deployment and R&D.
- *Monitoring framework*: assuring appropriate support levels and a good balance between R&D and deployment, in order to minimise total cumulative costs to reach commercialisation.
- *Identify synergies with other options*, such as second generation biomass-to-liquids (BTL from biomass gasification) and hybrid vehicles.
- *Education and training*: to facilitate large employment shifts and public understanding.

This series of measures can be seen as support mechanisms for promoting technology acceleration and delivering the ambitions of the fuel cell sector as outlined in UK and European roadmaps.

8.3 Modelling Hydrogen and Fuel Cell Technology Acceleration

8.3.1 Input Assumptions

An extensive literature review was carried out on the state of each FC technology so as to collect reliable input data for the accelerated development modelling. Fuel cell pathways lead into several end-use sectors in the Markal model (industry, electricity, residential, service, transport). For electricity generation, three fuel cell pathways were selected for revision under the acceleration scenarios: gas driven SOFC-CHP, gas driven MCFC-CHP and hydrogen PEMFC - CHP plant.

In the transport sector, fuel cell hydrogen bus and car were selected for accelerated scenarios, so as to illustrate the potential impact of fuel cell vehicles. Input data were collected for a number of key parameters to characterise the transport vehicle technologies: availability, vehicle lifetime, technical efficiency, annual fixed O&M cost and capital cost of vehicle. The revised input data are shown in Tables 8.1 and 8.2.

Technology Description	Start year	Life (years)	Efficiency (MJ/km)	Fixed O&M cost ($/km)	Capital cost of vehicle ($/vehicle)
Bus Hydrogen FC	2005	15	10.6	0.333(a)	500,000(b)

Table 8.1: Input data for hydrogen fuel cell bus (IEA, 2005)

Notes:

(a) O&M costs are 4% of the investment cost ($500,000); assuming 60,000 km per year (based on 2004 $).
(b) The cost for hydrogen fuel cell bus is based on a production of some 100 buses a year (based on 2004 $).

For the capital cost of hydrogen FC buses, data from Lane (2002) were extrapolated up to 2050 using a similar rate to the reduction from 2010 to 2015 (a 3% annual capital cost reduction rate). Also the data for the hydrogen FC car, Table 8.2 below, were interpolated between the 2010 and 2030 data points.

Start year	**2010**	**2030**[(a)]
Life (years)	12	12
Efficiency (MJ/km)	-[(b)]	-
Fixed O&M cost ($/km)	0.168[(c)]	0.069
Capital cost of vehicle ($/vehicle)	60,750[(d)]	25,150

Table 8.2: Input data for hydrogen fuel cell car (IEA, 2005)

Notes:

(a) Based on the 'Optimistic, but slower' data from IEA, 2005.

(b) No data for efficiency were available.

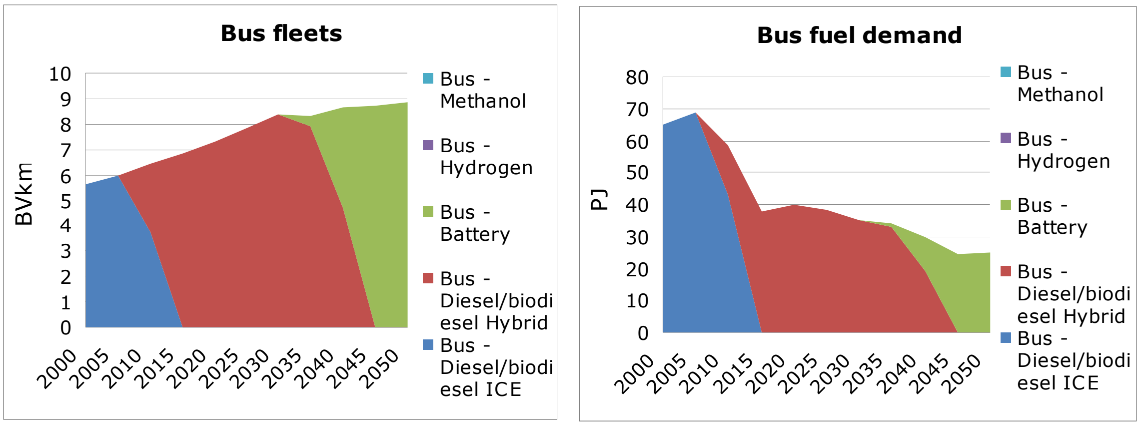
(c) O&M costs are 4% of the investment cost; assuming 14,481 km per year (based on $2005).

(d) The cost of a fuel cell vehicle is the sum of costs for the PEM fuel cell stack (including power electronics and other peripherals), the hydrogen storage system, the electric battery (if hybrid system is used) and the reformer (if fuels other than hydrogen are used). It is estimated that the cost of a fuel cell vehicle might fall to between $22,000 and $27,000 in 2030. Three cost scenarios are considered for year 2030. The main assumptions are that PEM fuel cell stack costs would drop over time to between $35/Kw and $75/kW and that the optimistic case of $35/kW for the PEM FC stack could occur between 2025 and 2040. The optimistic scenario of $35/kW renders the price of FC vehicles competitive with conventional ICE vehicles, whose costs averages a mere $30/kW, (based on 2005 $).

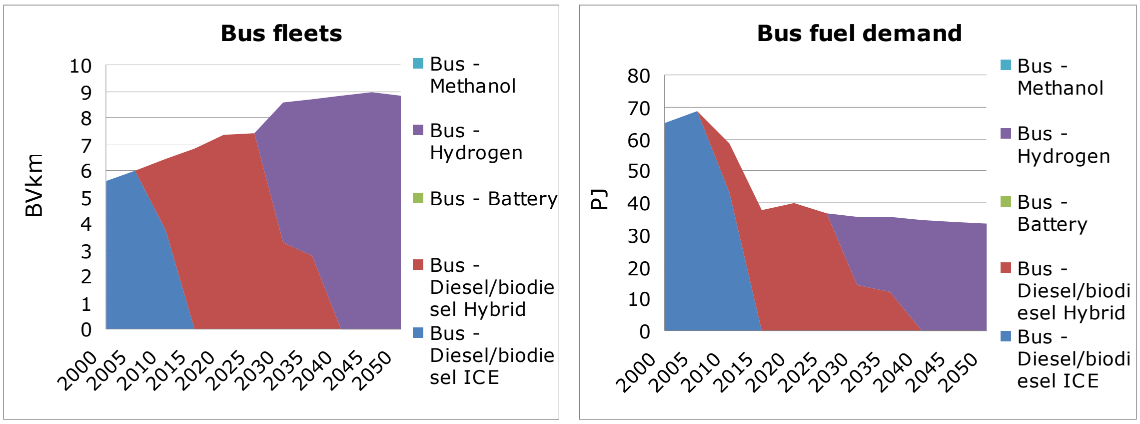
8.3.2 Results: Single Technology Scenario

In the reference (LC-Core) scenario hydrogen and fuel cell technologies are never deployed. In the single-technology ATD hydrogen-fuel cell scenario (ATD HFC), fuel cells are deployed for electricity generation and reach a peak of 6GW installed capacity in 2035. This is composed of 4GW of installed gas driven MCFC-CHP and 2GW of Hydrogen PEMFC- CHP. There is also a small amount (0.25GW) of gas driven SOFC-CHP installed in 2020.

The accelerated scenarios for fuel cell buses and cars are shown in Figures 8.2 and 8.3, below. In the ATD-Fuel Cells scenario, hydrogen vehicles now dominate in the later period after 2030.



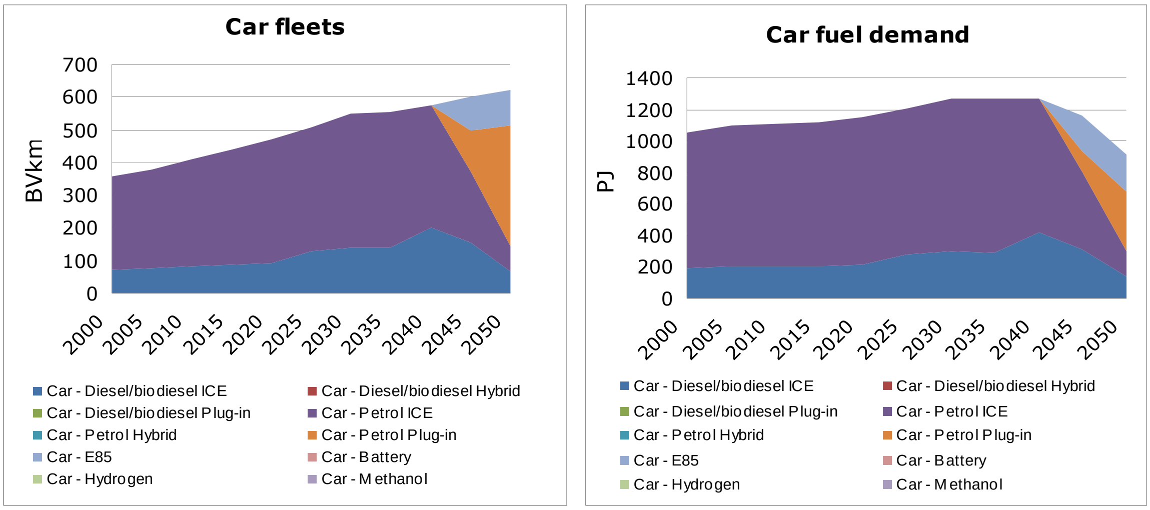
LC-Core (non-accelerated)



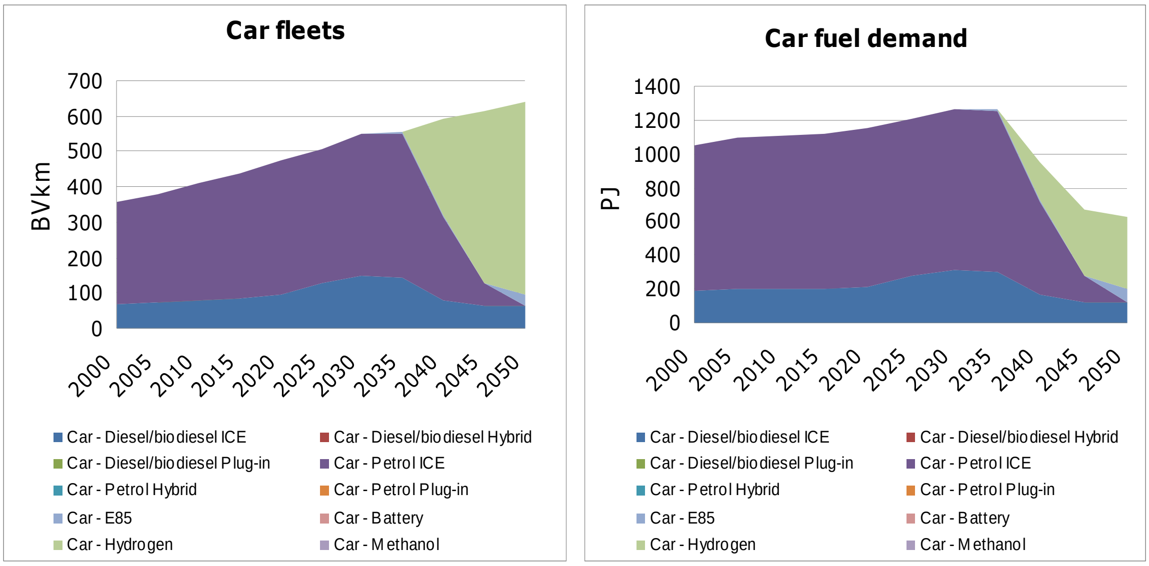
ATD-HFC (accelerated)

Figure 8.2: Fuel cell buses (in BVkm) and hydrogen fuel demand: the impact of fuel cells accelerated technology development

Similar results are obtained for hydrogen fuel cells cars. Figure 8.3 displays the deployment of hydrogen fuel cell cars from 2040 and hydrogen fuel demand after 2040, reaching 486PJ (12 mtoe) by year 2050.



LC-Core (non-accelerated)



ATD-HFC (accelerated)

Figure 8.3: Fuel cell cars (in BVkm) and hydrogen fuel demand: the impact of fuel cells accelerated technology development

8.3.3 Results: Aggregated Scenarios

In the LC-Acctech scenario, all technologies are accelerated in parallel (including fuel cells) and compete for market share. Both 60% and 80% aggregated scenarios, (LC-Acctech 60 and 80) repeat the same pattern as described above for the single technology case: accelerated development of fuel cells technology makes little impact on the power generation sector, but transforms the transport sector after 2030.

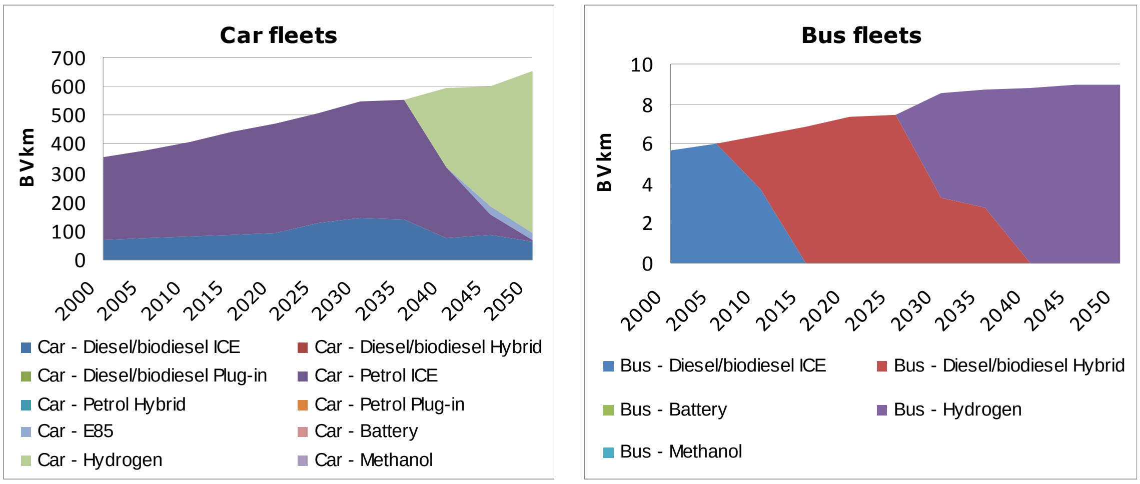
60% scenarios

In the 60% LC-Acctech scenario, fuel cells have a minor contribution to the electricity generation mix, with around 2.5GW of gas-driven SOFC-CHP and

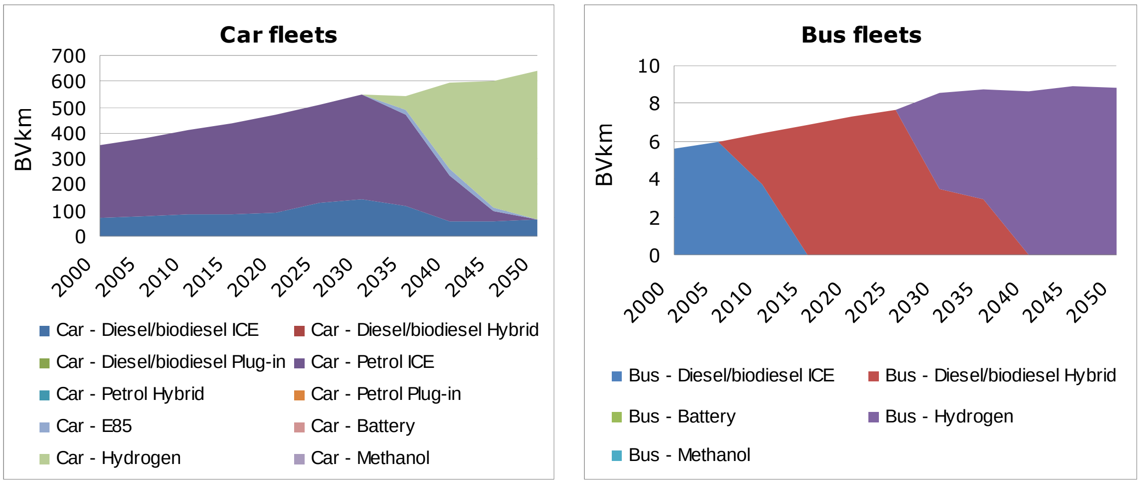
1.5GW of Hydrogen PEMFC – CHP installed after 2020. However, as in the single technology case, transport technologies are substantially converted to Hydrogen-Fuel Cells technologies after 2030 (Figure 8.4).

80% scenarios

In LC-Acctech 80, fuel cells again have a minor contribution to the electricity generation mix (with around 2GW of Hydrogen PEMFC - CHP plant installed after 2020), but transport technologies are substantially converted to Hydrogen-Fuel Cells technologies after 2030 (Figure 8.4).



Acctech 60



Acctech 80

Figure 8.4: Impact of Hydrogen / Fuel Cell Vehicles under ATD assumption, aggregated scenarios

There is a significant difference in the hydrogen production technology between 60% and 80% scenarios: in the 60% cases, hydrogen is mostly produced from steam reforming of natural gas, with minor contributions from electrolysis and membrane coal gasification with CO_2 capture. Some additional carbon emissions are therefore associated with hydrogen production in 60% scenarios. In 80% scenarios, hydrogen production is wholly from electrolysis, using low or zero-carbon generation technologies.

8.4 Discussion and Summary

The deployment of hydrogen and fuel cells in the acceleration scenario is generally in line with goals and milestones published in international FC roadmaps. For example, *Snapshots* 2020 and 2030 predict a growth phase between 2020 and 2030 with hydrogen and fuel cell technologies becoming commercially viable by 2030. Under accelerated development assumptions, hydrogen vehicles dominate UK transport services in the later period, corresponding with the HyWays roadmap target. Fuel cell buses emerge after 2030 while fuel cell cars achieve market penetration at a slightly later stage. The earlier deployment of FC buses may be attributed to the fact that buses (like HGVs and LGVs) [58] are 'niche' markets where FC engines can be competitive with gasoline and diesel combustion engines at a higher cost than for cars. The later emergence of cars suggests that further reductions in the FC stack and powertrain costs are required, along with innovative solutions for hydrogen storage.

There is no single 'winning' hydrogen production and fuel cell conversion technology, based on current prospects, which offers the clearest and best potential of curbing emissions and improving the security of energy supply. Instead, a balanced RD&D approach is needed to develop a broad technology portfolio.

This modelling exercise confirms that hydrogen and fuel cells can play a significant role in the future energy market if the current targets for reducing technology costs can be met in a timely manner, and if governments enact new, concerted policies to mitigate emissions and limit oil dependency. From a system-level perspective, this offers an important way of affordably decarbonising the transport system. Policies solely aimed at enhancing energy-security would not

---

[58] Fuel cell-powered goods vehicles (LGVs and HGVs) have not been included in the ATD scenarios, because of lack of available data forecasting their long-term cost and performance. However, as with buses, they can be expected to play a major role under accelerated development assumptions. Even without accelerated development, the HGV (but not LGV) vehicle stock is substantially converted to hydrogen fuel cells by 2050 in the LC Core 80 scenario (see Anandrajah et al., 2008).

necessarily result in a transition to hydrogen. Other technologies and fuels would be more cost effective at increasing energy diversity in a CO_2-unconstrained world.

Development of a complete hydrogen supply infrastructure at this point in time is premature. Hydrogen and fuel cell research and demonstration are still at the development stage. The solutions to current technical issues and bottlenecks, such as better fuel cell performance and hydrogen on-board storage, may have a considerable impact on the choice of the technologies for hydrogen production, distribution and refuelling.

Hydrogen and fuel cell RD&D efforts should focus on hydrogen production (cost-effective, CO_2-free hydrogen and improved decentralised production technologies), fuel cells (cost reduction, durability, new materials and concepts) and on-board hydrogen storage. Emphasis should also be put on hydrogen transportation and distribution. Insufficient progress in reducing the cost and energy consumption of the technologies for hydrogen transportation and distribution – a precondition for centralised production – could have a negative impact on the future of hydrogen as an energy carrier.

There is also a category of *high-risk/high-reward* technology options such as photo electrolysis, biological production, water splitting by nuclear and solar heat, on-board solid storage, and new fuel cell concepts. If successful, some of these technologies may represent major breakthroughs in energy technology, with tremendous impacts on the future applications for hydrogen and fuel cells, and on the wider energy system. At present, most of these options are in a very early stage of development and the data available on their potential performance and costs are too uncertain to conduct a quantitative analysis. However, a balanced RD&D investment strategy based on costs/benefit criteria should take into account these technology options.

Basic research into transformative hydrogen technologies related to production and storage are important to realising hydrogen’s promise. Economic, environmentally friendly hydrogen production could potentially be accomplished through:

- the production of hydrogen from fossil fuels by such methods as gasification, coupled with the geological storage of the resulting carbon dioxide, or the gasification of waste biomass;

- technologies that significantly improve the economics and efficiency of producing hydrogen from water using electricity sources that do not emit CO_2
- the development of novel technologies for hydrogen production, such as direct hydrogen production from water using sunlight, and biological processes that decompose organic materials into hydrogen and other by-products.

The transition to hydrogen and fuel cell-based economy will not take place over the short term, particularly in the transport sector. A strategy will be required to maximize the benefits of 'transition technologies' such as combustion engines, and to explore on-board reforming options to enable fuel cell vehicles to use existing fuel infrastructures. During the transition phase and even afterwards, conventional technologies may still be needed; for example, hydrogen-fuelled internal combustion engines could be used for transport. Fuel cell vehicles will have to compete with very clean, efficient hybrid combustion engine/electric vehicles, although commercialisation of hybrid drive trains will reduce the costs of electrical and electronic components shared with fuel cell vehicles.

While electric cars are a relatively new automotive technology, they are fast becoming popular worldwide. Electric cars use a mixture of technologies such as internal combustion engines, gasoline, electric motors, and batteries to run. There are many advantages for all electric vehicles: they are emission free, compact, have very few moving parts and much more efficient than internal combustion engines.

The main challenges with the widespread adoption of electric vehicles are associated with battery technology. The biggest problem here is low energy density, which means that to provide a reasonable journey range they have to be large, heavy and expensive. Their major advantage versus alternative powertrain technologies is that a refuelling infrastructure already exists, with the national grid and a power socket in every building. By comparison, hydrogen fuel cells can provide high energy and power density; as energy storage medium hydrogen has the capacity to store large values of energy.

The main drawbacks currently associated with fuel cell cars are their high cost and limited availability. Fuel cell cars are not equipped to store the amount of hydrogen needed for long distances which means that they require refuelling more often. The use of hydrogen-fuelled transport will depend on the successful development of an affordable and widespread refuelling infrastructure. Currently, only a few expensive hydrogen refuelling stations exist worldwide, and refuelling station costs need to be reduced to make them commercially viable. The greatest challenge will be to support millions of private cars but, before that, fleet vehicle fuelling stations will be introduced.

The introduction of hydrogen vehicles is expected to start with centrally operated fleets of buses and city goods delivery vehicles in densely settled mega-cities, followed by private cars. Urban buses are attractive due to the centralised refuelling facilities, the availability of skilled personnel, the engineering tradition of public transport companies, and for the promotion of public awareness. A trans-European hydrogen energy network can then be progressively grown from these strategically sited nuclei.

Chapter 9: System Level Implications

9.1 Introduction

The previous chapters have provided detailed accounts of the scope for accelerated development of a series of emerging low carbon energy supply technologies, and the possible impact of this on the decarbonisation of the UK energy system.

This chapter considers the wider 'system-level' implications of supply side accelerated technology development, and also the interactions (competitive and synergistic) between different technologies when accelerated development assumptions are aggregated together. In most cases, these system-level and aggregated effects are examined by comparing non-accelerated scenarios (LC Core) with equivalent scenarios in which all the technologies considered in previous chapters are accelerated in parallel (LC Acctech). The discussion is framed broadly within short (up to 2020), medium (2020-2035) and longer (2035-2050) timescales.

In addition, where important differences may be expected to emerge by delaying or excluding the availability of specific technologies, other scenarios are also introduced. For example, CCS has a unique status in many of the aggregated scenarios as a still emerging technology whose progress is subject to considerable uncertainty, yet which potentially has a major role in energy system decarbonisation as early as the 2020s. Therefore, so as to consider other potential pathways for system decarbonisation in the event of CCS development being delayed or failing to become commercially attractive, aggregated accelerated development scenarios with later (post 2030) and non-availability of CCS are also considered. Similarly, as is discussed in Chapter 8, accelerated development of fuel cells may have a powerful long term impact on preferred decarbonisation pathways, not only on transport sector decarbonisation, but also on the relative attractiveness of decarbonising different energy services, such as power, transport and heating. Important system-level differences therefore emerge between version of LC-Acctech in which fuel cells acceleration is included or omitted, and these are also discussed below.[59]

---

[59] The examination of aggregated scenarios without fuels cells acceleration is particularly useful here because the potential for accelerated development of electricity storage technologies, such as advanced battery technologies, has not been included in this research. Advanced storage technologies

In describing and discussing system-level patterns over time, the primary focus is on the interplay between energy system *output* (in terms of meeting decarbonisation ambitions for least-cost), and supply side *input* (in terms of the availability, cost and performance of different technologies over time which help enable these ambitions to be met). In reality, many other technological and social factors concerning energy production, distribution and consumption will enable and constrain the ability of the UK energy system to respond to decarbonisation and other policy imperatives. While the particular concern here is with low carbon energy supply technologies, a number of these wider issues are being addressed in other parts of the UKERC 2050 project, as stated in Chapter 1.

Combining together the technology-specific accounts of accelerated development from earlier chapters allows consideration of cross-technology competition and synergy, and also the wider consequences, for preferred decarbonisation pathways, of introducing different supply-side options. **The system-level impacts of accelerated technology development are complex, changing over time as different low carbon supply options for providing different energy services are made available, and also as overall decarbonisation ambitions to 2050 are increased from 60% to 80%.** For example, the preferred use of bioenergy resources in different aggregated scenarios switches between electricity, heating and transport, according to the overall level of decarbonisation ambition and the availability of alternative ways of decarbonising particular energy services.

Two initial general observations are therefore: firstly, **accelerated development of multiple emerging low carbon supply options opens up alternative pathways for achieving UK energy system decarbonisation**; secondly, because of the evolving interactions between different supply options in providing different energy services, **the most attractive low carbon supply technologies – and the research priorities associated with their commercialisation – are sensitive to overall level of decarbonisation ambition**. **Raising the decarbonisation ambition from 60% to 80% does not simply mean doing 'more of the same' – it introduces new technology preferences and research priorities.** These issues are discussed in more detail below.

---

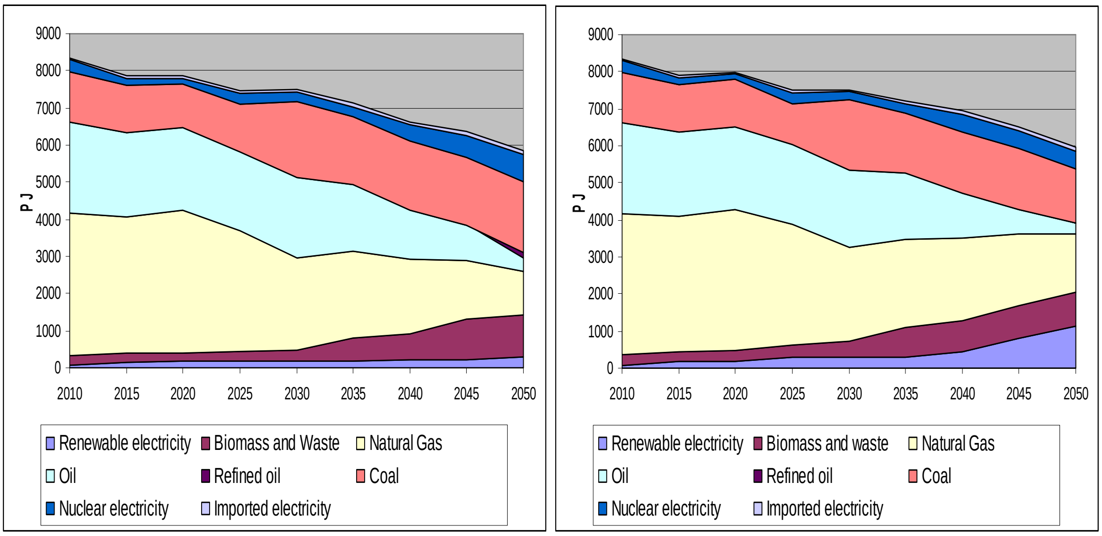
may change the relative economics of electricity-based and hydrogen-based low carbon transport systems; see Chapter 8.

The chapter proceeds in Section 9.2 by considering the impact of supply side technology acceleration on the wider UK energy system, in terms of overall patterns of energy supply and demand, and wider social costs and benefits. Section 9.3 focuses on the impact of technology acceleration on the power (electricity) supply sector, for both 60% and 80% decarbonisation scenarios to 2050. The chapter concludes by highlighting a number of wider implications and challenges associated with the accelerated technology development scenarios (Section 9.4).

9.2 Overall System Impacts

9.2.1 Impact of Technology Acceleration on Energy Supply and Demand

The same broad pattern of declining overall energy demand over time, as the energy system decarbonises, is followed with or without accelerated technology development (although primary energy demand in 2050 remains slightly higher in accelerated development scenarios) (Figure 9.1, below). Within this, **renewable electricity provides a much greater proportion of primary energy demand by 2050 in accelerated scenarios: almost 20% in LC Acctech 80, compared to under 5% in LC Core 80.** Gas and coal remain important primary fuels in 2050 with or without acceleration, although gas has much reduced demand over time, and oil is almost absent from the energy mix by 2050.



LC Core 80 **LC Acctech 80**

Figure 9.1: Primary Energy Demand by Fuel, LC Core 80 and LC Acctech 80

Final energy demand declines substantially after 2030 in both accelerated and non-accelerated scenarios, but again remains slightly higher in the accelerated scenario. By 2050, final energy demand by fuel has changed significantly in accelerated development scenarios, with higher demand for hydrogen, biomass and natural gas (the latter used in sectors which decarbonise least, such as industry and services), and lower final demand for electricity, petrol, ethanol/methanol and biodiesel (Figure 9.2). Accelerated fuel cells development has a major influence on these changes, increasing demand for hydrogen and reducing final demand for electricity and biodiesel as transport fuels.

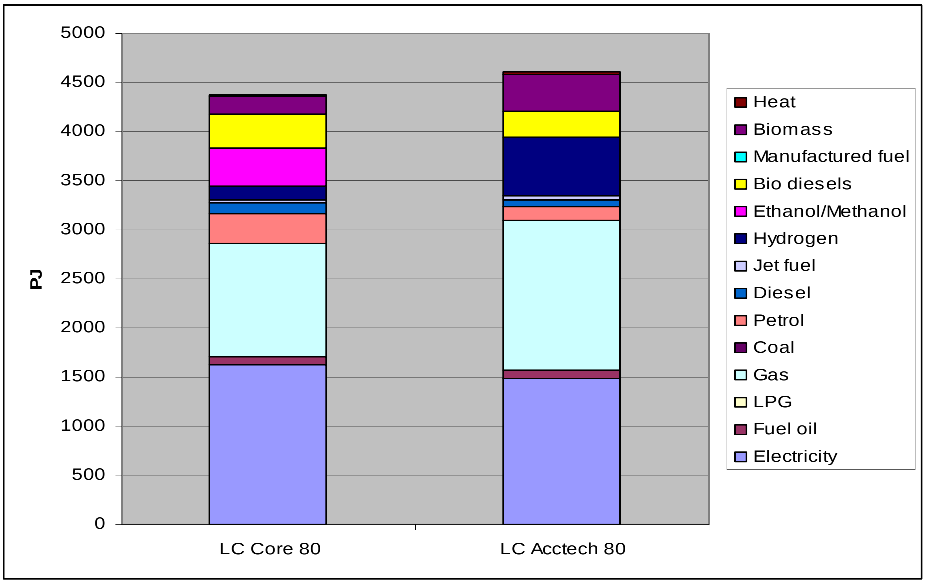
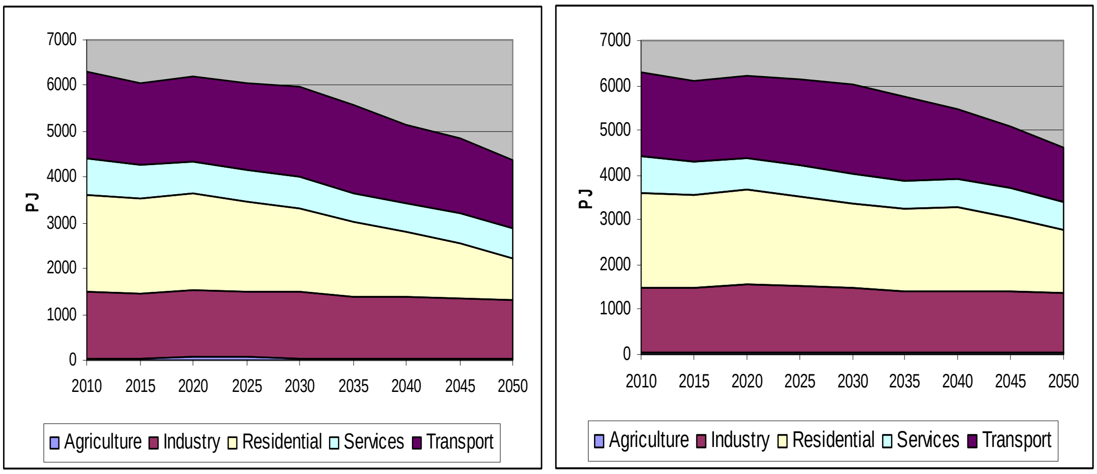


Figure 9.2: Final Energy Demand in 2050 by Fuel Type Non-Accelerated and Accelerated Scenarios

In terms of final energy demand by sector, accelerated technology development again makes a significant difference over the long term (Figure 9.3, below). In the non-accelerated LC Core 80 scenario, residential energy demand almost halves between 2035 and 2050 – a key contributor to long term system decarbonisation.[60] In LC Acctech 80, however, residential energy demand declines much less steeply – only by around 20% between 2035 and 2050 – and despite a larger reduction in transport sector final energy demand, overall final energy demand in 2050 is around 10% higher in the accelerated scenario.

---

[60] In the non-accelerated scenario, residential heat pumps become the main provider of residential space and water heating after 2040. Heat pumps are also deployed over the long term in the accelerated scenario, but to a much lesser extent. In 2050, heat pumps provide over 90% of residential energy demand in LC Core, but under 30% in LC Acctech.



LC Core 80 **LC Acctech 80**

Figure 9.3: Final Energy Demand by Sector, LC Core 80 and LC Acctech 80

The difference between accelerated and non-accelerated scenarios in terms of energy demand is most pronounced in the transport sector. By 2050, the introduction of accelerated fuels cells development means that hydrogen has become the dominant transport fuel in the accelerated scenario (Figure 9.4).[61]

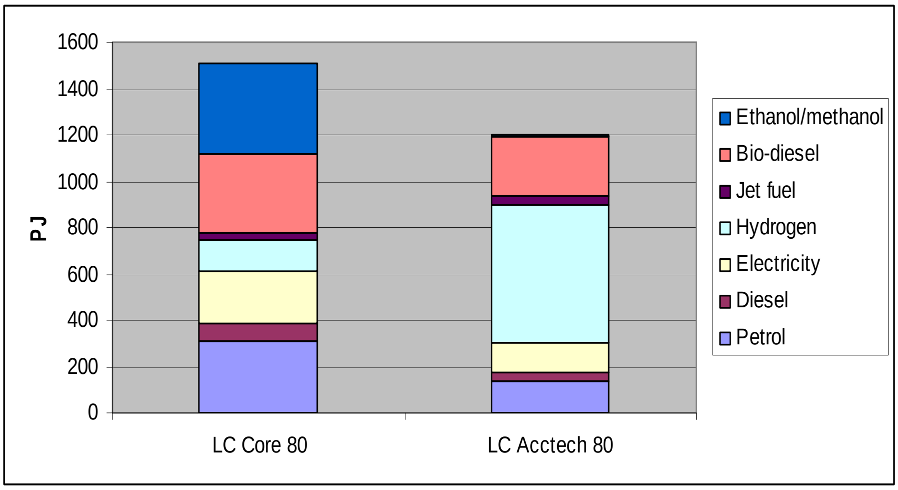


Figure 9.4: Transport Sector Energy Demand by Fuel, in 2050

9.2.2 Decarbonisation Trajectories

Overall levels of CO_2 emissions associated with the scenarios presented here are imposed as system-level constraints in the Markal model, so that scenarios sharing the same decarbonisation ambition by 2050 follow the same overall

---

[61] Overall final energy demand for transport is significantly less in the accelerated development scenario, but this reflects the higher contribution from hydrogen. Total journeys made, by vehicle km, actually increase in the accelerated scenario.

emissions trajectory. As stated in Chapter 1, the same decarbonisation ambition is imposed to 2020 (26% relative to 1990 levels) for both 60% and 80% scenarios, with 'straight-line' trajectories to reduced CO_2 emissions by 2050 in-between these points (Figure 9.5). Total cumulative CO_2 emissions between 2000 and 2050 are 22.46GT in 60% scenarios and 20.39GT in 80% scenarios.

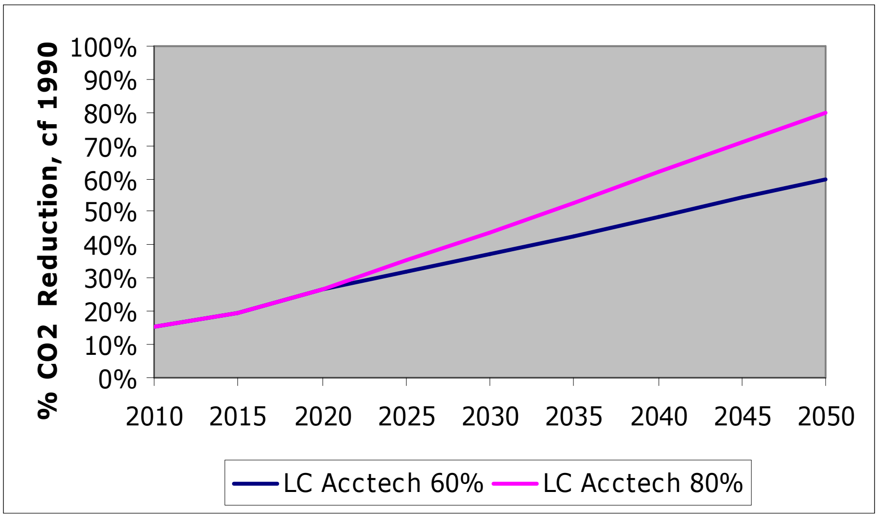


Figure 9.5: Decarbonisation Trajectories, LC-Acctech 60 and 80

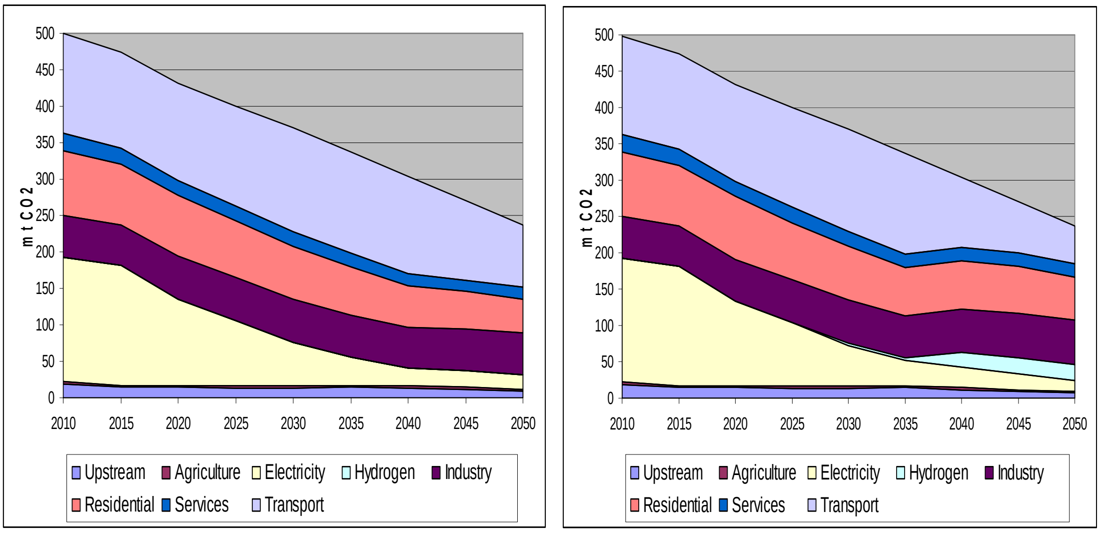
In all scenarios, the electricity supply sector decarbonises first and most thoroughly, and, in 80% scenarios, is substantially decarbonised by 2030, with or without accelerated technology development (Figures 9.6 and 9.7, below). Other carbon intensive energy services – especially transport, but also residential demand – decarbonise in the medium and longer terms, with both undergoing much more thorough decarbonisation in 80% scenarios than in 60% scenarios (Figures 9.6 and 9.7, below).

Accelerated development makes some difference to this broad pattern. For both 60% and 80% scenarios, the introduction of fuel cells acceleration is associated with greater decarbonisation of transport – and reduced decarbonisation of the residential sector – over the longer term.[62] Excluding fuel cells acceleration, there is less difference in the decarbonisation of different energy sectors over time between accelerated and non-accelerated scenarios. However, while technology acceleration makes only relatively modest differences to the pattern of emissions reductions by sector, much more substantial changes are seen in the supply-side

---

[62] In 60% scenarios, hydrogen production for fuel cells transport has some associated CO2 emissions after 2035, but in 80% scenarios, these emission are eliminated by using zero-carbon sources for hydrogen production by electrolysis.

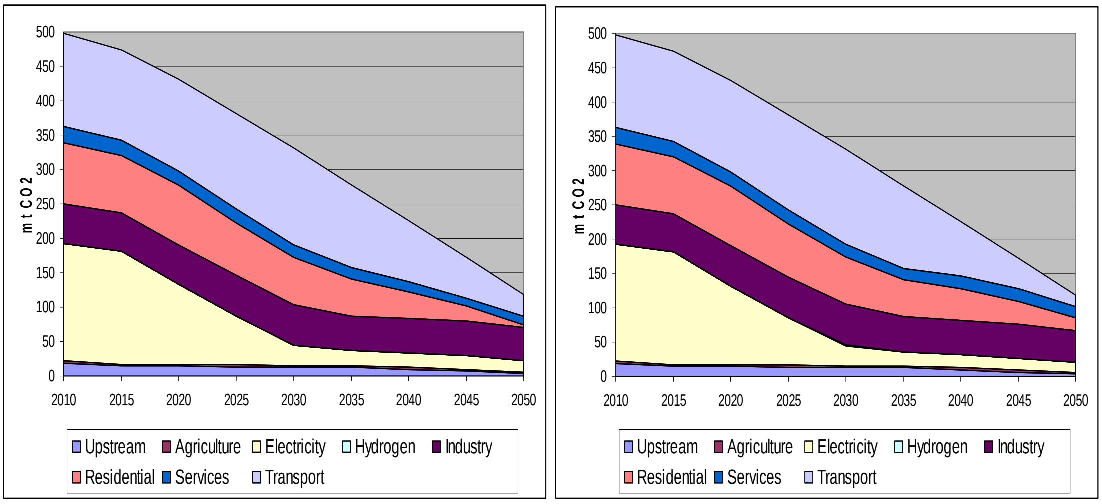
technology portfolio used to enable this pattern of decarbonisation. (The impact of accelerated development in the electricity sector are discussed in Section 9.3).



LC-Core 60

LC-Acctech 60

Figure 9.6: CO_2 Emissions by Sector, 60% Scenarios



LC-Core 80

LC-Acctech 80

Figure 9.7: CO_2 Emissions by Sector, 80% Scenarios

9.2.3 Costs and Benefits of Acceleration

The modelling results offer some indication of the overall advantages of supply-side technology acceleration in energy system decarbonisation. These advantages accrue mostly in the long term, as accelerated technology development enables more affordable ways to achieve more extensive decarbonisation. Two Markal output parameters – the marginal cost of CO_2 abatement, and the overall 'welfare cost' of decarbonisation – allow for quantification of this benefit. **Given the high levels of uncertainty embedded in the scenarios (especially over the**

longer term) these figures only offer a broad illustration of the possible benefits of accelerated development, under assumptions of high levels of progress, rather than any more reliable cost benefit analysis.

The marginal cost of carbon abatement – the effective carbon price that needs to offered by policy and regulatory frameworks to achieve the outcome portrayed in the scenarios – increases over the longer term as progressively more expensive carbon abatement options are deployed. In the LC-Acctech scenarios, however, this increase is considerably less than in non-accelerated equivalent scenarios (Figure 9.8, below) – **accelerated technology development significantly reduces the long term marginal cost of CO_2 abatement**. (Fuel cells technology acceleration is again an important differentiator here: without the option of low carbon transport presented by fuel cells acceleration after 2035, there is less difference in the marginal cost profiles of accelerated and non-accelerated scenarios).

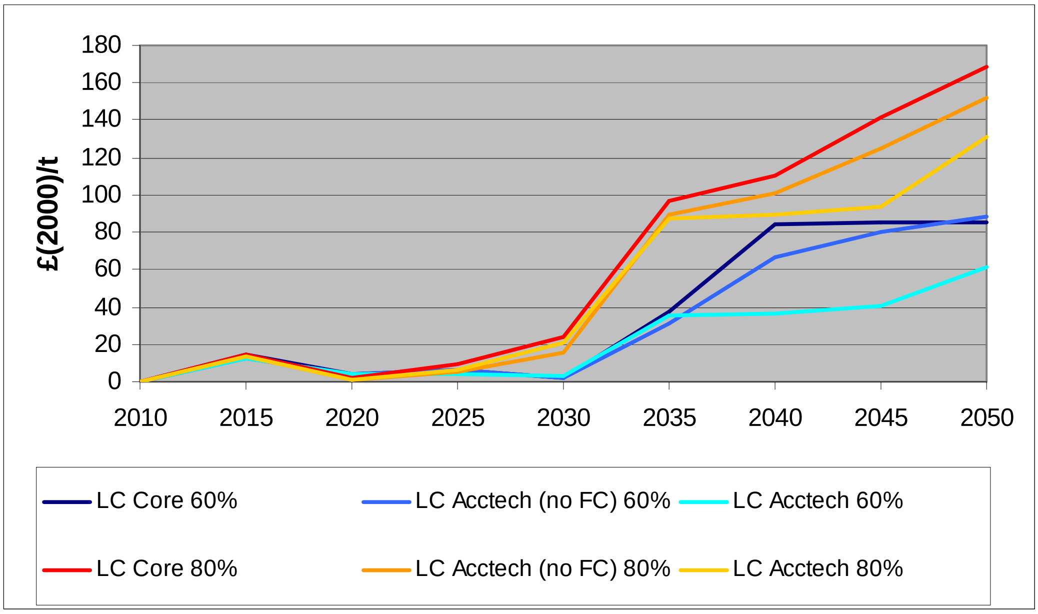


Figure 9.8: Marginal Cost of CO_2, Aggregated Scenarios

The UK Markal MED model represents the societal 'welfare costs' of decarbonisation as a sum of producer and consumer surplus (Anandarajah et al., 2008). This figure represents (to a limited extent) the overall added cost to society of decarbonisation, so that raising the level of decarbonisation ambition from 60% to 80% is associated with a doubling of welfare costs in non-accelerated scenarios – although it is important to note that this fails to take into account the societal costs of climate change. In both accelerated and non-accelerated scenarios, the welfare cost of decarbonisation increases significantly after 2030, as progressively more expensive carbon mitigation responses are deployed, but this increase is lower in accelerated scenarios than in their non-accelerated equivalents (Figure 9.9).

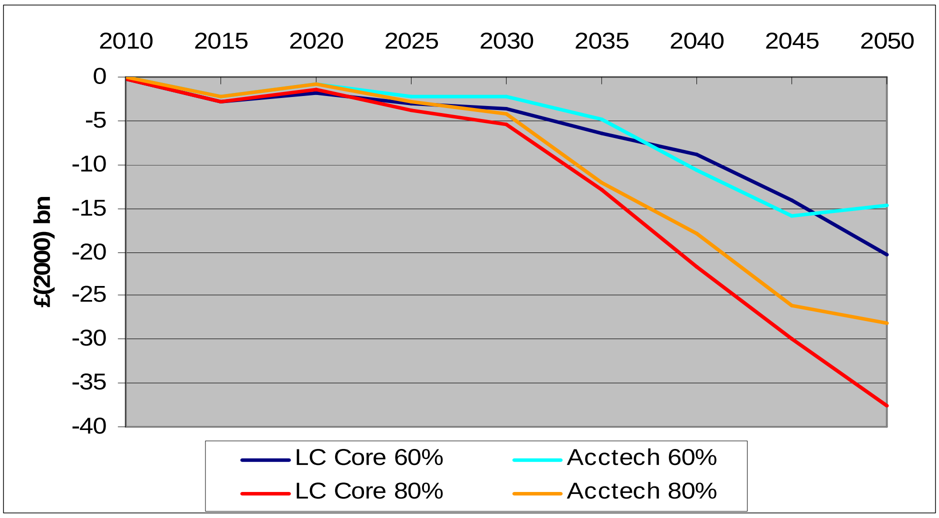


Figure 9.9: Change in Welfare Costs associated with Decarbonisation

Over the forty years 2010-2050, accelerated development is associated with a total saving in the welfare costs of achieving 80% decarbonisation by 2050 of £36bn.[63] Note that as Figure 9.9 shows, most of this benefit accrues in the longer term, after 2035. This 'saving' should be benchmarked against the added investment costs of accelerated development, in terms of additional spend on RD&D to realise the assumed performance and cost improvements embedded in the ATD scenarios. In practice, this comparison is far from straightforwards, given that the investments associated with technology acceleration will be made internationally.

The RD&D costs of global technology acceleration consistent with international decarbonisation ambitions were recently estimated by the IEA (IEA, 2008a). Although the IEA and UKERC scenarios are based on different regions, input assumptions and decarbonisation constraints – and therefore not reliably comparable in any detail – the IEA's 'ACT' and 'Blue' scenarios distinguish between lower and higher rates of supply side technology development and

---

[63] This is the Net Present Value (NPV) of the total difference in welfare costs between non-accelerated and accelerated development scenarios over the period 2010-2050, discounted at UK Government recommended long-term social discount rates of 3.5% for Years 1-30, and 3.0% for Years 31-40 (HM Treasury, 2008). Because most of the benefits of technology acceleration accrue in the long term, the non-discounted saving in welfare costs associated with accelerated development is much higher, around £88bn.

deployment in a broadly similar manner to UKERC Core and ATD scenarios. Considering only a similar basket of technologies as those analysed by UKERC, the additional RD&D investment costs to the UK associated with the accelerated scenario compared to the non-accelerated case is around \$8bn (c.£5.5bn).[64] While this figure can only be seen as a broad indicator, it suggests that **the overall benefits to the UK of accelerated technology development of low carbon supply technologies considerably outweigh the investment costs.**

From a purely UK perspective, **the suggested savings associated with low carbon technology acceleration of around £36bn could be translated into an equivalent budget for additional UK RD&D investment in low carbon technology development of around £1bn per annum.** (Although much of this investment will be needed to be committed well before significant 'returns' from acceleration start appearing after 2030). The RD&D priorities associated with accelerated technology development have been detailed in Chapters 2 to 8. They are summarised in Table 9.1, below, indicating areas where investments are needed to generate the suggested savings in the costs of decarbonisation.

---

[64] Based on the difference in RD&D investment costs for IEA ACT and BLUE scenarios, as specified for different supply technologies in Chapter 8 of the IEA's Energy Technology Perspectives, 2008 (IEA, 2008a). Note that the IEA analysis excludes marine energy.

	General Research Themes, examples	Specific Research Priorities, examples	Contribution in ATD Scenarios
Wind Power	• Improved wind turbine efficiency for low speed onshore locations • Improved condition monitoring and enhanced reliability of offshore turbines • Expanded offshore electricity transmission infrastructure • Electricity storage technologies and/or demand-side management	• Blade materials technology • Control algorithms • Generator design • Aerodynamic design (limited scope) • Offshore 'balance of system' costs • Offshore resource characterisation	Offshore wind has a significant medium and major long term role in ATD scenarios (Chapter 2).
Marine Energy	• Consensus on designs (concepts and components) • Greater collaboration on generic technologies and components • Improved operational data on prototype performance in real operating conditions • Explore feasibility of more radical design options • Promote knowledge transfer from other sectors	• Resource modelling & measurement • Device modelling • Moorings and sea bed attachments • Power take off and control • Installation and O&M costs • Environmental impact assessment • System simulation	Marine energy (wave and tidal flow) has a significant long term role in ATD scenarios, with first deployments appearing much earlier than in non-accelerated scenarios (Chapter 3).
Solar PV	• Low cost, stable and efficient cells • Reduced production costs • Improved control systems and storage technologies • Reduced Balance of System costs • Bringing together materials researchers and plant designers • Improved performance prediction tools	*For Crystalline Silicon* • Increasing cell efficiency • Cheaper feedstock production • Higher yielding processing *For Thin Film Cells* • Higher quality component layers • Reduced substrate costs • Improved encapsulation and production processes *For Organic Cells* • Increased cell efficiencies and device lifetimes	Third generation organic solar cells have a significant long term role. Earlier deployments of first, second and third generation solar cells are not represented in the ATD scenarios, but may be anticipated in practice (Chapter 4).
Bioenergy	• Improved crop feedstocks • Improved conversion technologies • System-level research on optimal use of limited biomass resources • Lifecycle and environmental impact analysis • Establishing standards for biomass trade and use	• Improved efficiency, cost, flexibility of existing conversion technologies • High yielding second generation biomass with minimal land and water requirements • 'Third generation' novel feedstocks such as algae and artificial photosynthetic systems • Novel conversion technologies, e.g. pyrolysis	Significant medium and long term impact, arising from bioengineering improvements to energy crops and improved gasification technology; second generation ligno-cellulosic ethanol technology also deploys (Chapter 5).

Table 9.1a: Indicative Research Themes and Priorities associated with ATD Scenarios, Renewables Technologies

	General Research Themes, examples	Specific Research Priorities, examples	Contribution in ATD Scenarios
Nuclear Power	*Fission* • Supporting existing plant operations • Enabling deployment of advanced reactor systems • Solutions for waste management (including legacy waste) and plant decommissioning *Fusion* • Plasma performance • Enabling technologies • Materials, component performance and lifetime	*For Generation III Reactors* • Long term materials irradiation and structural integrity • Control, instrumentation, monitoring and lifetime prediction *For Generation III+ Reactors* • High temperature materials • Fuel burn-up and long-life fuel cores • Demonstrating inherent safety characteristics *For Generation IV Reactors* • Advanced materials • Fuel fabrication and high burn-up fuel • Thermal hydraulics • Spent fuel reprocessing and recycling *For Nuclear Fusion* • Plasma disruption avoidance, steady-state operation and divertor performance • Superconducting machine • Power plant diagnostics & control • Tritium inventory control & processing • First wall blanket/divertor materials and components	Generation III Fission reactors have significant medium and long term role (Chapter 6). Later generations of fission reactors (III+ and IV) not represented in ATD scenarios, but their deployment may be anticipated in practice over the longer term. Fusion ATD assumptions are relatively modest; projected fusion deployment is post-2050.
CCS	• Demonstrating existing technologies • Planning and building transport infrastructure • Optimising the retrofitting of capture technology onto power plants • R&D for potential future improvements, e.g. efficient, low-cost capture and integrity and capacity of storage, especially aquifers	*Capture* • *Post-combustion:* resistant amine solvents or alternatives • *Pre-combustion:* improved membrane or pressure swing separation of CO_2 from H_2 and improved O_2 separation • *Oxyfuel:* lower cost O_2 separation from air, better membranes for CO_2 separation, chemical looping *Storage* • Assessing aquifer storage potentials • Evaluating co_2 sealing and leakage • Monitoring and verification technology from existing applications	CCS technology has a major medium and long term role. Long term impact is sensitive to assumed capture rate. (The ATD modelling assumptions do not explicitly distinguish between different forms of CCS technology); (Chapter 7).
Hydrogen and Fuel Cells	• Cost reduction of the H2 drivetrain • Cost reduction of hydrogen production chains • System integration for hydrogen • Safety and reliability of hydrogen applications • Compliance with long-term sustainability needs	*Drivetrain* • Cell components (membrane, catalyst, materials) • Periphery component (air supply, humidification, valves, power and control electronics) • Onboard storage *Hydrogen production chains* • Electrolysers, biomass gasification systems, CCS and standard components and instruments *System integration* • Integration of drivetrain, onboard storage and auxiliary safety equipment, valves, and electronics • Integration of renewables and hydrogen in 'island / remote' systems *Safety, reliability, sustainability* • Harmonized regulations, codes and standards • Hydrogen from renewables, fossil fuel with CCS, or nuclear pathways	Hydrogen Fuel Cells (HFCs) have a major long term role in transport sector decarbonisation in ATD scenarios. The ATD modelling assumptions do not explicitly distinguish between different types of HFCs for transport (Chapter 8).

Table 9.1b: Indicative Research Themes & Priorities associated with ATD Scenarios, other low carbon supply technologies

9.3 Electricity Supply System

9.3.1 60% Decarbonisation Scenarios

Under an overall decarbonisation ambition of 60% by 2050, accelerated technology development has a significant impact on the power mix in the medium term (2020-2035) and a more substantial long term impact, after 2035; however, only very minor changes are seen in the short term, to 2020 (Figure 9.10, below). In both non-accelerated and accelerated scenarios, coal-CCS begins to displace unabated coal-fired generation by 2020, and nuclear generation declines rapidly after 2010 with the retirement of existing plant (although, as noted in Chapter 6, this doesn't allow for possible lifetime extensions). In all cases, gas-fired combined-cycle plant remains the largest contributor to the overall power sector supply mix in 2020.

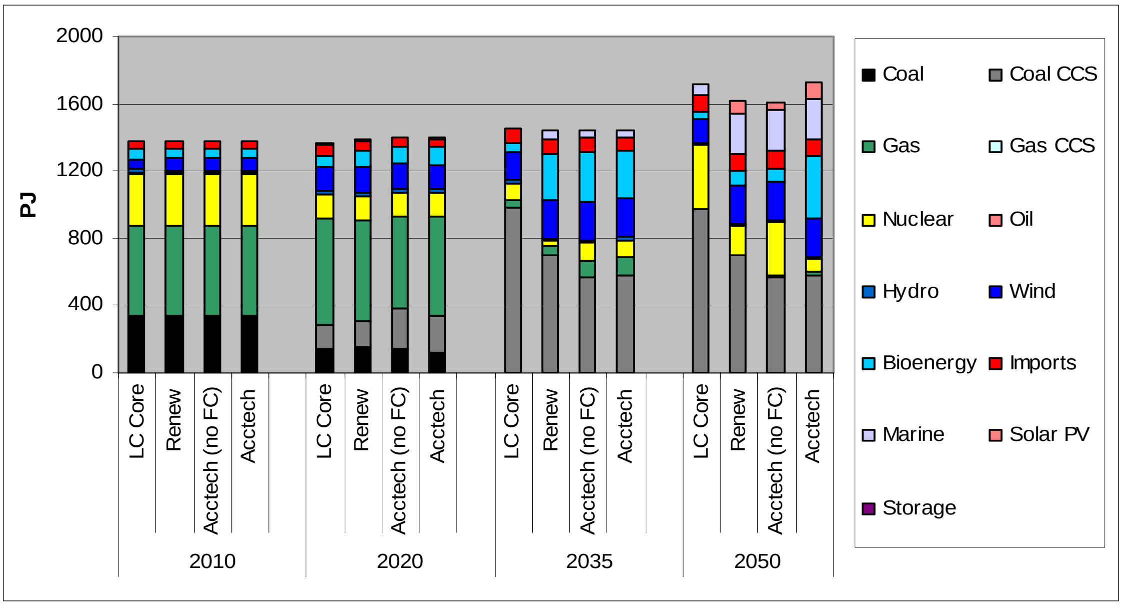


Figure 9.10: Power Sector Supply Technology Portfolios - Aggregated Scenarios, 60% Decarbonisation to 2050

By 2035 the generation mix is transformed in all scenarios, but significant differences have emerged between non-accelerated and accelerated cases. Gas-fired generation plant is now largely retired and replaced by very large deployments of coal-CCS plant. However, whilst coal-CCS provides around 2/3rds of all power supplied in the non-accelerated (LC Core) scenario, its contribution is significantly less (40% in 2035, and under 30% in 2050) in accelerated development scenarios, with greater contributions from bioenergy and wind power, and initial deployments of marine energy. **Technology acceleration is**

associated with the emergence of more diverse low carbon energy supply portfolios over the medium term.

By 2050, the difference between accelerated and non-accelerated scenarios (and between different accelerated scenarios) is more pronounced. In all cases, the overall size of the power sector has grown, as low carbon electricity is used to decarbonise non-power energy services, especially transport and heating. Coal-CCS remains the largest single supply technology in all scenarios, but no additional deployment of coal-CCS is seen after 2035. In this later period, the demand for additional low carbon power supplies is provided mostly by nuclear power, in the non-accelerated scenario, or renewables technologies (especially marine energy and solar PV) and nuclear in the accelerated scenarios. **Accelerated development is associated with a more significant role for renewables technologies in the long-term decarbonisation of the UK energy system.**

By 2050, there is a substantial difference in the power supply portfolio between versions of LC Acctech which include or exclude fuel cells acceleration, with much greater levels of bioelectricity (and much less nuclear power) when fuel cells acceleration is included. Accelerated fuel cells development is associated with a preference for decarbonisation of transport rather than residential heating, so that bioenergy resources are available for use in power generation. With fuel cells acceleration excluded, residential sector decarbonisation using bioenergy is a more attractive use of bioenergy resources, together with higher levels of nuclear deployment for decarbonised power and transport (using electric vehicles). By enabling more affordable low carbon transport, **accelerated development of fuel cells changes the relative attractiveness of decarbonising different energy services, and the supply technologies (and associated research needs) involved in decarbonisation**.[65]

The proportion of overall power supplied from renewables technologies in accelerated 60% scenarios increases steadily over short, medium and longer timescales from 10% in 2010, to 20% in 2020, 40% by 2035 and almost 50% by 2050 (Figure 9.11, below).

---

[65] There is also a small difference in the carbon intensities of different sectors with or without fuel cells, due to the CO_2 emissions associated with hydrogen production in 60% scenarios.

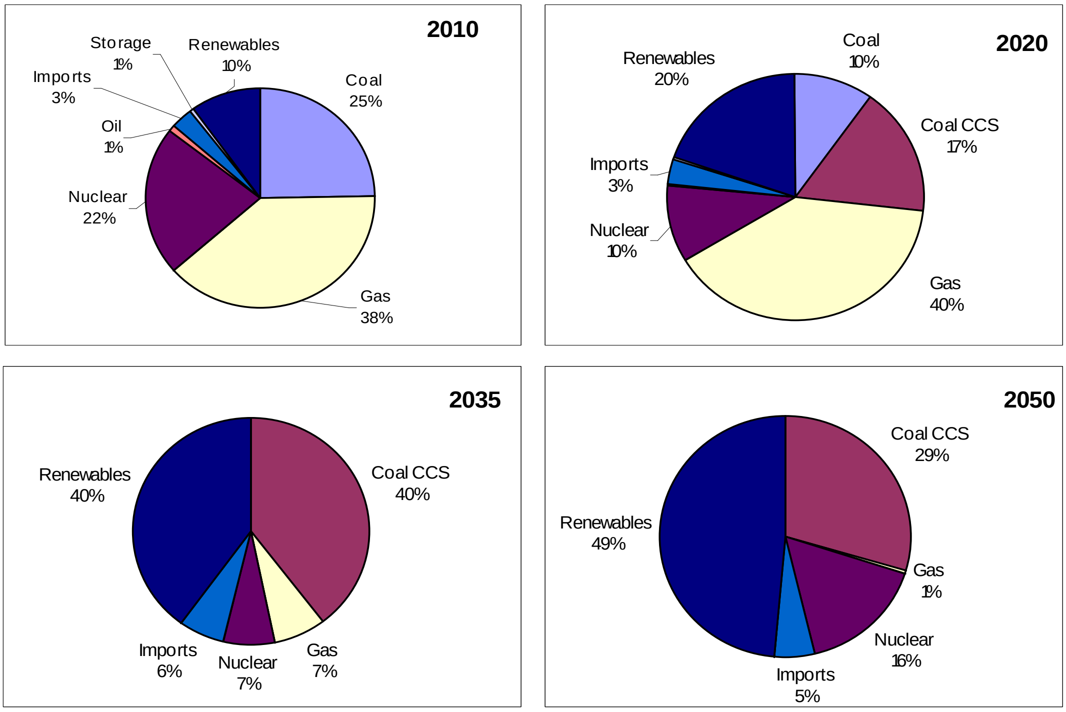


Figure 9.11: Proportion of Power from Different Supply Options, LC-Acctech 60

9.3.2 80% Decarbonisation Scenarios

For all scenarios in which the overall decarbonisation ambition to 2050 is raised to 80%, the electricity supply sector undergoes near complete decarbonisation over the period 2010-2030. Additionally, achieving 80% decarbonisation also requires that transport and residential sectors are also decarbonised to a much greater extent, after 2030, than under 60% ambition (Figure 9.7).

In 80% decarbonisation scenarios (as in 60% scenarios) **accelerated technology development has very little impact on the preferred UK power supply mix over the short term up to 2020; over the medium term, to 2035, accelerated development scenarios differ significantly from their non-accelerated counterparts, and diverge substantially over the longer term to 2050** (Figure 9.12).

Between 2010 and 2020, generation from conventional coal and nuclear power both decline significantly in LC Acctech 80, and are replaced by coal-CCS (with 10GW of coal-fired CCS plant installed by 2020), and also increased contributions from combined cycle gas fired generation (CCGT), wind power and bioelectricity.

CCGT remains the most important power generation technology in 2020, providing around 40% of power supplied in all 80% scenarios. Output from wind power and bioenergy increases slightly in LC Acctech 80 compared to LC Core 80.

By 2035, there is almost no contribution from gas-fired plant, and coal-CCS has emerged as the largest supplier of electricity in accelerated and non-accelerated scenarios. In accelerated scenarios, however, the expansion of coal-CCS is moderated by increased contributions from bioenergy, wind power and marine energy. As in 60% scenarios, **technology acceleration is associated with the emergence of more diverse low carbon energy supply portfolios over the medium term.** Overall levels of electricity demand in 2035 remain largely unchanged.

After 2035, however, the overall size of the power sector increases substantially in 80% scenarios, to a far greater degree than under 60% scenarios, as low carbon electricity is used to decarbonise transport and heating more deeply. This expansion is seen in both LC Core and LC Acctech, but is more pronounced in LC Acctech, with 50% more power supplied in 2050 compared to 2035 (Figure 9.12). Installed plant capacity also doubles during this period, to a total capacity of over 220GW by 2050; much of this expansion is intermittent renewables capacity – primarily offshore wind power – and also back-up / reserve plant. **Achieving 80% decarbonisation ambition of the UK energy system may involve the development a much larger UK power supply industry over the long term (compared to 60% scenarios), with a much larger exploitation of the UK offshore wind power resource**.

Within this overall growth, coal-CCS – the largest single contributor to the power mix in 2035 – has no added capacity by 2050 in the non-accelerated scenario, and provides *less* power in all accelerated cases. This diminished role is associated with residual CO_2 emissions associated with coal-CCS (with a higher capture rate, coal-CCS continues to play a very large role, see Chapter 7).[66]

---

[66] The assumed CO2 capture rate is 90% for most of the scenarios discussed here; when the capture rate is raised to 95% (for the same technology cost), coal CCS deployment increases significantly.

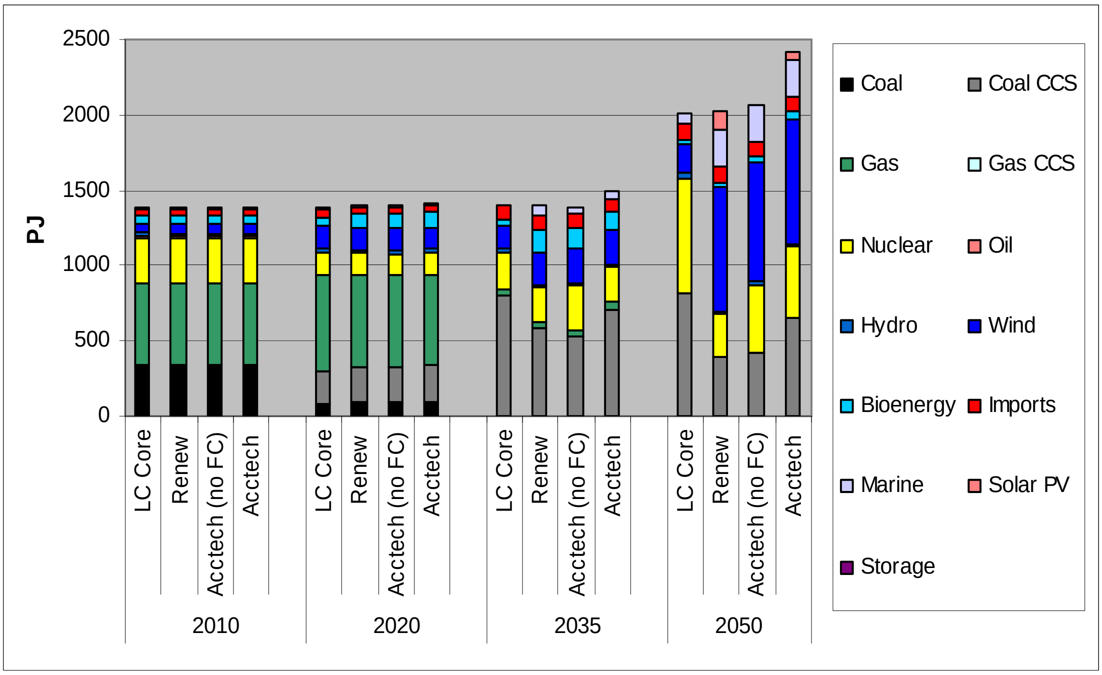


Figure 9.12: Power Sector Supply Technology Portfolios, Aggregated Scenarios, 80% Decarbonisation to 2050

Other technologies expand rapidly after 2035: nuclear power in the non-accelerated case, and offshore wind power and marine energy in accelerated scenarios (the further growth of marine energy is constrained by modelling assumptions of the exploitable resource; see Chapter 3). Deployment of solar PV is also seen after 2040 in LC Renew 80 and, to a lesser extent, LC Acctech 80. Wind power provides the largest single technology contribution by 2050 in all accelerated scenarios, suggesting significant long-term challenges to system infrastructure and balancing. Overall, **accelerated technology development introduces alternative pathways for decarbonising the UK power system in the longer term, and is associated with significantly increased contributions from a number of different renewable technologies (marine, solar PV and especially offshore wind power).**

Fuel cells acceleration has a distinctive influence on preferred decarbonisation pathways, and the overall size and technological make-up of the power sector. The LC Acctech 80 scenario which includes fuel cells acceleration is associated with lower carbon intensity in the transport sector after 2030, but higher carbon intensity in the power sector, than in the same scenario with fuel cells excluded. As a result, coal CCS has a larger long-term role in the power mix when fuel cells vehicles are deployed (Figure 9.12, above). Hydrogen production by electrolysis creates substantially raised demands for electricity, and by 2050, LC Acctech with fuel cells acceleration has significantly higher installed capacity compared to LC Acctech without fuel cells acceleration (an increase of over 35GW). Combined together, **accelerated development of renewable and hydrogen / fuel cells technologies are associated with an unprecedented long term expansion of the UK power sector.**

The proportion of overall power supplied from renewables under 80% decarbonisation ambition increases steadily over short, medium and longer timescales, from 10% in 2010, to 20% in 2020, 30% in 2035 and 55% by 2050 (Figure 9.13). Perhaps surprisingly, however, the medium-term contribution from renewables is lower in Acctech 80 compared to Acctech 60 (see also Figure 9.11). This highlights the enhanced medium term role of carbon savings from non-electricity sectors, especially transport, in 80% scenarios. As Figure 9.14 below shows, the transport sector is the main source of carbon savings after 2030 in LC Acctech 80.

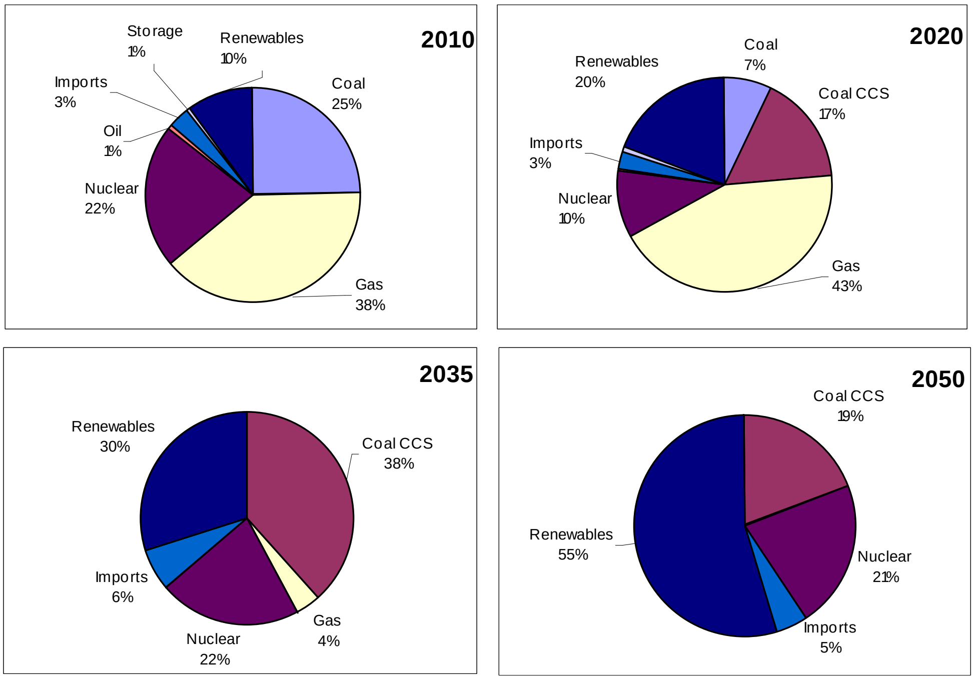


Figure 9.13: Proportion of Power from Different Supply Options, LC-Acctech 80

The reduced medium term role for renewables electricity also reflects the reduced role of bioenergy in power generation in accelerated 80% scenarios compared to 60% equivalent scenarios (Figure 9.15, below), and the interaction between bioenergy and fuel cells technologies in 80% decarbonisation pathways. From a system-level perspective, the preferred pathways for achieving 80% decarbonisation involve using the limited amounts of bioenergy feedstocks for decarbonisation of *transport* in LC Acctech 80 with fuel cells acceleration excluded, and *residential heating* when fuel cells acceleration is included (discussed in Chapter 5). In general terms, **raising the overall level of decarbonisation ambition changes the most attractive technology supply options (and associated research priorities) used to provide low carbon power, transport and heat.**

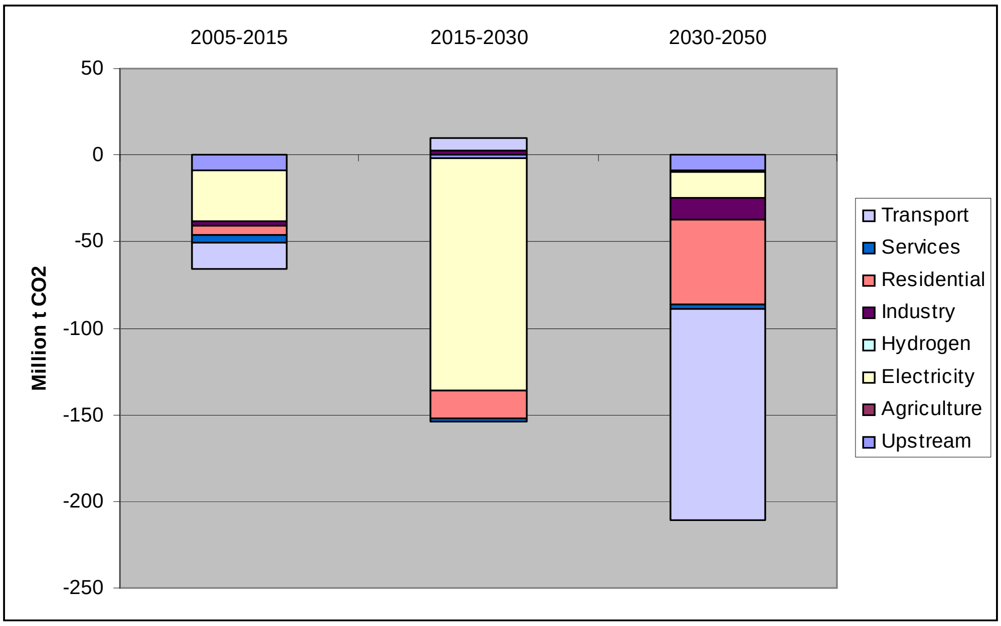
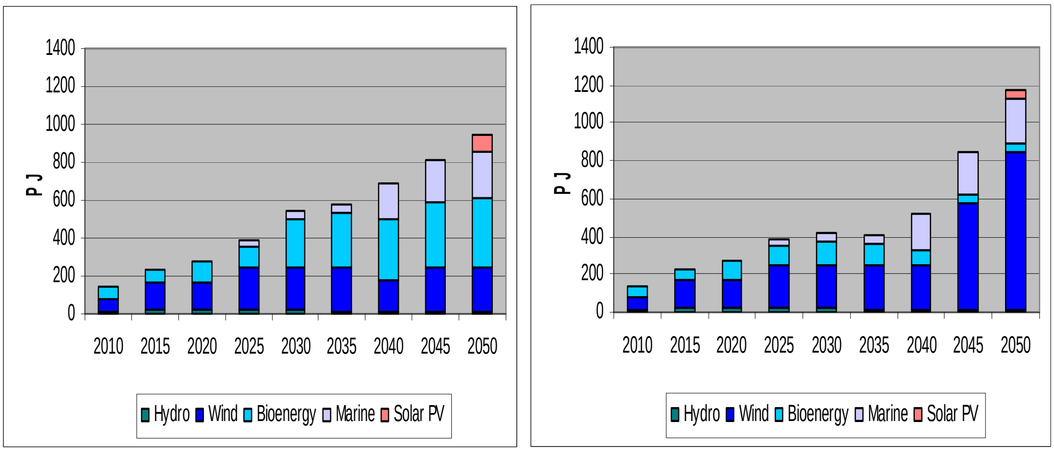


Figure 9.14: CO_2 emission reductions in LC Acctech 80, by Supply Sector
(Note: The time intervals in this figure differ slightly from those used elsewhere so as to highlight the main differences over time more clearly).



Acctech 60 **Acctech 80**

Figure 9.15: Electricity Generation from Renewables, LC Acctech 60 and 80

9.3.3 Delayed or Non-Availability of CCS

Carbon Capture and Storage occupies a special position in many scenarios of energy system futures. Although it is still emerging, and therefore subject to considerable uncertainty in terms of its costs, performance and availability, coal-fired CCS has a major role in power system decarbonisation as early as the 2020s in the aggregated scenarios presented here.[67] In contrast with many other low carbon technologies, CCS has only recently emerged as a possible means of energy system decarbonisation, and as discussed in Chapter 7, there is, as yet, little real operational evidence to assess its costs and performance. So as to take account of this uncertainty, and identify possible pathways for system decarbonisation in the event of CCS development being delayed or failing to become commercially attractive, additional versions of the LC Acctech scenario with delayed or non-availability of CCS were generated (Figure 9.16, below).

Because low carbon electricity is an important enabler of 80% decarbonisation ambitions, the removal of an important source of low carbon power such as coal CCS has significant effects across the energy system. Compared to LC Acctech, LC Acctech (no CCS) features less overall demand for electricity, reduced take-up of hydrogen fuel cells, and a switching of bioenergy resources from residential heating to transport.

By 2050, the carbon intensity of different energy services is altered in the absence of CCS: the electricity sector now has zero carbon emissions, while the residential sector has higher emissions, despite reduced residential energy demand. By 2050, bioenergy resources are wholly used to decarbonise transport (as biodiesel in HGVs). **The overall pattern of energy service demands and associated carbon emission reductions are significantly altered if CCS is assumed to be unavailable.**

---

[67] As discussed in Chapter 7, gas-fired CCS may also be an attractive low carbon supply technology; its non-deployment in the scenarios presented here reflects price assumptions about the future cost of coal and gas.

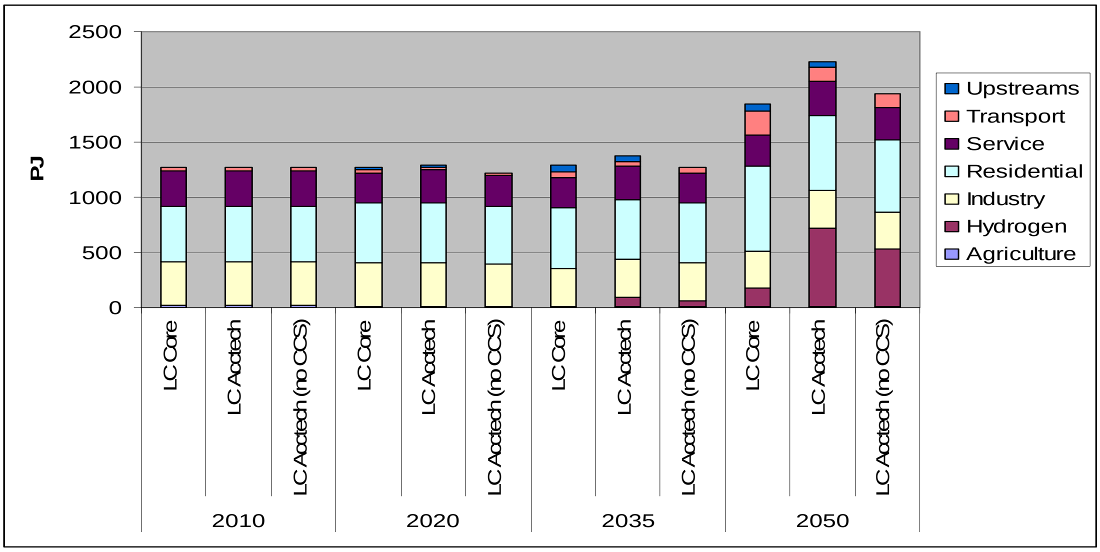


Figure 9.16: Electricity Demands by Sector

The power sector technology mix also changes significantly in the absence of CCS, with nuclear power and renewables assuming significantly expanded roles in power system decarbonisation (Figure 9.17, below). In the short term to 2020, the shortfall from coal CCS is made up by windpower (50% more windpower is installed by 2020 in the absence of CCS, up from 14GW to 21GW) and also some continued conventional coal-fired generation. Between 2020 and 2035, without the major expansion of coal CCS generation seen in LC Core and LC Acctech, the LC Acctech (no CCS) scenario involves expanded contributions from nuclear power, bioelectricity and marine energy. In the long term, after 2035, wind power undergoes major expansion and solar PV is introduced more significantly.

In the delayed CCS scenario, nuclear capacity again expands in the 2020s to enable power sector decarbonisation. Once Coal CCS becomes available after 2030 it deploys rapidly, but by 2050 its deployment ceiling is around 30% lower than in the LC Acctech case (19GW compared to 27GW), suggesting that **delayed commercialisation of CCS reduces its long term market share as decarbonisation ambitions increase (so that residual emissions from CCS become significant) and as other low carbon supply technologies, such as solar PV, mature (Figure 9.17, below).**

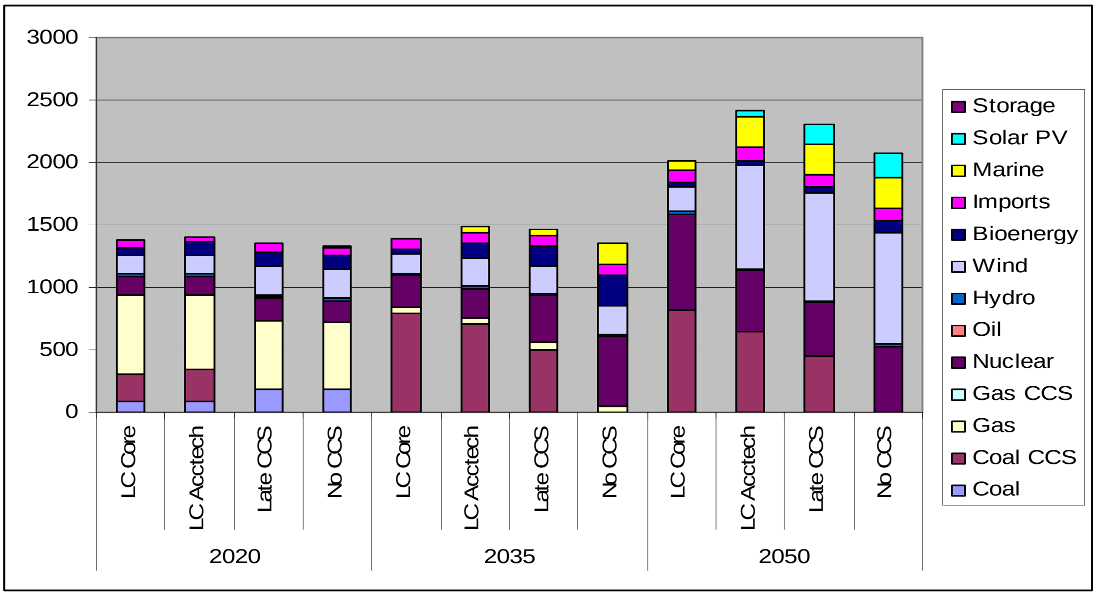


Figure 9.17: Electricity Generation (PJ) in LC Core 80, LC Acctech 80 and LC Acctech 80 (no CCS and delayed CCS)

9.4 Implications and Challenges

The scenarios presented here allow a structured exploration and illustration of the potential of emerging energy supply technologies to contribute substantially to the decarbonisation of the UK energy system over the next forty years. A summary of this potential, in terms of the added contributions from emerging supply technologies seen in the ATD scenarios, is provided in Table 9.2, below.

The implications of this work, for policymakers and other UK energy system stakeholders, need to be considered in the context of emerging policy measures for energy system change in the UK and beyond. The policy and regulatory framework for the UK energy system is now being substantially remade, and ambitious targets are being identified for both decarbonisation and renewables deployment, especially over the next decade to 2020. For example, the UK Climate Change Committee (CCC, 2008) recently suggested that the UK should aim for carbon emission reductions by 2020 (relative to 1990 levels) of at least 34%, and possibly as high as 42%, rather than the 26% reduction achieved in the scenarios discussed here. In the LC Acctech 80 accelerated scenario, 34% carbon reduction is not achieved until the mid-2020s and 42% until around 2030 (Figure 9.5).

	Short Term (2020)		**Medium Term (2035)**		**Long Term (2050)**		**Comments**
	Single 60	**Acctech 80**	**Single 60**	**Acctech 80**	**Single 60**	**Acctech 80**	
Wind Power (GW)	14 (14)	14 (15)	20 (16)	20 (15)	45 (14)	71 (18)	Wind power acceleration has major long term impact (and moderate medium term impact) in single technology and Acctech 80 scenarios.
Marine Energy (GW)	2 (0)	0 (0)	9 (0)	4 (0)	21 (5)	20 (5)	Marine energy acceleration has major long term impact (and moderate medium term impact) in single technology and Acctech 80 scenarios.
Solar PV (GW)	0 (0)	0 (0)	0 (0)	0 (0)	40 (0)	16 (0)	Solar PV acceleration has major long term impact in single technology scenario; moderate impact in aggregated scenarios.
Nuclear Power (GW)	5 (5)	5 (5)	10 (4)	9 (9)	19 (14)	18 (29)	Nuclear power acceleration has moderate medium and long term impact in single technology scenarios; ATD assumptions are relatively modest, so long term deployment reduces in aggregated accelerated scenarios; much greater role if is CCS excluded.
Coal CCS (GW)	8 (6)	10 (8)	39 (37)	27 (30)	39 (37)	27 (31)	Coal CCS has major medium and long term role with or without acceleration. Core scenario assumptions are relatively aggressive, and were left essentially unchanged for ATD scenario.
Fuel Cell Electricity (GW)	2 (0)	2 (0)	6 (0)	2 (0)	4 (0)	2 (0)	Fuel cell power generation has minor role with or without acceleration.
Bioelectricity (GW)	6 (4)	7 (6)	20 (12)	17 (12)	9 (3)	4 (4)	Bioenergy acceleration has major medium and long term impacts. Biomass resources are limited and their preferred uses are sensitive to overall decarbonisation ambition, and the evolving availability of other low carbon supply technologies over time. For example, preferred use of bioenergy resources in 2050: - in LC Acctech 60 (without fuel cells): heat and transport - in LC Acctech 60 (with fuel cells): power - in LC Acctech 80 (without fuel cells): transport - in LC Acctech 80 (with fuel cells): heat and transport
Bioenergy by Final Use (PJ)							
- Residential	*3 (3)*	*3 (3)*	*0 (0)*	*254 (88)*	*380 (80)*	*343 (0)*	
- Services	*9 (9)*	*3 (9)*	*14 (29)*	*5 (29)*	*14 (47)*	*0 (146)*	
- Transport	*67 (67)*	*67 (67)*	*116 (102)*	*175 (305)*	*261 (282)*	*265 (730)*	
- Total Bioenergy in Final Energy	79 (79)	73 (79)	130 (131)	434 (422)	656 (410)	608 (876)	
Hydrogen / Fuel Cells (PJ)	0 (0)	0 (0)	24 (0)	64 (0)	486 (0)	598 (138)	Fuel cells acceleration has a major long term impact on transport sector decarbonisation.

Table 9.2: Summary of ATD Impacts: Single Technology Accelerated Scenarios and Aggregated Accelerated Development Scenarios[68]

---

[68] Figures in brackets refer to non-accelerated equivalent scenarios

In addition, the UK Government is now considering reform of the Renewables Obligation to encourage up to 30-35% of electricity generation to be produced from renewable sources by 2020 (BERR, 2008a), so as to enable the UK to meet its commitments under European Union renewable energy ambitions. In the LC Acctech 80 scenario, the proportion of electricity from renewable technologies is just under 20% in 2020, over 27% in 2025, but does not rise above 30% until after 2035. By 2030, the power sector is essentially decarbonised in 80% scenarios, using a combination of coal CCS, nuclear power and renewables. Further decarbonisation after 2030 is achieved largely by changes to the transport and residential heating sectors.

Achieving these relatively short-term policy targets cannot simply involve bringing forwards, in time, the supply portfolios seen in the Acctech scenarios after 2020. For example, it is not feasible to assume that CCS technology, an important contributor to system decarbonisation in almost all the scenarios presented here, be commercially available at significant scale before 2020; as discussed above and in Chapter 7, a significantly delayed impact from CCS is seen as more credible by some observers. There are also substantial challenges involved in increasing the contribution of nuclear power in the UK by 2020, although a combination of extended lifetimes of existing plant, and a programme of fleet build of new reactors could provide for a more sustained nuclear contribution in the UK energy mix over time (see Chapter 6).

Windpower is a key technology for meeting UK policy ambitions to 2020 in many scenario exercises (e.g. SKM, 2008b). As Chapter 3 discussed, however, there is only modest potential for additional onshore wind capacity in the UK (relative to the size of policy ambition), and while the UK has a vast offshore wind resource, the scenarios presented here portray offshore wind as an emerging technology whose potential is mostly realised after 2030. (Even with CCS excluded, offshore wind is not deployed at levels implied by 2020 renewables policy targets until after 2035 in the LC Acctech 80 scenario). Other renewables technologies – bioenergy, marine and solar PV – are all significant contributors to UK energy system decarbonisation in the scenarios presented here, but most of this potential is only realised over medium or longer timescales (Chapters 3-5).

Although it carries short and medium term implications for system planning and innovation support, **supply-side technology acceleration only changes deployment patterns over medium and longer terms.** This suggests that

shorter term policy ambitions for decarbonisation and low carbon technology deployment over the next decade require responses from other system drivers and opportunities than supply side innovation, such as demand reduction, improved energy efficiency, greater focus on renewable heat, and making best use of currently available technologies by investing in supply chain and installation capacity, and institutional reforms regarding planning, regulatory and permitting procedures.

From this perspective, the ATD scenarios suggest some disparity between the availability, performance and cost of low carbon power supply technologies, and political aspirations for energy system decarbonisation and renewables deployment, especially in the short term to 2020. In particular, the 'learning potential' of emerging low carbon technologies over longer timescales imply that **short term policy targets for technology deployment may not be consistent with the most economically desirable long term decarbonisation pathways**. Indeed, given energy system tendencies to show 'lock-in' and 'path dependencies', short term targets may direct the energy system into less attractive pathways, seen from a longer term perspective.

For example, the major expansion of emerging renewables technologies, including offshore wind, happens some time after 2020 in the ATD scenarios, rather than over the next decade, as is envisaged in some suggested responses to renewables deployment policy ambitions. The scenarios also suggest that the long term contribution of CCS in 80% decarbonisation scenarios may be limited by residual emissions, so that a relatively early mass deployments of less well-developed CCS technology may 'lock' the energy system into residual emissions for a considerable period. Rather, a programme of R&D and early demonstration, so as to improve the cost and performance of high capture rate technology for CCS, may be more appropriate in the longer term.

There is also a danger of inconsistent signals from different policy targets for decarbonisation and renewables deployment. In particular, **maximising renewables deployment in the power sector may not be consistent with the most attractive overall decarbonisation pathways.** For example, the results here suggest that one consequence of raising the overall decarbonisation ambition achieved by 2050 is to *reduce* the optimal proportion of electricity supplied from renewables in the medium term, and focus bioenergy resources on decarbonisation in other parts of the energy system.

At the same time, it is important to recognise the limitations of the present study in terms of policy implications: the UKERC ATD scenarios illustrate preferred (least-cost) means by which the UK energy system is able to meet a prescribed decarbonisation pathway to 2050, assuming high levels of technology progress in a number of emerging low carbon supply technologies. **Clearly, realising other policy aims (not prescribed in the ATD scenarios), such as very high levels of renewables deployment by 2020, will require policy support measures and market interventions that go well beyond those embedded in the ATD modelling assumptions.**

The modelling exercises also make certain simplifying and unrealistic assumptions about the drivers of energy system change, such as 'perfect foresight' about the future cost and performance of supply technologies (and other input factors), and an emphasis on cost and market-based decisionmaking. Clearly, many other political, societal organisational and environmental concerns drive energy system change in practice, so that following the least-cost decarbonisation trajectories presented here may not be seen as preferable, taking account of wider imperatives and interests such as diversity, security and reliability. For example, given the inertia associated with energy systems, and the importance of cumulative emission reductions, ambitious short term targets provide a useful catalyst for system change, even though they raise concerns about lock-in to ultimately less preferred paths from economically or technological perspectives.

Other, more specific, environmental and social concerns may also be identified with the scenarios outlined here. For example, the widespread electrification of energy service provision poses a number of challenges. The scenarios suggest that a great deal of new power system capacity be added between 2035 and 2050, requiring very high rates of plant build, and major changes to systems of power storage, transmission and distribution – going beyond previous build programmes for coal and gas fired generation seen in the UK. This expansion raises issues of environmental impact, locally as well as nationally. Given the need for wider international efforts to decarbonise, it also highlights possible pressures on natural resource availability, manufacturing capacity, and human and financial resources. The vision of a future energy system involving high levels of hydrogen / fuel cells transport technologies, embedded in many of the accelerated development scenarios, also presents major infrastructure challenges over the longer term.

As well as these challenges, however, there are distinct opportunities implied in the accelerated development scenarios, in terms of making short and medium term preparations for the more radical energy system changes suggested over the longer term. As well as the particular research needs associated with accelerated development of the supply side technologies analysed here, these opportunities include the need for parallel support for innovation in system-level enabling technologies and techniques not analysed here, such as new types of power storage, network management, distributed generation and demand side management.

The overall message from the accelerated development scenarios is that energy system decarbonisation involves a complex interaction between changing patterns of production and consumption, and within this, supply side technological innovation can play a key role over the longer term. As energy policy shifts increasingly from target setting to delivery mechanisms, there is a need to systematically analyse different opportunities for decarbonisation across the energy system, to anticipate, as far as possible, how these are likely to change over time, and identify the research needs associated with different decarbonisation pathways.

Accelerating the development of emerging low carbon energy supply technologies offers significant long term benefit, in enabling alternative and potentially more affordable decarbonisation of the UK energy system. It may well also offer wider benefits in terms of diversity, security and sustainability. Realising this potential will require the UK to participate fully in global efforts at low carbon technology innovation; this investment promises significant reward in the longer term.

There are many uncertainties involved here, and no simple messages in terms of 'picking winners' – almost all the technologies analysed here – and many others not included here – have a significant potential role in UK energy system decarbonisation. Rather than a premature selection of winners and losers, the need is for sustained international support of a broad range of emerging low carbon technologies, with the UK playing a committed role as a developer and deployer in the wider international context.

References

Allinson, W. Guy, Ho, Minh T., Neal, Peter R., Wiley, Dianne E. (2006) "The methodology used for estimating the costs of CCS", Presented at *the Eighth International Conference on Greenhouse Gas Control Technologies*, Trondheim, Norway. 19-22 June.

Anandarajah, G. N. Strachan, P. Ekins, R. Kannan, N. Hughes (2008) *Pathways to a Low Carbon Economy: Energy Systems Modelling.* UK Energy Research Centre, London.

BERR (2008a) *UK Renewable Energy Strategy Consultation*, UK Department for Business, Enterprise & Regulatory Reform, London.

BERR (2008b) *Meeting the Energy Challenge: A White Paper on Nuclear Power*. UK Department for Business, Enterprise & Regulatory Reform. London.

BERR (2008c) *Historical electricity data: 1920 to 2007*, http://www.berr.gov.uk/whatwedo/energy/statistics/publications/trends/index.html

BERR (2008d) *UK Energy In Brief. http://www.berr.gov.uk/files/file46983.pdf*

BERR (2008e) *Digest of UK Energy Statistics: Long Term Trends*. UK Department for Business, Enterprise & Regulatory Reform. London

Brabec, C., Dyakonov, V., Scherf, U. (2008) *Organic Photovoltaics: Materials, Device Physics, and Manufacturing Technologies*. Wiley-VCH, Weinheim.

BWEA (2006) BWEA and npower Juice, *The Path to Power: Delivering confidence in Britain's wave and tidal stream industry*. London, British Wind Energy Association.

Carbon Trust (2006) *Future Marine Energy: Results of the Marine Energy Challenge: Cost competitiveness and growth of wave and tidal stream energy.* London, Carbon Trust.

Carbon Trust (2008a) *Offshore Wind Power: Big Challenge, Big Opportunity*. Carbon Trust, London.

Carbon Trust (2008b) *Policy frameworks for renewables - Analysis on policy frameworks to drive future investment in near and long-term renewable power in the UK*, London, 40 pp

CCC (Committee on Climate Change) (2008) Building a low-carbon economy - the UK's contribution to tackling climate change. TSO, London.

CEC (Commission of the European Communities (2007) *A European Strategic Energy Technology Plan (SET-Plan): Technology Map*. Commission of the European Communities, Brussels.

CEC (Commission of the European Communities) (2008) *Proposal for a Directive of the European Parliament and of the Council on the promotion of the use of energy from renewable sources*. Com (2008) 19 Final. Commission of the European Communities, Brussels.

Cramer, G. (2008) “Power Network Integration – Challenges and Solutions”, Presented at the 5th European PV Industry Forum, September 3rd 2008, Valencia.

DEFRA (2007). *UK Biomass Strategy*. London, DEFRA.

DCLG (2007), *Building a Greener Future: policy statement*, UK Department for Communities and Local Government, London, 2007.

DOE (2002) *A Technology Roadmap for Generation IV Nuclear Energy Systems*. US DOE Nuclear Energy Research Advisory Committee and the Generation IV International Forum.

DTI (2005) *A Strategy For Developing Carbon Abatement Technologies For Fossil Fuel Use*. Department for Trade and Industry, London.

DTI (2007) Meeting the Energy Challenge: A White Paper on Energy. Department for Trade and Industry, London.

Enviros (2005) *The Cost of Supplying Renewable Energy.* Enviros Consulting / DTI, London.

EU (2007) “PV Technology Platform, A strategic research agenda for photovoltaic solar energy technology”. Prepared by Working Group 3 "Science, technology and Applications" of the EU PV Technology Platform ,2007.

Gibbins, J. and Chalmers, H. (2008) *Preparing for global roll-out: A ‘developed country first’ demonstration programme for rapid CCS deployment*. *Energy Policy*, 36:501-507.

Gross, R., P. Heptonstall and W. Blyth (2007). *Investment in electricity generation: the role of costs, incentives and risks*. UK Energy Research Centre, London.

Centre. GWEC (2005) *Wind Force 12: a blueprint to achieve 12% of the world’s electricity from wind power by 2020*. Global Wind Energy Council. http://www.ewea.org/fileadmin/ewea_documents/documents/publications/WF12/wf12-2005.pdf

Halliday, J. and Ruddell, A. (2008) *UKERC Energy Research Atlas: Wind energy*. http://ukerc.rl.ac.uk/ERL001.html

Haszeldine, S, Wilkinson, M and Markusson, N. (2008) *UKERC Energy Research Atlas: Carbon capture and storage*, http://ukerc.rl.ac.uk/ERL001.html

Hansson, A. (2008) Kolets återkomst: Koldioxidavskiljning och lagring i vetenskap och politik, Linköping University, Sweden.

HFP (European Hydrogen & Fuel Cell Technology Platform) (2005). *Deployment Strategy* https://www.hfpeurope.org/hfp/keydocs

HFP (European Hydrogen & Fuel Cell Technology Platform) (2007) *Implementation plan Status 2006* https://www.hfpeurope.org/hfp/keydocs

HM Treasury (2008) *Intergenerational wealth transfers and social discounting: Supplementary Green Book guidance* HM Treasury, London.

HyWays (2007) *HyWays Action Plan, Policy Measures for the Introduction of Hydrogen Energy in Europe* http://www.hyways.de

HyWays (2008) *HyWays Roadmap - The European Hydrogen Energy Roadmap* http://www.hyways.de

IEA (International Energy Agency) (2005) Prospects *for hydrogen and fuel cells*. Paris, IEA.

IEA (2008a) *Energy Technology Perspectives: Scenarios and Strategies to 2050*. Paris, IEA.

IEA (2008b) *Deploying Renewables: Principles for Effective Policies*. Paris, IEA.

IEA (2008c) *World Energy Outlook 2008*. International Energy Agency, Paris, IEA.

Infield, D. (2007) *A roadmap for photovoltaics research in the UK*. UKERC Research Report. August 2007. http://ukerc.rl.ac.uk/Roadmaps/Solar/A_Road_Map_for_Photovoltaics_Research_in_the_UK.pdf

Innovation Norway and Gassnova (2008) International CCS (Carbon Capture and Storage technology survey). http://www.climit.no/wsp/gassnova/frontend.cgi?func=publish.show&func_id=1516& table=CONTENT

IPCC (2005) *IPCC Special Report on Carbon Dioxide Capture and Storage*. Prepared by Working Group III of the Intergovernmental Panel on Climate Change [Metz, B., O. Davidson, H. C. de Coninck, M. Loos, and L. A. Meyer (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 442 pp

IPCC (Intergovernmental Panel on Climate Change) (2007). *The Fourth Assessment Report: Climate Change 2007. IPCC, Geneva.*

Jablonski, S, C Brand, A Pantaleo, A Bauen and N Strachan (2007). *Review of bioenergy in the UK Markal Energy System Model.* ICEPT Working paper.

Jeffrey H. (2008) *An Overview of the issues associated with the future costing of marine energy and the application of learning rate theory*, ICOE, Brest 2008.

Kazmerski, L.L., Solar photovoltaics R&D at the tipping point: A 2005 technology overview. *Journal of Electron Spectroscopy and Related Phenomena*, 2006. 150(2-3): p. 105-135

Lane, B. (2002) *Implementation Strategies for Fuel-cell powered Road Transport Systems in UK*, unpublished PhD Thesis (and references within), Open University, Milton Keynes.

Maisonnier, D., I. Cook et al. (2006) *DEMO and fusion power plant conceptual studies in Europe*, Fusion Engineering and Design, 81, 1123–1130.

MacKerron, G. (2004) *Nuclear power and the characteristics of 'ordinariness' – the case of UK energy policy*. Energy Policy 32(17), 1957-1965.

McKinsey & Company, McKinsey Climate Change Special Initiative (2008) *Carbon Capture & Storage: Assessing the Economics*,

Miles, R.W., K.M. Hynes, and I. Forbes, Photovoltaic solar cells: An overview of state-of-the-art cell development and environmental issues. *Progress in Crystal Growth and Characterization of Materials*, 2005. 51(1-3): p. 1-42.

NREL (2008) *Opportunities and challenges for development of a mature concentrating photovoltaic power industry*, US National Renewable Energy Laboratory (NREL) Technical Report, September 2008. Golden, CO.

Panoutsou C, S. Alberici, S. Jablonski, M. Pepinster, R. Slade, A. Bauen and P. Pearson (2008) Power Point Presentation "Defining the key cost areas in a supply chain analysis: The case of woodfuel supply chains in the UK". http://www.biomassenergycentre.org.uk/pls/portal/docs/PAGE/BEC_RESOURCES/EVENTS/IEA%20TASK%2031%20CONFERENCE/PRESENTATIONS/CALLIOPE%20PANOUTSOU.PDF

Pöyry (2008) *Compliance Costs for Meeting the 20% Renewable Energy Target in 2020*, Pöyry Consulting, Oxford.

RAB (2008) *2020 Vision – How the UK can meet its target of 15% renewable energy*, Renewables Advisory Board, London

Renewable Fuels Agency (2008). *The Gallagher Review of the indirect effects of biofuels production*. St Leonards-on-Sea, Renewable Fuels Agency.

Reuters (2008) EU Lawmakers watch credit crisis in climate fight. October 2008. www.reuters.com/article/rbssIndustryMaterialsUtilitiesNews/idUSL711408420081007?sp=true

Richards, K. (2004) *A Brief Overview of Carbon Sequestration Economics and Policy*, Environmental Management 33(4):545-558.

Scottish Centre for Carbon Storage, School of Geosciences, University of Edinburgh (2008) CCS Map http://www.geos.ed.ac.uk/ccsmap

Scottish Government (2008) *Renewables Obligation (Scotland): Introduction Of* Banding, Statutory Consultation, September 2008.

SKM (2008a) *Quantification of Constraints on the Growth of UK Renewable Generating Capacity*. SKM / AEA, Newcastle.

SKM (2008b) *Growth Scenarios for UK Renewables Generation and Implications for Future Developments and Operation of Electricity Networks*, SKM Newcastle.

Stern N. (2006) Stern Review on The Economics of Climate Change, HM Treasury, London.

Strachan, N., S. Pye and R. Kannan (2009). The iterative contribution and relevance of modelling to UK energy policy. *Energy Policy* 37(3): 850-860.

UKAEA (2005) *Accelerated development of Fusion Power*, UKAEA FUS 521, Available from: http://fusion.org.uk/techdocs/

UKERC / EDC (2008). *Global Wind Energy Capacity*.

http://data.ukedc.rl.ac.uk/cgi-bin/dataset_catalogue/view.cgi.py?id=11

UKERC (2008a) *UKERC Marine (Wave and Tidal Current) Renewable Energy Technology Roadmap: Summary Report*. UKERC, Edinburgh.

UKERC (2008b). *UKERC Research Atlas: Bioenergy for Heat, Power and Liquid transportation fuels*. http://ukerc.rl.ac.uk/Landscapes/Bioenergy.pdf

UNEP (United Nations Environment Programme) (2008) Global Trends in Sustainable Energy Investment 2008. http://sefi.unep.org/english/globaltrends.html

UK Government (2008a) *Climate Change Act 2008 (Chapter 27)* TSO, London.

UK Government (2008b) *Energy Act 2008 (Chapter 32)* TSO, London.

Worrall A. and R. Gregg (2007) *Scenario Analyses of Future UK Fuel Cycle Options*. Journal of Nuclear Science and Technology, Vol. 44, No. 3, p. 249–256.

Winskel, M. (2007) *Renewable Energy Innovation: Collaborative Learning and Intellectual Property*. International Journal of Global Energy Issues, Vol. 27, No. 4, 472-491.