THE UK ENERGY RESEARCH CENTRE

The UK Energy Research Centre is the focal point for UK research on sustainable energy. It takes a whole systems approach to energy research, drawing on engineering, economics and the physical, environmental and social sciences.

The Centre's role is to promote cohesion within the overall UK energy research effort. It acts as a bridge between the UK energy research community and the wider world, including business, policymakers and the international energy research community and is the centrepiece of the Research Councils' Energy Programme.

The partner institutions in UKERC are: Cardiff University, Centre for Ecology and Hydrology, University of Edinburgh, University of Exeter, Imperial College London, King's College London, University of Manchester, University of Oxford, Policy Studies Institute, Rutherford Appleton Laboratory

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THE UKERC ENERGY 2050 PROJECT

Since 2006, researchers at UKERC have been working together on an ambitious project assessing how the UK can move to a resilient ('secure') and low-carbon energy system over the period to 2050. This report synthesises the project findings. A more extended account of the project will be published in book form in early 2010.

The Energy 2050 project brought together a wide range of researchers coming from several disciplines to address a common problem, exploring all dimensions of the possible development of the UK energy system through to 2050. A common set of scenarios was used, making it possible to relate the different elements of the project to each other. While the project relied heavily on scenarios and modelling, it also placed great emphasis on the underlying policy and research questions and the conclusions and implications for action. This report focuses on these aspects of the work, in order to make it more relevant to policy makers and a wider readership. Technical detail is kept to a minimum but is available in the full Research Reports that were produced by the various work streams of the project. These are being made available on the UKERC website.

ACKNOWLEDGEMENTS

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Executive Summary

This report takes a whole systems approach to the development of the UK energy system over the next 40 years

Understanding the energy system and its relationship with society, the economy and the environment is a complex multi-faceted challenge. The UK Energy Research Centre (UKERC) has been charged by the Research Councils with taking a 'whole systems' approach to the development of UK energy. This means thinking about all the dimensions of change and drawing on a range of disciplines and expertise. We bring together a unique team of engineers, natural, environmental and social scientists, and economists all of whom have worked on this report.

Achieving a resilient low-carbon energy system is technically and economically feasible at an affordable cost

Extensive modelling and analysis of the UK energy system through to 2050 shows that the UK's target of reducing CO_2 emissions by 80% below 1990 levels by 2050 is achievable and that the aggregate costs are small in relation to GDP. By 2050, the electricity system must be effectively de-carbonised whatever pathway is followed. Nuclear, renewables and fossil fuels with carbon capture and storage (CCS) are all likely to have an important role to play. Reducing demand in the residential sector and, later, in the transport sector will also be required. Early action and a readiness to invest in infrastructure and more capital intensive solutions could lead to lower costs in the long-term. A resilient energy system which provides adequate energy security is also achievable and can be realised on a much faster timescale.

There are multiple potential pathways to a low-carbon economy. A key trade-off across the energy system is the speed of reduction in energy demand versus decarbonisation of energy supply. There is also a number of more specific trade-offs and uncertainties, such as the degree to which biomass, as opposed to electricity and perhaps hydrogen, is used in transport and other sectors.

Although electricity decarbonisation is essential in the long term in all scenarios, there are choices to be made about the balance to be struck between it and the more aggressive pursuit of energy efficiency and demand reduction. If supply side decarbonisation is emphasised, electricity will be substantially decarbonised by 2030. However, under a scenario where energy demand is reduced more quickly, electricity sector decarbonisation could take place around a decade later. Given the many uncertainties and risks involved, there are strong arguments for pursuing both demand and supply side solutions in parallel: should there be any delay in commercialising key technologies such as CCS, demand side measures may be necessary to keep us on the path to an 80% emissions reduction. Bioenergy provides additional flexibility: it could play a variety of roles in the power, heat and transport sectors depending on how sustainably it can be developed, and how quickly alternatives such as electric or perhaps hydrogen fuel cell vehicles come to the market.

Deploying new and improved technologies on the supply side will require substantially increased commitment to RD&D, the strengthening of financial incentives and the dismantling of regulatory and market barriers. A major increase in efforts to accelerate the development of emerging low-carbon energy supply technologies promises significant reward, in terms of more affordable decarbonisation pathways, in the long term.

Investing in research, development and demonstration (RD&D) could substantially reduce the cost of meeting long-term CO_2 targets. The pay-off from such an investment has grown considerably since the UK moved from a 60% to an 80% CO_2 reduction target, with much greater potential contribution from advanced low-carbon supply technologies. There is a case for a substantial expansion of expenditure on energy R&D but careful thought needs to be given to the relative contributions of the public and private sectors, the balance between early-stage R&D and later-stage demonstration and deployment, and the UK's role in wider EU and global efforts. The deployment of new and improved technologies needs to be encouraged by a reliable carbon price. In most scenarios an 80% carbon reduction is achieved with a market signal of less than £200/tonne CO_2 by 2050, but this is increased to £300-350/tonne CO_2 by delayed action or a more stringent carbon target. In the shorter-term, barriers to the deployment of renewable energy include the planning regime and market rules in the electricity sector. The aggressive pursuit of energy efficiency may need the development of new policy delivery and business models.

Increasing the uptake of existing and cost-effective energy efficiency and conservation technologies will reduce the welfare costs associated with demand reduction.

Reducing energy demand plays a key role in any secure, low-carbon future. It contributes to CO_2 reduction, reduces import dependence and exposure to volatile global energy markets, and reduces other environmental pressures. If demand reduction takes place simply as a response to higher prices, the welfare costs could be high in sectors where there are many barriers to action. The residential sector is a notable example. Policy needs to find a way of increasing the uptake of energy efficiency through increased awareness and environmental commitment, and a shift in lifestyles and social values.

A resilient energy system needs a range of measures, but reducing energy demand is key. This will reduce our exposure to energy price shocks and could help us to ride out major disruptions to infrastructure.

Building a resilient energy system requires action to reduce energy demand, promote diversity of supply and ensure that market and regulatory arrangements encourage adequate investment in capacity and infrastructure. The case for energy efficiency is clear. Our work has shown that a smaller energy supply system is better able to ride out the loss of critical infrastructure. There needs to be an informed debate about investment in infrastructure, particularly in the gas network, and whether strategic investment, for example in storage, is needed to supplement market investments.

Changes will be needed to market design and regulation to facilitate the move to a resilient low-carbon energy system

Changes to current market and regulatory arrangements are needed to ensure that the significant expansion of renewable energy does not reduce the reliability of the electricity system. The UK's target of 15% renewable energy by 2020 under a new EU Directive implies a huge expansion in the renewable heat, transport and electricity sectors. A renewable share of at least 30% will be required in the electricity sector if the target is to be met. Changes to regulatory arrangements are needed to ensure a more strategic approach to grid connection which obviates delays and does not allow the securing of planning permission to become an obstacle. It is not clear that current market arrangements give sufficient incentives for capacity to back-up intermittent renewable generation. A range of options needs to be considered.

Lifestyle changes that reduce energy demand would enhance energy system resilience and reduce the costs of CO_2 reduction. Further work is needed to assess how such changes might be induced and the role that policy could play.

There is little existing evidence of how to bring about comprehensive changes in people's lifestyle and behaviour that will lead to reduced energy demand and CO_2 emissions. We explored a scenario in which people were more prepared to invest in energy efficiency measures, were prepared to change their approach to thermal comfort levels in the home, and were willing to travel less while using less energy-intensive travel modes. The scenarios foresaw energy demand falling by roughly half by 2050 in both the residential and transport sectors. Research is needed to understand the conditions under which people would voluntarily take on lifestyles embodying these types of behaviour.

If public concern about specific technologies prevents their deployment, the cost of meeting CO_2 targets will significantly increase, and a greater burden will be imposed on demand side responses.

We explore a number of scenarios in which the development of certain types of technologies and fuels was constrained by public concerns about their development. The scenarios reflected different attitudes and values towards the natural environment. All the scenarios pushed up the cost of reaching CO_2 targets and resulted in greater emphasis on demand side measures. The more low-carbon options are constrained by such concerns, the more difficult it will be to meet CO_2 reduction targets, or conversely the greater the chance that they will not be met.

Reducing CO_2 will broadly lead to improvements in other environmental areas, but regulatory attention may be needed in some areas (air quality, water stress) where there are potentially adverse effects.

The way the energy system develops will have direct environmental impacts other than those resulting from climate change. Broadly speaking, measures to reduce CO_2 emissions will bring down emissions of pollutants such as sulphur dioxide, though some pollutant levels, e.g. carbon monoxide, will be unchanged. Radioactive releases could go up slightly under a low-carbon scenario. It is very clear that emphasising energy demand reduction as part of an overall energy strategy will bring the biggest environmental benefits. Emissions of many pollutants – e.g. sulphur, particulates, nitrous oxide and carbon monoxide – will be half of what they otherwise would be by 2050 if energy efficiency is emphasised.

List of Acronyms

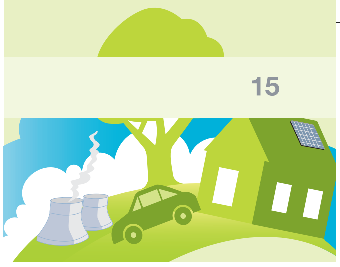
ATD	accelerated technology development
bcm	billion cubic metres
BERR	Department for Business, Enterprise and Regulatory Reform
BETTA	British Electricity Transmission and Trading Arrangements
BEV	Battery Electric Vehicles
BIEE	British Institute of Energy Economics
BWEA	British Wind Energy Association
CCC	Committee on Climate Change
CCGT	combined cycle gas turbine
CCS	carbon capture and storage
CDM	Clean Development Mechanism
CEC	Commission of the European Communities
CEGB	Central Electricity Generating Board
CERT	Carbon Emission Reduction Target
CFL	compact fluorescent lamp
CGEN	Combined Gas and Electricity Networks (as in CGEN model)
CH_4	methane
CHP	combined heat and power
CLG	Communities and Local Government
CO	carbon monoxide
CO_2	carbon dioxide
CRC	Carbon Reduction Commitment
CSA	Chief Scientific Adviser
DECC	Department of Energy and Climate Change
DEFRA	Department for Environment Food and Rural Affairs
DfT	Department for Transport
DIUS	Department for Innovation, Universities and Skills
DNO	District Network Operator
DTI	Department of Trade and Industry
DUKES	Digest of UK Energy Statistics
EEC	Energy Efficiency Commitment
ENA	Energy Networks Association
ESD	energy service demand

EST	Energy Saving Trust
ETI	Energy Technologies Institute
ETSAP	Energy Technology and Systems Analysis Program
EU ETS	EU Emissions Trading Scheme
EU	European Union
EUA	EU allowance unit
EWP	Energy White Paper
FGD	flue gas desulphurisation
GDP	gross domestic product
GHG	greenhouse gas
GW	gigawatts
GWh	gigawatt hour
HEV	hybrid electric vehicle
HFC	hydrogen fuel cell
HGV	heavy goods vehicle
HPR	heat to power ratio
IAEA	International Atomic Energy Authority
ICT	information and communication technology
IEA	International Energy Agency
LCBP	Low-carbon Buildings Programme
LED	light emitting diode
LGV	light goods vehicle
LNG	liquefied natural gas
LOLE	loss-of-load expectation
LOLP	loss-of-load probability
MARKAL	MARKet Allocation (as in MARKAL model)
mcm	million cubic metres
MEA	Millennium Ecosystem Assessment
MW	megawatts
MWh	megawatt hours
N_2O	nitrous oxide
NO_X	nitrogen oxides
OFGEM	Office of the Gas and Electricity Markets

PEM	polymer electrolyte membrane (fuel cell)
PHEV	plug-in hybrid electric vehicle
PJ	petajoules
PM	particulate matter
PSA	Public Service Agreement
PTE	Passenger Transport Executive
PV	photovoltaics
RCEP	Royal Commission on Environmental Pollution
	Research Councils' Energy Programme
RD&D	research, development and demonstration
REC	Regional Electricity Company
RO	Renewables Obligation
ROC	Renewables Obligation Certificate
RTFO	Renewable Transport Fuel Obligation
SAP	Standard Assessment Procedure
SMMT	Society of Motor Manufacturers and Traders
SO_2	sulphur dioxide
TNO	Transmission Network Operator
TRL	technology readiness level
TSB	Technology Strategy Board
TWh	terawatt hour
UKDCM	UK Domestic Carbon Model
UKERC	UK Energy Research Centre
UKTCM	UK Transport Carbon Model
UNEP	UN Environment Programme
UNFCCC	UN Framework Convention on Climate Change
VAT	Value Added Tax
VOLL	value of lost load
WASP	Wien Automatic System Planning (as in WASP model)

Summary of UKERC Energy 2050 Scenarios

Scenario	**Scenario name**	**Notes**
CORE SCENARIOS (Chapters 1, 3, 7 and 8)		
REF	Reference	Includes ‘firm and funded’ policies at the time of the 2007 Energy White Paper
LC	Low-carbon	80% CO_2 reduction by 2050 and 26% by 2020 from a 1990 baseline. Known as *CAM* under Carbon Reduction and *LC Core* 80% under Accelerated Technology Development
LC RCEP	Low-carbon	60% CO_2 reduction by 2050. Known as *CLC* under Carbon Reduction and *LC Core* 60% under Accelerated Technology Development
R	Resilient	Reference scenario with constraints on final energy demand and supply diversity
LCR	Low-carbon Resilient	Combines the constraints in LC and R
CARBON REDUCTION (Chapters 2 and 8)		
CFH	Faint-heart	40% CO_2 reduction by 2050
CLC	Low-carbon	Equivalent to the *LC Core Scenario* (60% reduction)
CAM	Low-carbon	Equivalent to the *LC Core Scenario* (80% reduction)
CSAM	Super ambition	90% CO_2 reduction by 2050
CEA	Early action	80% CO_2 reduction by 2050, 32% by 2020
CCP	Least-cost path	Optimised carbon pathway using the 2010-2050 budget from *CEA*
CCSP	Socially optimal least-cost path	Optimised carbon pathway using the 2010-2050 budget from *CEA* and a social discount rate
ACCELERATED TECHNOLOGY DEVELOPMENT (Chapters 4 and 8)		
LC Core 60%	LC Core 60%	Equivalent to the LC RCEP Core Scenario (60% CO_2 reduction)
LC Core 80%	LC Core 80%	Equivalent to the LC Core Scenario (80% CO_2 reduction)
LC Renew	LC Renew	All four renewable technologies accelerated (60 and 80% variants)
LC Acctech	LC Acctech	All seven technologies accelerated (60 and 80% variants)
ATD XXX	ATD XXX	Several scenarios assuming acceleration of a single technology and a 60% CO_2 reduction. XXX can stand for nuclear, wind etc.
ENVIRONMENTAL SENSITIVITIES (Chapter 5 and 8)		
LC	Low-carbon	Core scenario with 80% CO_2 reduction
DREAD	DREAD	LC with unfamiliar technologies constrained
ECO	ECO	LC with technologies that impinge on ecosystem services constrained
NIMBY	NIMBY	LC with technologies with high local impact constrained
ENERGY LIFESTYLES (Chapter 6 and 8)		
REF	Reference	Core scenario REF
LC	Low-carbon	Core scenario LC (80% CO_2 reduction)
LS REF	Reference lifestyle	REF core scenario with lifestyle change
LS LC	Low-carbon lifestyle	LC core scenario with lifestyle change



1. Introduction

Key Messages

- The UK has a mature energy economy. Primary energy demand has not risen significantly in the last few decades and has started to decline. Within this, there have been major structural changes to energy use, with a halving of industrial energy demand and a doubling of transport energy demand since 1970
- The UK is not on course to meet its ambitious CO_2 reduction targets and is becoming increasingly reliant on imported energy
- The strategic dimensions of energy policy – climate change and energy security - have come to the fore and there is a re-appraisal under way of the respective roles of the state and the market
- Current market and regulatory arrangements sit uneasily with the transformational change required to achieve our strategic goals
- 'Energy system resilience' is a complex concept and we propose a definition and a basket of indicators to help capture it
- Future policies will need to take into account a range of issues: the timing and pathways for CO_2 reductions; the selection of measures that build in resilience; support for R&D and innovation; opportunities for behaviour and lifestyle change; the impact of our choices on environmental systems and ecosystem services; and the impact of early action on later action, in terms of 'path dependencies'

Overview

This report examines how the UK energy system could evolve through to 2050 while addressing the primary energy policy goals – radical reductions in carbon dioxide (CO_2) emissions from energy use, and the resilient provision of affordable energy services (such as heat, light, power and mobility). The shape of the UK energy system is not predestined. It will be determined both by the choices we make over the coming decades and by developments over which we have weak, or even no, control. We have the capacity to plan, at least partially, our future, but we also need to anticipate contingencies which we can foresee perhaps only dimly.

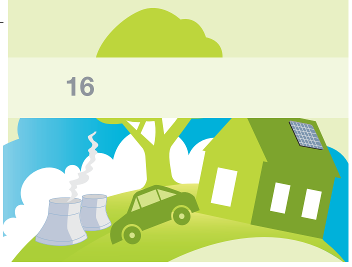
We do not therefore consider a single future for the UK energy system. This report explores systematically the uncertain future against which we need to plan, the choices we need to make and the trade-offs we need to consider.

The uncertainties include:

- The evolution of global markets for energy and carbon
- Political developments at the global level which affect energy prices and availability
- The degree to which new and improved technologies, which may depend on R&D investments made elsewhere, can contribute to the UK energy system

The key questions about choices include:

- How do we prioritise climate change goals vis-à-vis improving the resilience of the UK energy system?



- How much should the UK invest in energy innovation?
- Are we prepared to make lifestyle changes that will help us to reach our energy policy goals? How much can these contribute?
- Are there energy supply options which we, as a society, are not prepared to accept because we consider the environmental impacts to be unacceptable?
- How much are we prepared to invest to protect ourselves against improbable events that could have devastating impacts?
- Will we rely on markets to deliver our policy goals or is a more directed approach needed?

What do we Mean by an ‘Energy System’?

The UK Energy Research Centre (UKERC) is charged with taking a whole systems approach to energy. Our approach brings together many perspectives and is truly interdisciplinary. Our working definition of the energy system is correspondingly all-encompassing:

> *“the set of technologies, physical infrastructure, institutions, policies and practices located in and associated with the UK which enable energy services to be delivered to UK consumers”.*

All of these dimensions are explored in this report.

An energy system that addresses the needs and challenges of today cannot be built from scratch. The current UK energy system has been created in response to the energy resources available to us and the evolution of global markets. It reflects decades of investment in physical infrastructure and the creation of institutional arrangements that reflect political and economic priorities of the recent past. Though some physical infrastructure (e.g. houses, major electricity generation plants) will still be with us in 40 years time, it is possible to imagine a radically altered energy system in 2050. But in the short to medium-term, the scope for action and our ability to make rapid progress towards long-term goals is very much determined by the structures that we have inherited and our willingness to change them.

In this chapter we take stock of the UK energy system, starting with energy markets and moving on to institutional arrangements. From this analysis the rationale for current priorities for the UK’s energy strategy become apparent.

UK Energy Markets

The UK exhibits all the characteristics of a mature, almost post-industrial economy. Primary energy demand (Figure 1.1) peaked in 2001 and is still only 10% higher than it was in 1970 (BERR, 2008a, see Box 1.1. for an explanation of the energy units used in this report). Over the same period, gross domestic product (GDP) grew by 150%: it took only half as much energy to produce a unit of GDP in 2007 as it did in 1970.

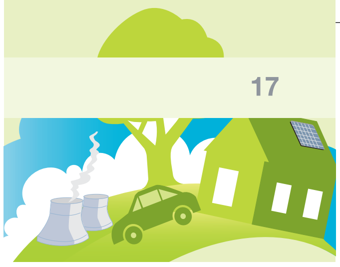
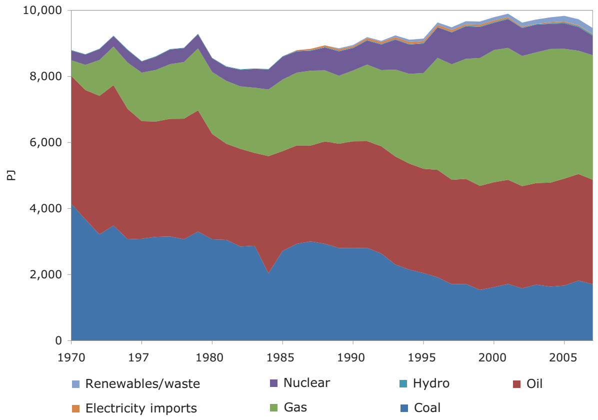


Figure 1.1 also shows that the energy mix has changed significantly. In 1970, coal and oil dominated the picture, while today natural gas has the largest market share and non-fossil energy sources (nuclear and renewables) are playing an increasingly important role. Coal use has fallen by about 60% with most of the coal-gas shift taking place during the 1990s.

This is explained by the rapid emergence of natural gas as the fuel of choice for electricity generation (Figure 1.2). The 'dash for gas' followed the privatisation of the electricity sector in 1990. At the same time, nuclear output has started to fall as older stations have started to close without being replaced. Wind, other renewables (mainly biomass) and waste have started to play a larger role. However, renewables still account for only 4.9% of electricity generation and 1.8% of inland energy consumption overall.

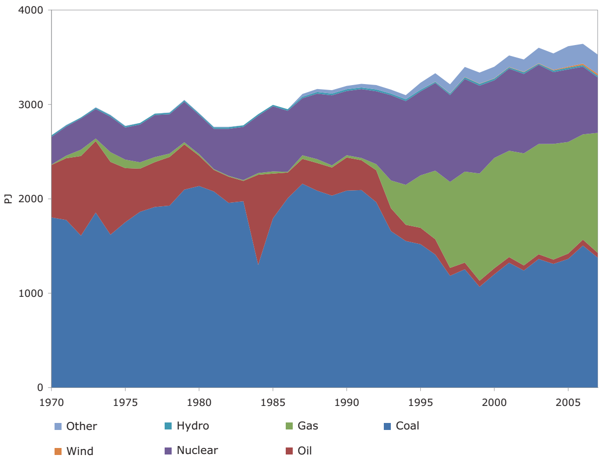
Final energy demand (ignoring energy transformed in power stations and refineries) has also grown little (Figure 1.3)

Figure 1.1: Primary energy demand by source



Source: BERR, 2008a

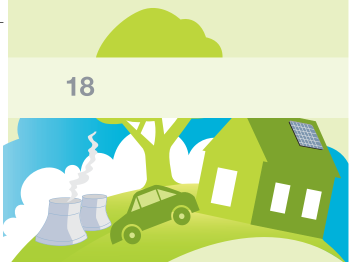
Figure 1.2: Electricity fuel mix



Source: BERR, 2008a

Box 1.1: Energy units used in this report

- The main unit used is the petajoule (PJ). Energy is often expressed in terms of tonnes of oil equivalent. One million tonnes of oil is equivalent to 41.868 PJ. As in the Digest of UK Energy Statistics (BERR, 2008a) we use the gross (higher) calorific value of fuels.
- 1 PJ = 1,000 TJ = 1,000,000 GJ = 1,000,000,000 MJ
- Electricity trading is generally conducted in terms of megawatt hours (MWh). In sections of the report referring only to electricity, we may use MWh or similar units. One MWh equals 3,6000 MJ
- 1 TWh = 1,000 GWh = 1,000,000 MWh
- Gas trading is generally conducted in terms of cubic metres (cm). In sections of the report referring only to gas, we may use million cubic metres (mcm) or similar units.
- 1 billion cubic metres (bcm) = 39.4 PJ

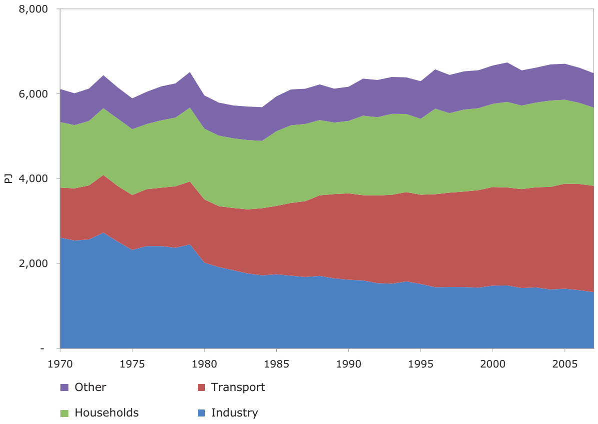


and is only 6% higher than in 1970. The key feature has been the reduction of industrial energy demand (now about half its 1970 level) coupled with the doubling of transport energy demand. Household energy use is about 20% higher than in 1970 while consumption by ’other users‵ (mainly the service and public sectors) is much the same. In terms of energy sources (Figure 1.4), coal’s contribution to final energy demand has virtually disappeared. Oil use fell back by about 15-20% of its peak level during the 1980s but has since recovered to its 1970 level as the result of growing transport demand. Gas use grew rapidly in the 1970s and early 1980s, making progress in all sectors other than transport. Its use peaked in 2001 though consumption is still 150% higher than in 1970. The final striking feature of final energy demand is the growth in the electricity share. It accounted for only 11% of final energy demand in 1970 but now has a 19% market share. This reflects the growth of markets such as IT and communications technology where there is no substitute for electricity.

Since the Kyoto Protocol was signed in 1997 the reduction of greenhouse gas (GHG) emissions has become a key priority for UK energy policy. CO_2 accounts for 85% of the UK’s GHG emissions (DECC, 2009) almost all of which arises from energy production, transformation and use. Total GHG emissions have fallen steadily since 1990 (Figure 1.5) and the UK will meet its Kyoto commitment to reduce emissions by 12% compared to 1990 in the period 2008-2012 by a considerable margin. Non-CO_2 gases have contributed disproportionately to this reduction, with reductions in methane and nitrous oxide. Progress in reducing CO_2 emissions has stopped from the late 1990s onwards. Previous reductions were largely associated with the switch to gas in electricity generation during the 1990s. Emissions have stabilised since that process essentially came to an end. The UK will not meet its domestic target of reducing CO_2 emissions by 20% by 2010 starting from a 1990 baseline.

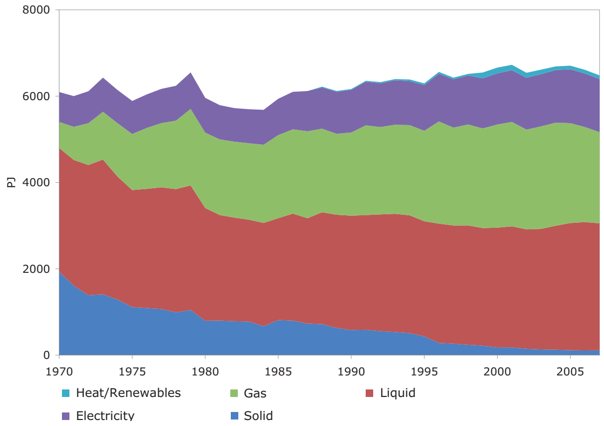
Looking forward, the Climate Change Act 2008 sets a target for an 80% reduction in

Figure 1.3: Final energy demand by sector



Source: BERR, 2008a

Figure 1.4 Final energy demand by fuel



Source: BERR, 2008a

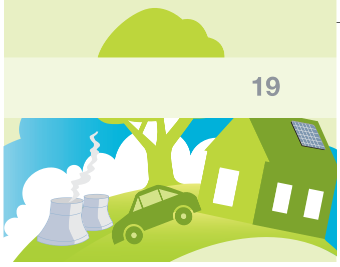
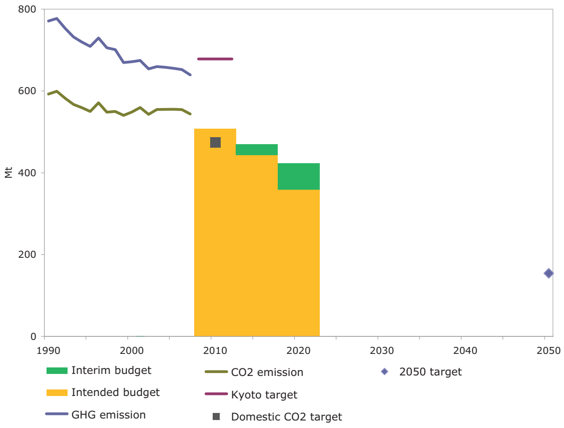


Figure 1.5: Greenhouse gas emissions and targets



Source: Committee on Climate Change (CCC), 2008

GHG emissions in 2050 compared to 1990 levels. In December 2008, the Committee on Climate Change (CCC) (Committee on Climate Change, 2008) recommended three carbon budgets for the periods 2008-12, 2013-17 and 2018-2022. These were proposed in two parts. The more ambitious 'intended' budgets would apply when international agreement on a post-Kyoto climate change regime is agreed. An 'interim' budget would be applied unilaterally pending international agreement. The two sets of budgets, along with the 2050 target, are also shown in Figure 1.5. Meeting either the interim or intended target and budgets will require a major turn-round in the development of the UK energy system. As we will show in this report, incremental change is not an option – a transformation of the energy system is required.

The other significant development in recent years has been the UK's status as a major energy producer. Both oil and gas production from the North Sea peaked in 1999-2000. The UK was never more than self-sufficient in natural gas (Figure 1.6) and a rapid fall in production has translated rapidly into a significant degree of import dependence. In 2007, almost 30% of the UK's supplies were imported and this dependency on imports will grow rapidly. In 2007, 70% of UK gas imports came from Norway, 24% from the Netherlands and 5% - which will also grow rapidly - from liquid natural gas (LNG). The UK sold gas equivalent to 16% of imports on to the Republic of Ireland. The UK can also export through the interconnector to mainland Europe. So far, the UK has been little exposed to the possibility of supply interruptions in Eastern Europe, but this exposure will rise over time.

Figure 1.6: Natural gas demand and production

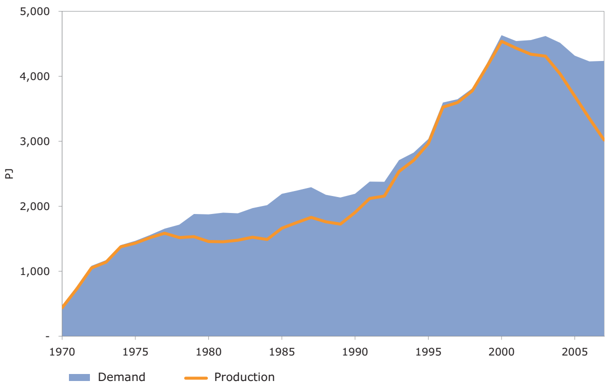


Figure 1.7: Petroleum demand and production

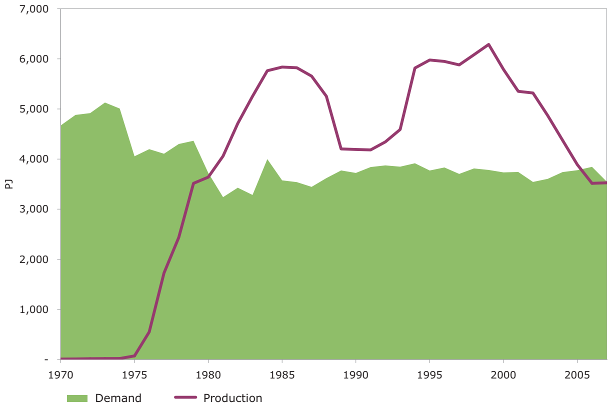
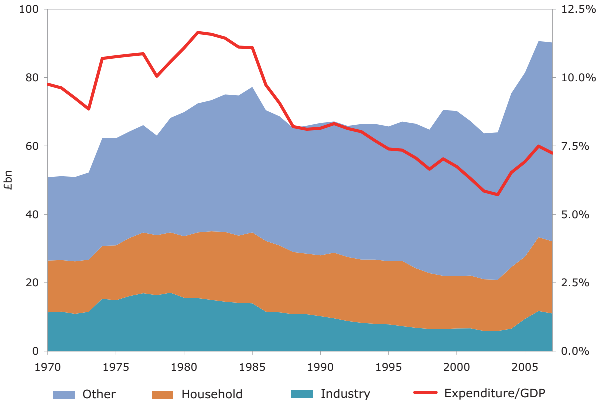


Figure 1.8: Expenditure on energy



Source: BERR, 2008a

The UK had been a net exporter of petroleum since 1980 (Figure 1.7) but, in 2006, production fell below consumption if allowance is made for stocks and international bunker fuels. The UK had been heading towards becoming a net oil importer around 1990 following a period of low oil prices and falling production. However, production rose again in the 1990s and there was a second 'peak' in the UK's production profile in 1999.

The UK imports 75% of its coal requirements, the highest import dependency for all the fossil fuels. However, international coal supplies are diverse and there is little perceived risk of supply interruption.

Expenditure on energy is a key indicator of the UK's exposure to disruptions in international energy markets. Figure 1.8 shows that, between 1985 and 2002-03, total UK expenditure on energy (in real terms) fell steadily. Energy expenditure as a proportion of GDP fell from 11.6% in 1981 to 5.7% in 2003. With rising energy prices, this trend has since reversed and energy expenditure as a proportion of GDP had risen to 7.5% by 2006.

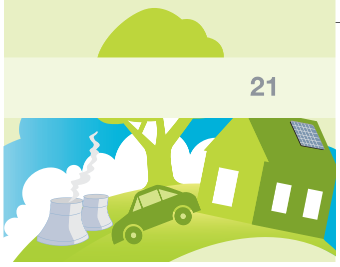
The messages from this overview are clear. Climate change policy is calling for transformational change in the energy sector. Secondly, the UK's declining role as an energy producer, coupled with higher energy prices, means that the UK economy is more exposed to volatility and instability than at any point since the oil crises of the 1970s. This sets clear priorities for UK energy strategy over the coming decades. We now turn to the established policies and institutional frameworks which provide the starting point for UK responses to these imperatives.

Policy Framework and Regulation

The UK energy sector, and its relationship with government through policy and regulation, has gone through deep changes in the last twenty years. In 1990, just as the climate change problem was starting to be taken seriously, the electricity industry was privatised, marking the end of over forty years of public ownership. The gas industry had been privatised in 1986. The three main themes running through energy policy over this period have been: privatisation and increasing market liberalisation throughout the 1990s; increased prioritisation of social and environmental issues since the 1997 General Election; and, very recently, a re-focusing on strategic energy issues led by heightened concern about climate change and the loss of self-sufficiency in oil and gas.

Privatisation and liberalisation

Electricity privatisation in 1990 brought about radical changes. The old nationalised monopolies were broken up. In electricity



generation, the large successor companies were first challenged by the Regional Electricity Companies (RECs) and merchant generators during the 'dash for gas'. The market has subsequently consolidated and is now dominated by a small number of vertically integrated groups, only one of which is UK-owned. Utilities have become suppliers of both gas and electricity.

The residual monopolies in gas and electricity transmission and distribution are regulated through a system of five-yearly price reviews conducted by OFGEM. These were originally based on the simple 'RPI-x' formula to squeeze costs out of the industry in the absence of competitive markets. They have become increasingly sophisticated over time, separating out capital and operating expenditure and allowing ex-post adjustments. There is now a concern that the transmission regime has been holding up required investment in new capacity, especially renewables, because of the requirement for operators to pay for grid reinforcement up front.

The third element of the post-1990 regime has been the development of retail competition for electricity and gas. This process took place gradually with full competition, where householders could choose their gas and electricity suppliers and the end of price regulation, arriving only in 1998.

The regulatory regime has evolved considerably since 1990. The early focus on cost reduction in the monopoly parts of the business has been followed by an increasing recognition of the need for regulation that actively promotes competition in the generation markets (Helm, 2003). This eventually resulted in BETTA (British Electricity Transmission and Trading Arrangements) which has covered the entire mainland of Great Britain since 2005.

Social and environmental issues

The Labour manifesto for the 1997 General Election included a commitment to reduce CO_2 emissions by 20% by 2010 below 1990 levels. This set in train a number of policy measures which targeted mainly the electricity and business sectors. Following the Marshall report on economic instruments and the business use of energy (Lord Marshall, 1998), these included the Climate Change Levy package and the introduction of emission trading, but not a carbon tax which business had been keen to avoid. At the same time, the government's concern with fuel poverty inhibited price rises for residential consumers and brought new measures, such as the Energy Efficiency Commitment for utilities and 'Warm Front' to encourage more efficient energy use in the home, especially for vulnerable consumers. In spite of these efforts, CO_2 emissions are not now significantly lower than they were in 1997.

The re-emergence of energy strategy

After a long gap, there have been two White Papers on energy policy since the year 2000. In the 2003 White Paper (DTI, 2003), the Government accepted the Royal Commission on Environmental Pollution's proposal that the UK should reduce its CO_2 emissions by 60% by 2050 and established four goals for energy policy:

- to put ourselves on a path to cut the UK's CO$_2$ emissions by some 60% by 2050, with real progress by 2020
- to maintain the reliability of energy supplies
- to promote competitive markets in the UK and beyond
- to ensure that every home is adequately and affordably heated

However, the White Paper did not focus heavily on security of supply. Subsequently, the Government has taken strenuous efforts to create the conditions under which private companies would undertake nuclear new build in the UK to reduce export dependence and reduce CO$_2$ emissions. The 2007 White Paper (BERR, 2007) underlined this new approach and set out a number of ambitious new measures to drive down CO$_2$ emissions. The Climate Change Act 2008 and the establishment of the new Department of Energy and Climate Change (DECC) in 2008 underlined the increasing importance being attached to strategic energy and climate policies. A speech by the Secretary of State (Miliband, 2008) sought to re-position the respective roles of the market and state guidance in taking forward energy strategy.

Key Bodies and Institutions

Currently, three central government departments have the main responsibilities for UK energy policy. DECC has the lead while the Department of Communities and Local Government (CLG) and the Department of Transport (DfT) cover energy use in buildings and transport respectively. The establishment of DECC in October 2008 brought together the Energy Group from the Department of Business, Enterprise and Regulatory Reform (BERR), which had overall responsibility for energy strategy, energy supply and energy sector regulation, together with the energy efficiency, climate change mitigation and international climate policy functions previously in the Department for Environment, Food and Rural Affairs (DEFRA). In addition, the Department of Innovation, Universities and Skills (DIUS) has responsibilities for energy research and development (R&D) while DEFRA's broader environmental responsibilities also impinge on the energy sector.

There were many structural changes in government between 1997 and 2008 which affected energy both on the supply and on the demand side. The establishment of DECC virtually restores the situation before the Department of Energy was abolished in 1992 following the completion of gas and electricity privatisation. The crucial difference is that climate change has now been added to the Department's responsibilities.

Since 1998, the responsibilities of specific departments have been set through a framework of Public Service Agreements (PSAs) which set out the key priority outcomes the Government wants to achieve. Table 1.1 shows current PSAs relevant to the energy sector. DECC's leading role covers the energy sector's contribution to sustainable growth and prosperity, to be achieved through competitively priced energy markets and better regulation. Climate change has a PSA to itself with six different indicators, five of which fall within DECC's remit. The focus on competitive markets, security of supply and climate change is very evident.

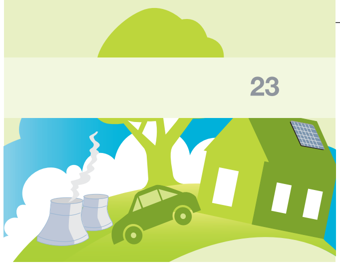


Table 1.1: Public service agreements relevant to energy

PSA Theme	Public Service Agreement	Indicator	Lead Government Department
Sustainable growth and prosperity	Promote world class science and innovation in the UK	• Business research and development (R&D) expenditure – the average UK R&D intensity in the six most R&D intensive industries, relative to the US, Japan, France and Germany	DIUS
	Deliver reliable and efficient transport networks that support economic growth	• Average benefit cost ratio of investments approved over the CSR07 period	DfT
	Deliver the conditions for business success in the UK	• Maintenance of competitively priced energy markets • Deliver better regulation that works for everyone	DECC, BERR
Stronger communities and a better quality of life	Increase long term housing supply and affordability	• Average Energy Efficiency Rating for new homes (SAP)	CLG
A more secure, fair and environmentally sustainable world	Lead the global effort to avoid dangerous climate change	• Global CO_2 emissions to 2050 • Size of the global carbon market • Total UK greenhouse gas and CO_2 emissions • Greenhouse gas and CO_2 intensity of the UK economy • Proportion of emissions reductions from new policies below the Shadow Price of Carbon	DECC
	Secure a healthy natural environment for today and the future	• Water quality • Biodiversity • Air quality • Marine health • Land management	DEFRA

Source: HM Treasury, 2007

Two independent regulatory bodies have a considerable influence on the energy sector. The Office of the Gas and Electricity Markets' (OFGEM's) primary responsibility is to protect consumers, which it does by promoting competition and regulating the monopoly companies which run the gas and electricity networks. It also helps to protect vulnerable customers and contributes to climate change and sustainable development policies by helping environmental improvements to be achieved efficiently. The Environment Agency (which operates in England and Wales) regulates business and administers some of the policies and measures described below.

Two further bodies have a role in promoting CO_2 reduction and energy efficiency. The Carbon Trust works with business and other organisations to reduce carbon emissions and develop commercial low-carbon technologies. The Energy Saving Trust works with private consumers, focusing on energy conservation in the home, energy-efficient products, energy-saving behaviour and renewable energy.

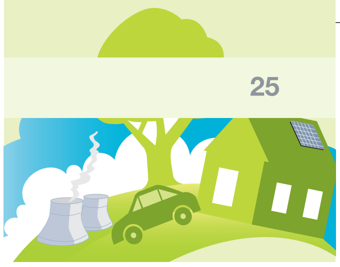
Following devolution to Scotland and Wales, and changes in Northern Ireland, energy policy remains a reserved area of policy for the Westminster government. However, the devolved administrations have important powers and responsibilities. The Scottish Government has responsibility for giving consent for new energy developments such as power stations and power lines. The fact that the Scottish Government will not currently allow new nuclear development is therefore significant. The promotion of energy efficiency and renewables are devolved responsibilities. Scotland also supports innovation and business development through, for example, a Wave and Tidal Energy Support Scheme. The Welsh Assembly Government's powers are more limited but it also promotes energy efficiency and supports innovation and energy business development.

Policies and Measures for the Energy Sector

Market regulation

OFGEM has successfully driven down costs in the monopoly transmission and distribution sectors through its price control reviews and established competitive markets in electricity generation. However, it, and its predecessors, did so against a background of surplus electricity generation capacity and falling CO_2 emissions as a result of the 'dash for gas'. It has been argued forcefully in some quarters that OFGEM's primary focus on competition and market regulation is in tension with other goals, particularly those relating to climate policy (Sustainable Development Commission, 2007).

There is now anxiety about an 'energy gap' emerging beyond 2015 when a number of coal-fired stations may close as a result of the EU Large Combustion Plant Directive. At the same time, there are ambitious targets for renewable energy (see below) which will require back-up capacity to maintain reliable supplies. The growth of renewable electricity aspirations has raised some profound questions about the regulatory regime. Since 1990, developers were asked to finance the full cost of network expansion associated with new renewable (known as 'deep' connection charging). This can hold back renewable



expansion in two ways. First, the grid operator, National Grid, has not been guaranteed a regulated return on the capital it invests until all the other hurdles to development, especially planning consent, have been jumped. As a result, the network cannot be reinforced in anticipation of new generation coming online. Second, the grid rules have required network investment to provide for intermittent generation at its maximum output. In practice, intermittent generators can 'share' network capacity at lower cost. Fundamental questions about future regulation and market arrangements are now being asked (OFGEM, 2009).

Climate policy

Most policies and measures other than those directed at market operation fall within the scope of the UK's Climate Change Programme. The Climate Change Act 2008 set an emissions reduction target for greenhouse gases of 80% below 1990 levels by 2050, and also established the independent Committee on Climate Change (CCC), whose main duties are to recommend the UK's legally binding five-year 'carbon budgets' 15 years ahead, to monitor government's progress in achieving the budgets and to provide advice to the UK government and the devolved administrations. In its first report, the CCC recommended two sets of three five-year budgets for the period 2008-2022. The more ambitious 'intended' budgets would come into play in the event of post-Kyoto global deal under the UN Framework Convention on Climate Change (UNFCCC). The 'interim' budgets would be in effect prior to a global deal. The budget recommendations are summarised in Table 1.2 and will be set formally in June 2009 following consideration by the Government and Parliament.

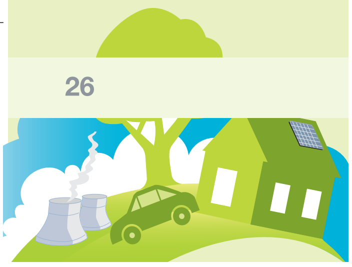
The carbon budget system can be seen as providing the framework within which more specific policies and measures will be developed and implemented. Table 1.3 summarises the main measures currently

Table 1.2: Committee on climate change budget recommendations

	Interim	Intended
GHG budget 2008-2012	2537 kt	2537 kt
GHG budget 2013-2017	2349 kt	2210 kt
GHG budget 2018-2022	2114 kt	1789 kt
GHG reductions 1990-2020	34%	42%
CO_2 reductions 1990-2020	29%	40%
CO_2 reduction 2005-2020	24%	36%
- EU ETS[1] excluding aviation	29%	44%
- Non-traded sector	19%	27%

Source: Committee on Climate Change (CCC), 2008

[1] The European Union's Emissions Trading Scheme



in place or under development which impact on the energy sector, along with estimates of their contribution to CO_2 reduction in 2020. The table distinguishes between policies in place prior to the 2007 Energy White Paper and those under development subsequently. The strong reliance on market-based instruments, reflecting the strong policy attachment to competitively priced energy markets, is striking.

In energy supply, the main mechanism is the EU Emissions Trading Scheme (ETS). Under this, the total emissions of power generators and energy intensive industry is capped. Phase II of the ETS runs from 2008-2012 and an EU Directive agreed in December 2008 establishes a Phase III running from 2013-20. National allocations for Phase III were determined by the European Commission rather than being proposed by Member States, and represent a considerable tightening on Phase II. Allowances for the electricity sector will be auctioned instead of being allocated. UK operators can trade EU allowances (EUAs) with others in the scheme and can purchase a limited number of overseas credits through, for example, the Clean Development mechanism (CDM). UK electricity companies have been among the most active purchasers of overseas credits.

The Renewables Obligation (RO) currently requires that 15.4% of electricity should come from renewable sources by 2015. Recently, it has been decided to 'band' the RO to give greater incentives to technologies, such as wave and tidal, that are further from commercialisation. Under the EU Renewables directive agreed in December 2008, the UK is obliged to meet 15% of its final energy consumption from renewable sources. In practice, this would require at least 30% of electricity to come from renewable sources.

Other than the EU ETS, the Climate Change Levy package introduced in 2001 is having the largest impact on energy-intensive industry. The Climate Change Agreements, under which business gets exemptions if agreements to reduce energy use are struck, is having a larger impact than the levy itself. For non energy-intensive industry, building regulations have had the largest impact so far. However, the Carbon Reduction Commitment (CRC) will establish caps on emissions from most businesses not covered by the Climate Change Agreements or the EU ETS. CRC allowances will be tradable.

In the transport sector, the most important measures have been the EU voluntary agreements to reduce CO_2 emissions from passenger cars coupled with fiscal measures that include vehicle excise duty according to CO_2 emissions and adjustments to company car taxation. Average CO_2 emissions from new cars fell from 190 g/km in 1997 to 165 g/km in 2007 (SMMT, 2008). The fuel duty escalator, whereby the duty paid on petrol and diesel rose automatically each year, has also had a significant impact. The Renewable Transport Fuel Obligation (RTFO) will also have achieved material reduction in emissions by 2020.

In the residential sector, building regulations have had the biggest impact so far. The Energy Efficiency Commitment (EEC) and its

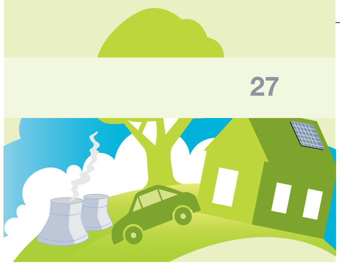


Table 1.3: Main climate policies and measures affecting energy

Sector	Measure	CO_2 Savings 2020 (mt)
Energy Supply	EU ETS Second phase	29.3
	Tightening of EU ETS cap	11.0
	Renewables obligation	14.0
Business (existing policies)	Climate change agreements	10.6
	Climate change levy	4.0
	Building regulations	5.9
	Carbon Trust	4.0
	Other	2.3
Business (EWP 2007 policies)	Products policy	3.3
	Carbon reduction commitment	2.9
	Other	1.8
Transport (existing policies)	Voluntary agreements /fiscal measures	13.2
	Fuel duty escalator	7.0
	RTFO	5.9
	Other	4.0
Transport (EWP 2007 policies)	Further improvements in vehicle efficiency	6.2
	Domestic aviation in EU ETS	1.1
Residential (existing policies)	Building regulations	12.1
	CERT (2008-11)	4.0
	EEC (2002-05)	2.9
	Other	5.2
Residential (EWP 2007 policies)	Supplier obligation	12.8
	Zero-carbon homes	4.4
	Product policy	3.3
	Other	2.3
Public Sector (existing policies)		2.2
Public Sector (EWP 2007 policies)		3.3

Source: DECC (2008); Climate Change Committee (2008)

Note: Impact of measures may not be additive

successor, the Carbon Emission Reduction Target (CERT) have also had a major impact on emissions. These obliged electricity and gas suppliers to invest in energy efficiency measures on behalf of their customers. The successor to CERT which will operate from 2012, currently known only as the 'Supplier Obligation' is expected to massively expand CO_2 and energy savings in the residential sector. 'Zero-carbon' homes, applying only to new build, will have a more modest impact.

Support for R&D and innovation

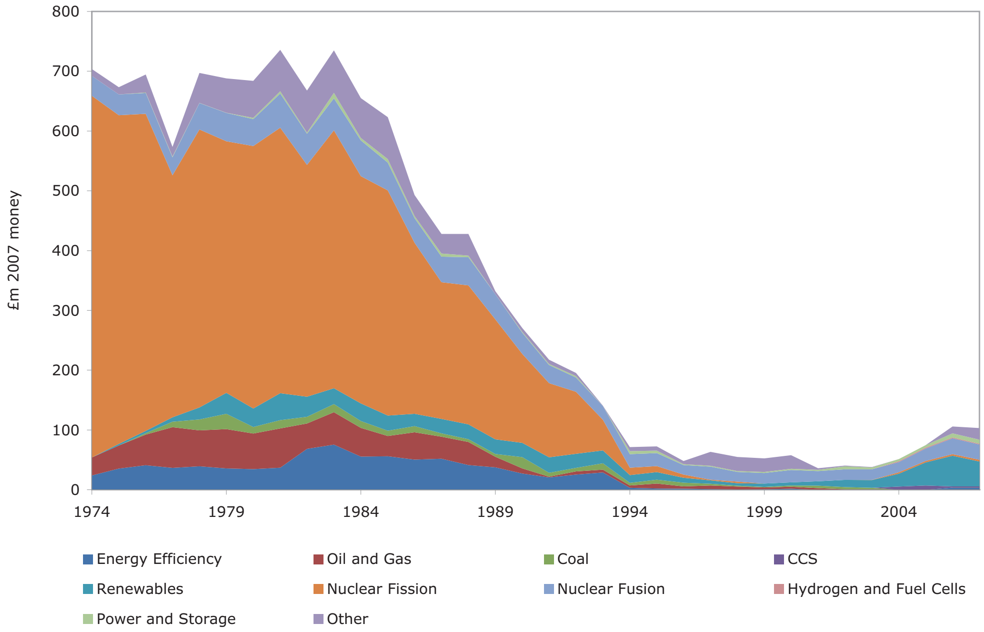
To reach ambitious targets for 2050 will require improvements to existing technology and the deployment of

technologies that are not yet available on the market. Figure 1.9 shows that public support for energy R&D in the UK plunged during the 1980s and 1990s. This reflects the fact that R&D conducted by the nationalised industries was not continued by the privatised electricity and gas companies as well as the decline of the national energy laboratories. In the 1970s and 1980s, nuclear fission accounted for the majority of R&D spend and this has now been greatly reduced. However, there were also significant declines in R&D on energy efficiency, oil and gas, and renewables.

Since a report by the Chief Scientific Adviser (CSA's Energy Research Review Group, 2002), energy R&D spend has started to recover and, according to IEA statistics is now around £100m pa compared to a low of £35m. Energy R&D is now supported by a range of public bodies operating at various points along the innovation chain, characterised by different stages of the so-called 'Technology Readiness Level' (TRL) (Figure 1.10). The Research Councils are responsible for early stage energy research, with applied R&D and early demonstration falling to the Technology Strategy Board (TSB), the Energy Technologies Institute (ETI) and the Carbon Trust.

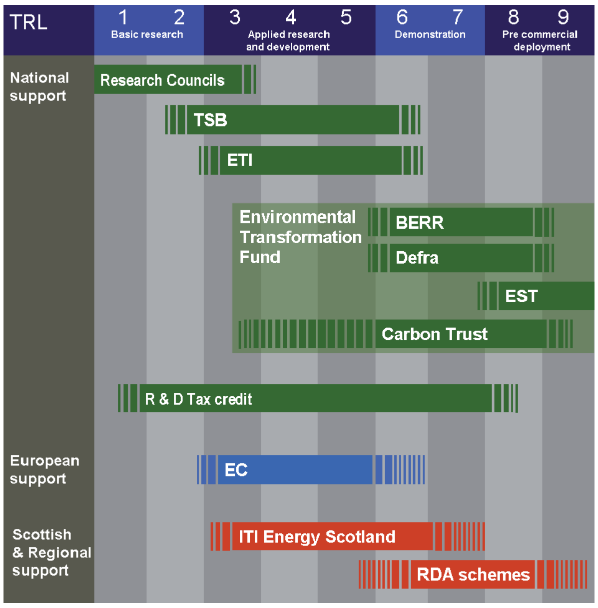
Carbon capture and storage (CCS) is only partly supported within this framework. Large-scale demonstration is so expensive that separate arrangements are being made. These include a competition to demonstrate post-combustion capture being operated by DECC and the use, at the EU level, of reserved EU ETS allowances to support demonstration. Here, the UK will compete with other Member States for the opportunity to take forward one or more out of a total of around twelve demonstration projects.

Figure 1.9 UK RD&D spend



Source: IEA, 2009

Figure 1.10: Support for energy technologies in the UK



Source: BERR, 2008b

The UKERC Energy 2050 Approach

This report explores a diverse range of uncertainties and choices facing the UK energy system. We have used a set of scenarios to integrate the work of different UKERC research teams from different disciplines addressing different facets of the energy system. To give equal weight to all the factors we consider would give rise to an unmanageable and confusing proliferation of scenarios. Following the market/policy analysis set out above, we therefore identify the two primary goals of UK energy strategy as contributing to the mitigation of climate change and the achievement of a 'resilient' energy system that addresses security needs.

Progress in reducing the energy sector's impact on the climate can be measured through a single metric, tonnes of CO_2 equivalent emitted. In contrast, the energy security agenda responds to anxieties and insecurities about a range of diverse contingencies which are often not well defined and differentiated. These include adequacy of investment in electricity generation capacity, loss of critical infrastructure whether through deliberate action or by accident, and interruptions to supply in global markets.

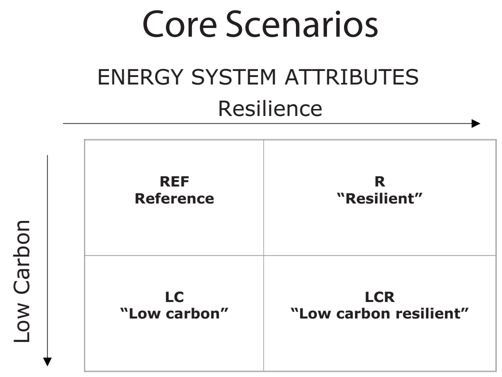
Our approach to resilience started by adopting a working definition of the concept as:

> *"The capacity of an energy system to tolerate disturbance and to continue to deliver affordable energy services to consumers. A resilient energy system can speedily recover from shocks and can provide alternative means of satisfying energy service needs in the event of changed external circumstances."*

To make this definition operational we have then defined a set of resilience indicators, which is set out in detail in Chapter 3. But, briefly here, resilience involves: reducing final energy demand below the levels it would otherwise have reached; promoting diversity of supply; and ensuring adequate investment in infrastructure and capacity.

The emphasis on CO_2 reduction and resilience leads us to focus on a set of four Core 'scenarios' (Figure 1.11) which form the starting point from which other issues, such as technology acceleration or lifestyle change, may be explored. Testing variants on the four Core scenarios enables the relevant issues to be explored coherently, enabling comparisons to be made across different topics.

Figure 1.11: Core scenario structure



REF **Reference**	**R** **"Resilient"**
LC **"Low carbon"**	**LCR** **"Low carbon resilient"**

None of the scenarios predicts a most likely future. Neither do they represent a consensus view of what a desirable future would look like - though the scenarios may have aspects which some people consider desirable, views will differ on what may be desirable.

Rather, the scenarios explore visions of the future which are internally consistent in their treatment of both policy drivers and external drivers, thereby exploring the choices that are available and their implications for achieving long-term goals. Most of the scenarios are 'back-casting' in that outcomes are specified and the social, economic and technological changes that might bring about these outcomes are tested.

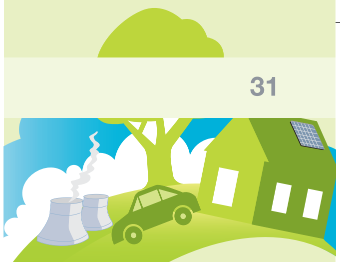
The "***Reference***" (REF) Core scenario assumes that 'firm and funded' policies and measures in place at the time of the 2007 Energy White Paper continue into the future but that no additional measures are introduced. It does not include measures that may be required to achieve the 80% carbon reduction goal, nor the five-year carbon budgets proposed by the CCC in December 2008. The Reference scenario is neither a prediction nor a preferred future: its sole purpose is to provide a baseline from which to assess the actions and costs associated with achieving policy goals.

The "***Low-Carbon***" (LC) Core scenario assumes the introduction of a range of policies leading to an 80% reduction in UK carbon emissions by 2050 relative to 1990 and a suitable trajectory towards that goal. Broadly, the policies assumed are those which will result, on the basis of the modelling assumptions employed, in the goal being achieved at the lowest possible welfare cost.

The "***Resilience***" (R) Core scenario takes no account of the carbon reduction goal but assumes additional investment in infrastructure, demand reduction and supply diversity with a view to making the energy system more resilient to external shocks.

The "***Low-Carbon Resilient***" (LCR) Core scenario combines the carbon and resilience goals.

When UKERC started the work, the UK's CO_2 reduction goal for 2050 was 60%. Some of the early work described in this report, particularly on technology acceleration, was based on the assumption that the Low-Carbon Core scenario would entail a 60% reduction. This policy goal was based on a recommendation from the Royal Commission on Environmental Pollution's 2000 report on energy and climate change (RCEP, 2000). The nomenclature to describe the Low-Carbon core scenario in different chapters is set out in Chapter 2, ***as well as the Summary of Scenarios above***, where a range of different carbon reduction scenarios is considered.



Five cross-cutting factors are held constant across the four Core scenarios (but changed in the variants reported in later chapters of this report):

- the international context
- the trajectory of technological change
- the way energy investment decisions are made
- the evolution of people's lifestyles
- energy consumers' preferences, in the sense that we assume that consumers respond to price and other incentives as they have done in the past

Tables 1.4 and 1.5 summarise the key common assumptions of the Core scenarios.

The factors that change across the Core scenarios are:

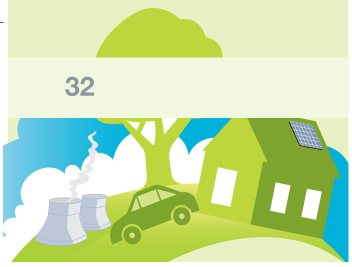
- final energy use resulting from changes in energy service demands (ESDs) and the take up of conservation and efficiency technologies in response to price signals and other policy incentives (but not from other kinds of behaviour changes, which is examined in later scenarios)
- actual investment in energy supply, infrastructure and technologies
- the technologies through which energy service demands are met
- the policy framework for post 2007 initiatives

Table 1.4: Key assumptions in the core scenarios

GDP growth	**2% per annum**
World energy prices	See Table 1.5. The assumed prices are translated into global supply curves. Some domestic energy may be available at a lower cost
Discount rates	10% real
'Hurdle' rates	Higher discount rates are applied in sectors with high transaction costs and consumer inertia
Technology performance and cost	Based on detailed stakeholder consultations

Table 1.5: World energy price assumptions

		2000	2005	2010	2015	2020	2030	2040	2050
Crude Oil	2005$/bbl	31.38	50.62	57.50	55.00	55.00	60.00	70.00	70.00
Gas	2005$/MMBTU	4.85	7.46	6.75	6.75	7.00	7.64	8.91	8.91
Coal	2005$/tonne	36.54	61.14	55.00	55.00	55.00	60.00	65.00	65.00
Crude Oil	2005£/GJ	3.39	4.56	4.49	4.40	4.51	4.92	5.74	5.74
Gas	2005£/GJ	3.20	4.10	3.21	3.29	3.50	3.82	4.45	4.45
Coal	2005£/GJ	0.90	1.25	0.98	1.00	1.03	1.120	1.21	1.21



- resulting primary and final energy, emissions, and economic indicators

The next chapter of the report, **Carbon Reduction Scenarios** explores the implications of two key variables: different levels of carbon reduction by 2050[1]; and the timing of carbon reductions, specifically 'late' versus 'early' action. This set of scenarios includes the Reference and *Low-Carbon Core* scenarios as well as a number of variants which look at lesser and greater levels of ambition than the 80% reduction in the Low-Carbon Core scenario (40%, 60% and 90% CO_2 reductions by 2050) and also the implications of early or late action, keeping cumulative carbon emissions constant, and of taking a short or long-term perspective, expressed through varying the discount rate, and the types of measures consequently taken up.

The subject of Chapter 3 is **A Resilient Energy System**. In this chapter, the two remaining Core scenarios, Resilient and Low-Carbon Resilient, are defined in terms of energy demand levels, supply diversity, and infrastructure and capacity criteria. Comparing these two scenarios with Reference and Low-Carbon, it is apparent that there are a number of synergies, but also differences, between the low-carbon and energy security agendas. The four Core scenarios are then tested against a number of hypothesised 'events' to assess the costs and benefits of investing in additional resilience. This chapter also considers the impact of a steep fossil fuel price increase on the resilient, compared with the Reference and Low-Carbon, Core senarios.

Many different technologies may have a role to play in decarbonising the UK energy system. Which come to play an important role will depend to some extent on how the technologies develop. Chapter 4 on **Technology Acceleration** explores a range of technological possibilities of decarbonisation, in relation to different renewables technologies, hydrogen fuel cells, nuclear power and carbon capture and storage (CCS). It assesses the size of the potential long-term pay-off from investing in research, development and demonstration (RD&D) projects and how the size of this pay-off depends on the level of ambition for carbon reductions.

All provision and use of energy, including low-carbon energy forms, has some impacts on the natural environment and there are likely to be societal responses. Chapter 5 on **Environmental Sensitivities** examines both the consequences of the Core scenarios, in terms of environmental impacts, other than those associated with climate change; and the implications for the overall UK energy system should it be impossible or very difficult to deploy important low-carbon technologies (e.g. onshore wind or nuclear power). This may be because of societal concern over their non-climate environmental impacts, such as other atmospheric emissions, water use and land use.

Chapter 6 explores the implications of different **Energy Lifestyles**. Different lifestyles lead to very different levels of energy use, and how this is distributed across different energy services such as

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[1] This report only explores the implications of reducing emissions of the main greenhouse gas (GHG), carbon dioxide (CO_2), and not of other GHGs.

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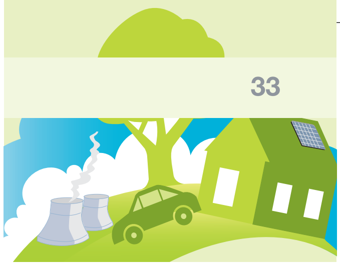

power, transport and heating. At least part of the increase in energy consumption in recent decades is the result of relatively energy-intensive ways of living having become embedded in, and accepted as necessary parts of, modern lifestyles. This chapter projects a number of key changes in behaviour relating to, for example, mobility or the acceptability of indoor temperatures, and discusses what changes in lifestyles might lead to reduced carbon emissions, how such lower-carbon lifestyles might be promoted, and what their impact would be on the Reference and Low-Carbon Core scenarios in this report.

An important aspect of changing energy lifestyles may be greater household responsibility for energy generation as well as consumption, called **Microgeneration**. The current UK electricity is based on relatively few large-scale power plants and a transmission and distribution grid to carry their power across the country to consumers. This is not the only way to organise an electricity system, and a decentralised electricity system, incorporating microgeneration technologies at the household level, might offer advantages in terms of both decarbonisation and resilience. Chapter 7 explores this possibility by assessing the suitability of various types of microgeneration technologies for application in dwellings, the potential CO_2 emissions savings, efficiency improvements, techno-economics and practical considerations, and the behavioural, regulatory and policy issues associated with the introduction of micro-generation technologies. Taking account of the varying levels of decarbonisation of grid electricity in the various scenarios, it assesses under what circumstances microgeneration is able to play a significant role.

Finally, the concluding Chapter 8, **Prospects and Policies for a Secure and Low-Carbon Energy System**, presents a synthesis of the discussion from the earlier chapters. It emphasises two aspects. Firstly, it presents an overview of the scenarios and scenario variants identifying overall patterns and highlighting some fundamental differences, in terms of energy sector development, between them. Secondly, it assesses policy choices, alternative institutional structures, especially in respect of energy markets and regulations, and implications for consumers, energy companies and others. It will seek to answer the question, on the basis of the evidence from the Energy 2050 project: How can the transition to a secure and low-carbon UK energy system be achieved over time, and how can opportunities over short and long timescales, and between different parts of the system (production and consumption, technology and behaviour) be best brought together and barriers overcome?

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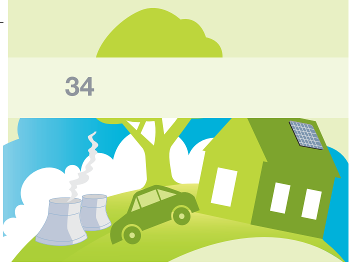

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2. Carbon Reduction Scenarios

Key Messages

- Without major policy intervention, climate goals will not be met
- Putting the emphasis on climate change mitigation will prioritise de-carbonisation of energy supply and transformation
- Progressively more ambitious carbon targets require first electricity de-carbonisation, then greater energy efficiency in the built environment, and finally, at higher levels of ambition, the adoption of more radical options in the transport sector
- Early action on carbon reduction implies taking a longer-term view of investment in a low-carbon energy system and being prepared to invest more in infrastructure and capital-intensive solutions
- Early action is unlikely to be achieved by measures that simply set boundary conditions on the market and leave private investors to choose the mix of technologies
- Higher target levels produce a deeper array of mitigation options, albeit probably with more uncertainty
- Early action produces greater mitigation in different sectors (e.g. transport) and technology chains (e.g. wind, hydrogen) than later decarbonisation
- There is a very wide range of economic impacts, which rise steeply as targets become more stringent (again probably with more uncertainty). CO_2 marginal costs in 2050 range from £20-300/tCO_2, and rise to £360/tCO_2 for the most extreme CO_2 reductions. Welfare costs in 2050 range from £5 - £52 billion, and in moving from a 60% to an 80% reduction scenario this alsmost doubles welfare costs.

Introduction

This report describes a range of low-carbon scenarios underpinned by energy systems and modelling analysis. Such modelling is designed to develop insights on a range of scenarios of future energy system evolution and the resultant technology pathways, sectoral trade-off and economic implications. Long-term energy scenario-modelling analysis is characterised by deep uncertainty over a range of drivers including resources, technology development, behavioural change and policy mechanisms. This underlines the importance of the broad scope of sensitivity analysis described in later chapters of this report, to investigate different scenarios of energy system evolution, with different drivers of the UK's energy supply and demand, and the importance of different parameters to the scenario results.

Heavily influenced by the strengthening scientific consensus on the costs and benefits of mitigation actions to respond to global climate change, over the last decade a series of UK policy papers have been commissioned on long-term decarbonisation targets and strategies. This has culminated in the inclusion of the 80% carbon reduction target in the Climate Change Act of 2008. Energy system modelling (using variants of the UK MARKAL model) has played a key underpinning role in assessing the costs, trade-offs and pathways related to achieving such long-term targets.

The UK MARKAL Model

MARKAL (acronym for MARKet ALlocation) is a widely applied bottom-up, dynamic, linear programming (LP) optimisation model (Loulou et al., 2004), supported by the International Energy Agency (IEA) via the Energy Technology and Systems Analysis Program (ETSAP). MARKAL portrays the entire energy system from imports and domestic production of fuel resources through to fuel processing and supply, explicit representation of infrastructures, conversion of fuels to secondary energy carriers (including electricity, heat and hydrogen (H_2)), end-use technologies and energy service demands of the entire economy. As a perfect foresight partial equilibrium optimisation model, MARKAL minimises discounted total energy system cost by considering the investment and operation levels of all the interconnected system elements. The inclusion of a range of policies and physical constraints, the implementation of all taxes and subsidies and calibration of the model to base-year capital stocks and flows of energy enables the evolution of the energy system under different scenarios to be plausibly represented.

A comprehensive description of the UK model, its applications and core insights can be found in Strachan et al. (2008a), and the model documentation (Kannan et al., 2007). Further peer reviewed papers focusing on specific variants and/or applications of the UK MARKAL model include Strachan and Kannan (2008), Strachan et al. (2009a), Kannan and Strachan (2008), Strachan et al. (2008b) and Strachan et al. (2009b).

The key enhancement to the MARKAL model for this project was the development of the elastic demand version (MED) described in more detail below. Other model developments for this Energy 2050 project include updated fossil resource costs; expanded categorisation of UK carbon capture and storage (CCS) and wind resources; expanded biomass chains to all end-use sectors; new hydrogen (H_2) infrastructures, improved treatment of electricity intermittency; non-price representation of residential demands and technology assumptions via the UK Domestic Carbon Model (UKDCM), developed and operated by Oxford University's Environmental Change Institute; a range of updated electricity technology assumptions; buildings technology updates (including micro-CHP and heat pumps); transport technology updates (including plug-in hybrid electric vehicles); updated energy service demand assumptions; and incorporation of all UK policy measures through to 2007 (including an assumption of an average EU ETS price of €20/tCO_2).

The MED model was fully recalibrated to standard UK energy statistics. A range of peer reviewed publications and the publicly available model documentation are detailed in Anandarajah et al. 2008. An important point to stress is that MARKAL is *not* a forecasting model and does *not* predict the future UK energy system over the next 50 years. Instead it offers a systematic tool to explore the trade-offs and tipping points between alternative energy system pathways, and the cost, energy supply and emissions implications of these alternative pathways.

System Costs and Social Welfare in the MED Model

The version of the MARKAL model with elastic demand (MED) accounts for the response of energy service demands (ESDs) to prices (increasing energy prices, here in response to carbon constraints, reduce consumer demands for energy services). When different scenarios are run, MED reports two key results related to cost and benefits: energy system cost and social welfare. The energy system cost we report here is the undiscounted[1] sum of all the investments (plus capital, fixed and variable costs, and taxes/subsidies) made in the energy system over the period under consideration. Generally the higher the energy use, the larger and more expensive the energy system needed to deliver it. This means that energy system cost can be reduced by decreasing the demand for energy services, which provides the rationale for the other measure of cost, social welfare. Technically, this is computed as the sum of consumer and producer surplus, which in economics is generally considered a valid metric of social welfare. Consuming energy services will tend to increase social welfare, as well as energy system cost. Reducing energy service demands may reduce energy system costs, but it will also tend to reduce social welfare. The scenarios in this and subsequent chapters have many examples of the interplay between these two cost/benefit variables.

Another cost-relevant factor that is important in understanding the results is the discount rate that MARKAL uses in optimising future energy system investments. The standard real discount rate (taking account of inflation), broadly in line with market considerations, is 10%. This can be increased when it is perceived that markets are not functioning properly, and there are non-financial barriers to the take up of some technologies (for example, energy conservation technologies in buildings such as cavity wall and loft insulation). Individuals may implicitly apply higher discount rates. Discount rates that have been increased in this way are called 'hurdle rates'. Alternatively, it will be appropriate to apply a lower discount rate if a societal perspective is taken, with current and future costs being balanced more evenly. Discount rates that have been reduced for this reason are called 'social discount rates'. The Government applies social discount rates to assess public investments. One of the carbon reduction scenarios in this chapter has a social discount rate which significantly changes the model results, as will be seen.

When a constraint on carbon emissions is applied, MARKAL implements this by computing the 'shadow' price for carbon required to meet the specified carbon target. This has the effect of increasing the cost of consuming carbon-based fuels. This makes technologies using these fuels effectively more expensive, and stimulates the uptake of low-carbon technologies, which were not used without the carbon price because they cost more than the carbon-intensive alternatives. In MED, this increased cost of energy reduces the

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[1] As stated above, MARKAL minimises the discounted energy system cost, but we report the undiscounted cost, so that runs with different discount rates can be compared with each other

demand for energy services and social welfare. However, as discussed above, it may increase or reduce the energy system cost, because the higher average cost of meeting energy service demands may be offset by the fact that a smaller energy system is required to meet the reduced level of those demands.

Because of their implications for energy system and welfare costs, it is necessary to be clear about the model's treatment of energy conservation measures (such as insulation) in the residential sector, and the assumptions made about them. These measures have the effect of reducing the energy that is required to meet a given level of demand for energy services. It is widely perceived that such measures in the residential sector are available at low cost, but that consumers do not take them up for various reasons (e.g. lack of awareness and interest, hassle factors). To reflect this, the model makes these measures in the residential sector effectively more expensive through the use of 'hurdle rates' (see Table 1.4). Businesses are perceived to be more responsive to prices and price changes.

This leads to the issue of how households react when energy prices increase. In response, consumers may be expected both to increase their take up of conservation measures, and reduce their demand for energy services. Energy price elasticities in MARKAL capture both factors, but there is little information about the individual effect of each factor. Conservation measures are low cost, while the loss of consumer welfare through forced reductions in the demand for energy services is more costly.

In all of the Core scenarios and most of the variants to be reported here, it was assumed that all of the response came through households reducing their demand for energy services. This results in high estimated welfare costs. To the extent that households were instead to respond by taking up conservation measures (and they would assuredly do some of this), the welfare costs would be lower and, depending on various assumptions, could even fall to zero.

The welfare costs reported in the Core scenarios and most variants are therefore very much an upper bound for the model. The only set of variants in which this treatment differs is the lifestyle scenarios reported in Chapter 6, where it is assumed that households take up conservation measures as part of the lifestyle change, rather than in response to higher energy prices. As will be seen, this reduces the associated welfare costs substantially.

The Low-Carbon Scenarios

A first set of scenarios (CFH, CLC, CAM, CSAM) focuses on levels of CO_2 reductions (in 2050) ranging from 40% to 90% reductions (from the 1990 base year). These runs also have intermediate targets from the same base year of 15% to 32% reductions by 2020. These scenarios investigate increasingly stringent targets and the ordering of technologies, behavioural change and policy measures to meet them. A second set of scenario runs (CEA, CCP, CCSP) undertakes sensitivity analysis around 80% CO_2 reductions, focusing on early action, cumulative CO_2 emissions targets, and different discount rates. These scenarios investigate dynamic trade-offs and path dependency in decarbonisation pathways.

As discussed in Chapter 1, it was initially intended that the Low-Carbon Core scenario would have a carbon emissions reduction (from 1990 level) of 60%, following the recommendation in 2000 of the Royal Commission on Environmental Pollution. However, after the modelling of these ‘carbon ambition’ scenarios had been completed, the Climate Change Committee recommended, and the Government accepted, that the target should be 80%. This was incorporated in the Climate Change Act. The Energy 2050 project then decided that the 80% carbon reduction scenario called CAM (because of the extra ambition involved) should be the Low-Carbon Core scenario, and throughout subsequent chapters this Low-Carbon Core scenario is given the acronym LC.

Table 2.1 gives the names and acronyms of the various decarbonisation scenarios, indicating the different usage in this chapter. The Core scenarios referred to in Chapter 1 are shown in bold.

Table 2.1: Carbon pathway scenarios

Scenario	**Scenario name**	**Carbon reduction targets (from 1990 level)**	**Cumulative targets**	**Cumulative emissions $GTCO_2$ (2000-2050)**	**2050 emissions $MTCO_2$**
REF	**Reference**	-	-	**30.03**	**583.5**
CFH	Faint-heart	15% by 2020 40% by 2050	-	25.67	355.4
CLC= LC-RCEP	Low-carbon	26% by 2020 60% by 2050	- -	22.46	236.9
CAM= LC[1]	**Ambition (Low-Carbon Core)**	**26% by 2020** **80% by 2050**	**-**	**20.39**	**118.5**
CSAM	Super ambition	32% by 2020 90% by 2050	-	17.98	59.2
CEA	Early action	32% by 2020 80% by 2050	-	19.24	118.5
CCP	Least-cost path	-	Budget (2010-2050) similar to CEA	19.24	67.1
CCSP	Socially optimal least- cost path	80% post 2050	Budget (2010-2050) similar to CEA	19.24	178.6

Note:

[1] This scenario is called CAM in this chapter, and LC in other chapters.

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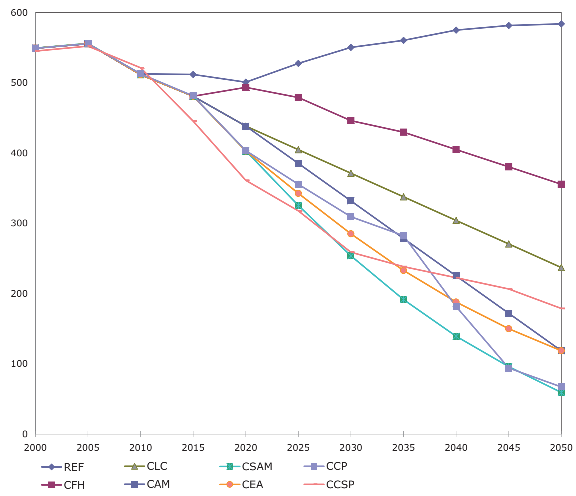
Table 2.1 shows that, in the Reference (REF) Core scenario, existing (as of 2007) policies and technologies would result in CO_2 emissions in 2050 of 584 $MtCO_2$, only 1% lower than 1990 levels. In 2020 (not shown in Table 2.1), if no new policies/measures are taken, emissions would be about 500 $MtCO_2$ - a 15% reduction. However this would be considerably higher than the Government target range in the Climate Change Act of at least a 26% reduction by 2020. In the absence of a strong carbon price signal, the electricity sector is the largest contributor to CO_2 emissions driven by conventional coal fired power plants, with substantial contributions from the transport and residential sectors. Figure 2.1 shows the carbon pathways to 2050 of many of the carbon reduction runs.

Overall, the runs with greater CO_2 reductions follow similar routes, with additional technologies and measures being required as targets become more stringent and costs rapidly increase (as seen below).

Figure 2.1: CO_2 emissions under scenarios with different annual carbon constraints



However, a cumulative constraint with a lowered (social) discount rate (CCSP) gives more weight to later costs and hence decarbonises earlier - with CO_2 reductions of 39% in 2020 and only 70% in 2050. Similar to the early action case (CEA), this CCSP focus on early action gives radically different technology and behavioural solutions. In particular, as will be seen, effort is placed on different sectors (transport instead of power, because some low-carbon power technologies are not available before 2020), different technologies (choosing wind in preference to early nuclear technologies), and increased near-term demand reductions, which are lower cost than later low-carbon supply options.

Figure 2.2 shows sectoral emissions for the Reference scenario, i.e. with no emission constraints. Figure 2.3, with results summarised for 2035 and 2050, shows the dramatic changes when the carbon constraints are applied.

Under decarbonisation pathways, the power sector is key where decarbonisation begins with the deployment of CCS for coal

Figure 2.2: Sectoral CO_2 emissions during 2000-2050 in the Reference scenario

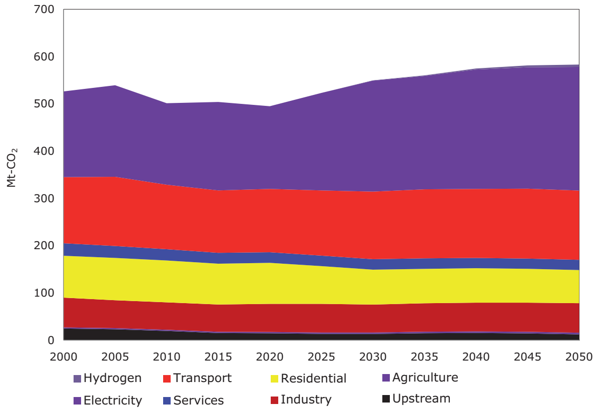
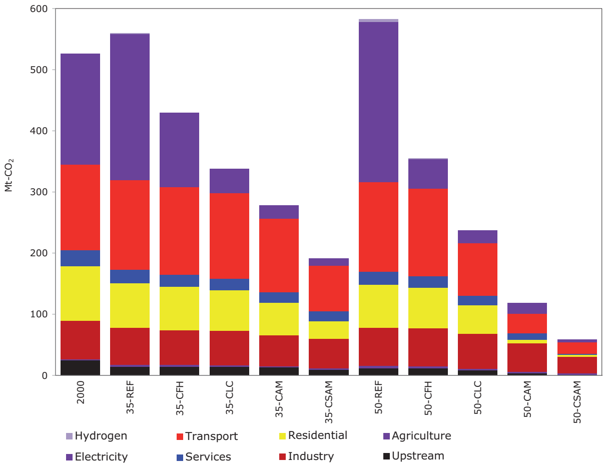


Figure 2.3: Sectoral CO_2 emissions in years 2000, 2035, 2050 for different carbon reduction scenarios



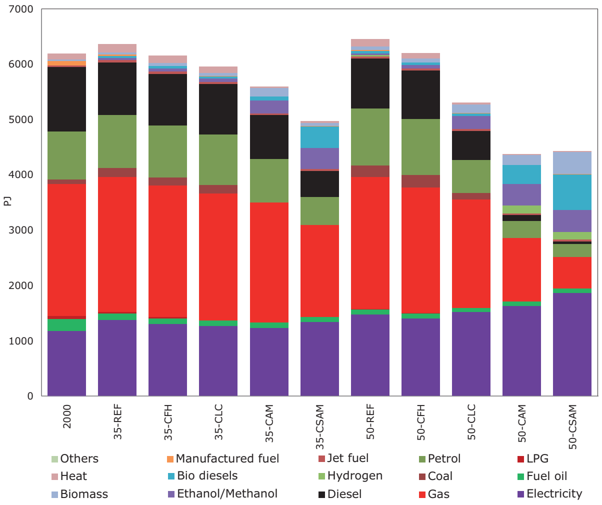
plants in 2020-2025 in all mitigation scenarios. However, it is worth stressing that the close marginal costs of CCS, nuclear and wind, and future uncertainties about their development, mean that any or all of these technologies may turn out to be the cost-effective technologies in the future and play a substantial role in decarbonising the power sector.

When the target is increased, nuclear plus wind is selected alongside CCS. Note that in the most ambitious scenarios (especially 90% reductions), nuclear, in one sense a 'zero-carbon' source, gains at the expense of CCS (a 'low-carbon' source). Since the contribution of increasing levels of (off-shore) wind to peak load is limited, the balanced low-carbon portfolio of plants requires large amounts (20GW) of gas plants (combined cycle gas turbine - CCGT) as reserve capacity. Under stringent CO_2 reduction scenarios, zero carbon electricity is rounded out by imported electricity, waste generation (landfill and sewage gas plants), and marine sources.

Electricity decarbonisation via CCS can provide the bulk of a 40% reduction in CO_2 by 2050 (CFH). To get deeper cuts in emissions requires three things: a) deeper de-carbonisation of the electricity sector with progressively larger deployments of low-carbon sources; b) increased energy efficiency and demand reductions particularly in the industrial and residential sectors; c) changing transport technologies to zero carbon fuel and more efficient vintages. For example, by 2050, to meet the 80% target in CAM, the power sector emissions are reduced by 93% compared to the Reference. The reduction figures for the residential, transport, services and industrial sectors are 92%, 78%, 47% and 26% respectively. Hence remaining CO_2 emissions are concentrated in selected industrial sectors, and in transport modes (especially aviation).

Figure 2.4 shows both the decline in final energy demand and the increasing role of electricity in satisfying that demand, for the scenarios with different 2050 targets.

Figure 2.4: Final energy demand by fuel under different carbon reduction scenarios



It can be seen that by 2050, electricity generation increases in line with the successively tougher targets. This is because the electricity sector has highly important interactions with transport (plug-in vehicles) and buildings (boilers and heat pumps), as these end-use sectors contribute significantly to later period decarbonisation. As a result, electricity demand rises in all scenarios, and is roughly 50% higher than the Reference in 2050 in most of the 80% reduction scenarios.

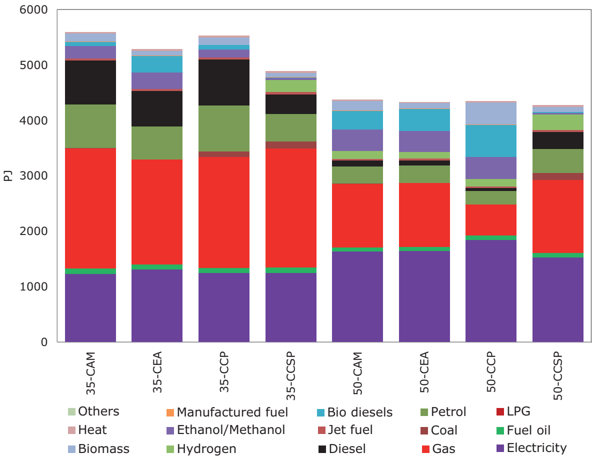
The shift to electricity use in the residential sector (from gas), combines with technology switching from boilers to heat pumps for space heating and hot water heating. The service sector is similarly decarbonised by shifting to electricity (along with biomass penetration in the most stringent scenarios). Natural gas, although increasing in efficiency, is still used in residential and service sectors for space heating and is a contributor to remaining emissions.

The transport sector is decarbonised via a range of technology options by mode, but principally first by electricity (hybrid plug-in), and later by bio-fuel vehicles in more stringent scenarios (CAM, CSAM). There is a trade-off between options to reduce energy service demands, efficiency to further reduce final energy, and use of zero-carbon transport fuels. For example, bio-fuels in stringent reduction scenarios do not reduce energy demand as their efficiency is similar to petrol and diesel vehicles. Different modes adopt alternate technology solutions depending on the characteristics of the model. Cars (the dominant mode - consuming 2/3 of the transport energy) utilize plug-in vehicles and then ethanol (E85). Buses switch to battery options. Goods vehicles (HGV and LGV) switch to bio-diesel then hydrogen (only for HGV).

Figure 2.5 shows the final energy demand by fuel for the three scenarios with equal cumulative carbon emissions to 2050, CEA, CCP and CCSP, with the Low-Carbon Core scenario (CAM) for comparison.

In the early/later action scenarios of CCSP and CCP, which culminate respectively in a 70% and 90% reduction in CO_2 emissions by 2050 (see Figure 2.1), the differing time paths of abatement not only result in different marginal carbon and welfare costs, as seen below, they also give a completely different final energy demand pattern and mix of mitigation technologies. CCP demands more final energy than CEA (the 'early action' scenario) in 2035, as the yearly emission reduction in 2035 is lower. Conversely, CCSP demands less final energy than CEA in 2050 as well as 2035 despite the fact that its annual CO_2 mitigation level in 2035 is similar to CEA.

Figure 2.5: Final energy demand by fuel for the equal cumulative carbon reduction scenarios



Early action in CCSP also drives early and greater use of wind electric generation, and due to lower hurdle rates the greater decarbonisation of transport and use of hydrogen in more modes. The dynamic change thus introduces some path dependency even in a perfect foresight model.

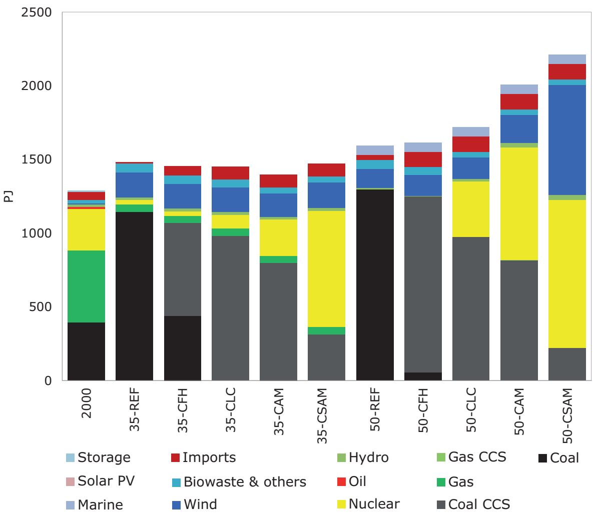
The reason for the low final energy demand in the medium term in CCSP is the relatively low energy demand in the transport sector as the sector is decarbonised by shifting to electricity (hybrid plug in) and hydrogen vehicles (with H_2 generated from electrolysis), with bio-fuel options not being commercialised in mid-periods. High capital cost hydrogen vehicles become relatively cheaper in CCSP. The annualised cost is lower due to the technology specific social hurdle rates. As hydrogen and electric vehicles dominate the transport mix by 2050, this has resultant impacts on the power sector with vehicles being recharged during low demand (night time). Note that the selection of these highly efficient but high capital cost vehicles is strongly dependent on the lowered discount rates in CCSP. By 2050, bio-fuels are not directly used for transport modes in CCSP, in marked contrast to the other scenarios.

Natural gas is mainly used in the industrial sector followed by the residential and service sectors. The residential and service sectors use a very low amount of natural gas in CCP in 2050. The natural gas is replaced by biomass in the service sector and by electricity in the residential sector. Since the natural gas is replaced by biomass in the service sector, some available inexpensive gas is used for power generation gas-CCS in 2050 under CCP. In the CCSP, a large amount of gas goes to boilers for heating.

Figure 2.6 illustrates the electricity generation mix for the different carbon reduction scenarios, showing how a change in the target can result in different levels of the various technologies being chosen by the model.

Total electricity generation would increase or decrease in the mitigation scenarios compared to that in REF depending on the electricity demand. In 2035, electricity generation decreases in line with the successive targets CFH, CLC and CAM (not in CSAM). Conversely in 2050, electricity generation increases in line with the successive targets including CSAM. Decarbonisation by means of efficiency improvement and demand reduction of end-use sectors at lower mitigation targets early and in the middle of the period is the reason for having a decreasing trend for electricity generation in line with the

Figure 2.6: Electricity generation mix under different carbon reduction scenarios (CFH, CLC, CAM, CSAM)



mitigation target. As decarbonisation efforts tighten through to 2050, end-use sectors shifting to electricity leads to relatively high demand for electricity, which has to be generated from low-carbon sources. Hence there is a trade off between the decarbonisation of end-use sectors by shifting to electricity, and both efficiency improvements and demand reductions affect the overall demand for electricity.

As carbon reduction requirements increase in the power sector (almost complete decarbonisation in 2050 in CSAM) the role of coal CCS is assisted and eventually supplanted by nuclear and wind as available CCS capacity is used for hydrogen production and as residual CCS emissions are squeezed out. A large amount of electricity (more than one third) is generated from wind (with capacity balancing) in CSAM in 2050.

Figure 2.7 presents the electricity generation mix in CEA, CCP and CCSP. There is no big difference in overall levels of electricity generation in 2050 among the scenarios. But in 2035, early action CCSP requires a larger amount of electricity as it reduces CO_2 emissions by 60%, including the use of plug-in electric vehicles and electric heat boilers. Electricity demand under CCSP in 2050 is met by a large wind expansion (as an early commercialised zero carbon technology) that necessitates a very large expansion in overall electricity capacity for peak constraints. Wind expansion is mainly offshore as all cost effective onshore wind is already selected in REF itself. The contribution of intermittent renewables such as wind, marine and solar to peak load is limited. Therefore, the selection of renewables (wind power plants) to meet the carbon target needs a large amount of reserve capacity from gas plants, as shown in Figure 2.8, which gives the differences in installed capacity in those scenarios under which carbon abatement takes place earlier (CCSP) or later (CCP).

The higher target levels (CFH to CLC to CAM to CSAM) of carbon reductions produce a deeper array of mitigation

Figure 2.7: Electricity generation mix in CAM, CEA, CCP and CCSP

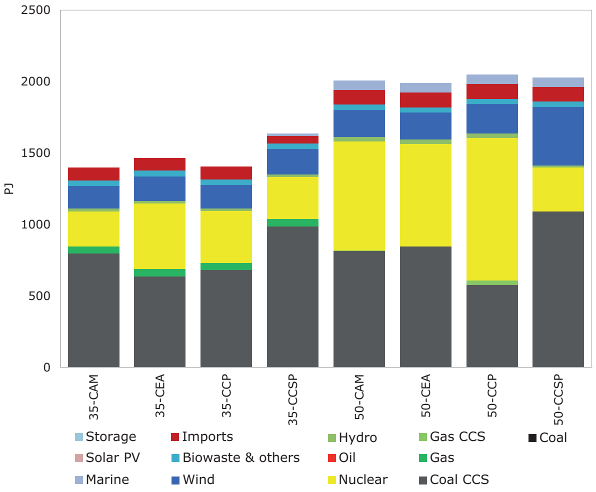
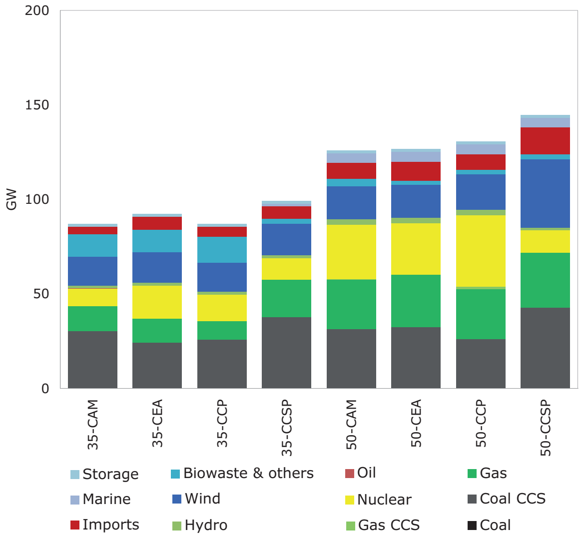


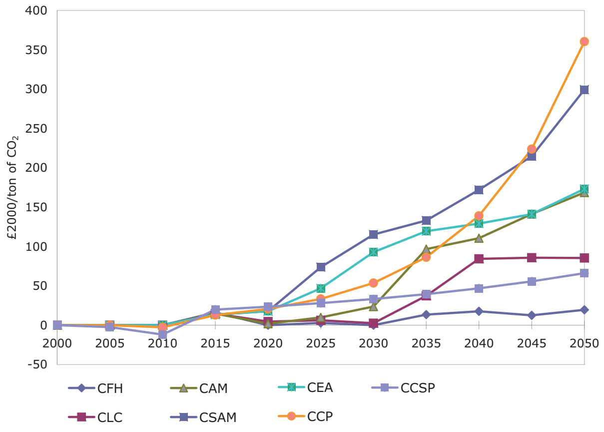
Figure 2.8: Installed capacity under CAM, CEA, CCP and CCSP scenarios



options (likely with more uncertainty), and result in increasing marginal costs of CO_2, as shown in Figure 2.9. In fact the CO_2 marginal costs in 2035 range from £13 - £133t/tCO_2 and in 2050 from £20 - £300/tCO_2. This convexity in costs as targets tighten illustrates the difficulty in meeting more stringent carbon reduction targets.

Giving the model freedom to choose timing of reductions under a cumulative carbon constraint illustrates inter-temporal trade-offs in decarbonisation pathways. CEA, with early action, has a relatively low 2050 carbon price (comparable to the optimal CAM, which has the same 2050 target). Under a cumulative constraint (CCP) the model chooses to delay mitigation options, compared with both CEA and, even more, with CCSP, with this later action requiring CO_2 reduction of 89% in 2050. This results in very high marginal CO_2 costs in 2050, at £360/tCO_2 - higher even than in the conventional 90% reduction case. The CCSP carbon price is not strictly comparable with the others because it reflects the lower discount rate that has been applied.

Figure 2.9: Marginal price of CO_2 emissions under different scenarios

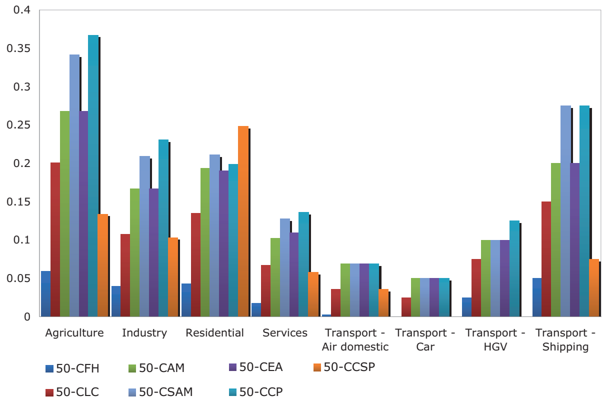


Besides stimulating efficiency and fuel switching (and technology shifting), the increasing price of carbon-based energy also plays a major role in reducing CO_2 emissions by reducing energy service demand (5% - 25% by scenario and by ESD). Agriculture, industry, residential and international shipping have higher demand reductions than the air, car and HGV (heavy good vehicles) transport sectors, as shown in Figure 2.10. This is driven both by the elasticities in these sectors but crucially by the lack of alternative (cost effective) technological substitution options.

The CCP scenario with an emphasis on later action sees its greatest demand reductions in later periods. In the CCSP case demand reductions in 2050 are much lower in most sectors as the model places more weight on (and therefore avoids) the late-period welfare losses in CCP from reductions in ESDs due to the very high carbon price. The exception is in residential electricity where demands are sharply reduced as an alternative to (relatively expensive) power sector decarbonisation.

The reduction in energy service demands is computed by the model as welfare costs (reduction in the sum of consumer and producer surpluses), which in 2050 between CFH and CSAM range from £5 - £52 billion (see Figure 2.11). In particular moving from a 60% to an 80% reduction scenario almost doubles welfare costs (from £20 - £39 billion). The attribution of the welfare loss components to either producers or consumers depends on the shape of the supply and demand curves, and crucially on the ability of producers to pass through costs onto consumers. This is not computed by MARKAL. Note that

Figure 2.10: Selected demand reduction levels in 2050 under different scenarios



welfare losses cannot be compared to a GDP cost as wider investment, trade and Government spending impacts are not accounted for.

Figure 2.12 provides an explicit comparison between energy system costs and welfare costs in the different scenarios (but note that the bars are in no sense additive). At the 2035 date, the energy system costs may be positive or negative (see CLC and CAM in 2035), because the more expensive technologies will tend to increase the costs. However, the downward pressure this puts on energy demand will tend to reduce the overall size (and therefore cost) of the energy system. By 2050, the increased cost of the technologies dominates, and the energy system cost is always positive.

Social welfare is always reduced by both the increased technology cost and the consequent downward pressure on energy demand, which is why the red bars at all dates and in all runs show a negative change in (i.e. a loss of) welfare.

The optimal abatement path in the CCP case gives lower cumulative welfare costs than the CEA scenario with equivalent cumulative CO_2 reductions (but constrained early action). The fact that the CCSP run produces the lowest costs is a reflection of its calculation of the optimal solution under social levels of discounting (and correspondingly reduced technology-specific hurdle rates). One interpretation of this is that consumer preferences change and/or Government works to remove uncertainty, information gaps and other non-price barriers. It should be noted, however, that the reduced discount rates mean that these social welfare costs are not strictly comparable with those in other scenarios.

Figure 2.11: Change in social welfare under different scenarios

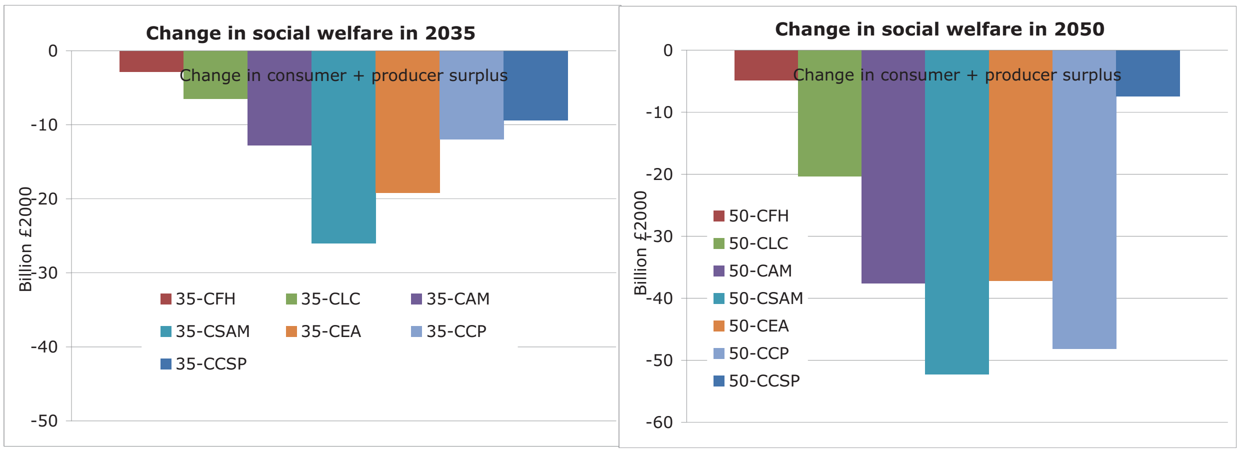
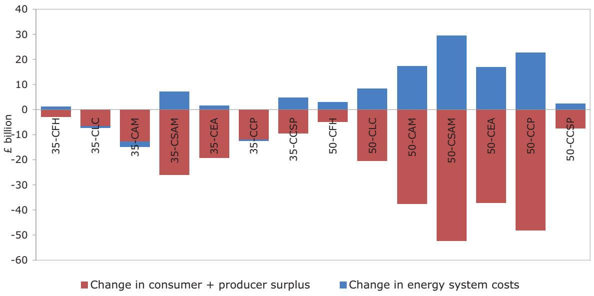


Figure 2.12: Energy system and welfare costs under different scenarios



It must also be stressed again that both these measures (energy system cost and social welfare) are quite different from a GDP cost, which is a metric often cited in such studies. To compute this, a macroeconomic model representation of these runs would be required, which took explicit account of, among other things, the interactions between innovation, investment, Government spending and trade. The Energy 2050 project did not include the use of such a model.

Conclusions for Low-Carbon Policy

Any policy discussion of these insights must recognise that these pathways and energy-economic implications come from a model with rational behaviour, competitive markets and perfect foresight on future policy and technological developments. Even so the policy challenges in achieving 80% CO_2 reductions in the UK are very considerable.

Current low-carbon policy mechanisms have generally been applied in policy packages and include market/incentive-based instruments, classic regulation instruments, voluntary/self-regulation measures, and information/education-based programmes. Three of the more significant policies are the Renewables Obligation (RO), the Carbon Emissions Reduction Target (CERT), and the EU emissions trading scheme (EU-ETS). While these policy packages have signalled the UK Government's aim for accelerated energy efficiency and low-carbon energy supply, the instruments have not been of the required stringency to meet the Government's near-term carbon reduction targets for 2010.

Looking forward, it should be particularly concerning to policy makers that these least-cost optimal model scenarios do not produce decarbonisation scenarios that are anywhere near compatible with the EU's renewables directive, which requires at least 15% of UK final energy demand to come from renewables by 2020. Major contributions of bio-fuels in transport and offshore wind in electricity production only occur in later periods in these model runs, following tightening CO_2 targets and advanced technology learning. In none of the runs is electricity generation from renewables anywhere near the 30-35% of final energy that the Government's recent Renewable Energy Strategy consultation identifies as necessary to meet the EU 2020 target. Very significant policies will need to be implemented to close this gap, as discussed further below.

In the model runs, rising carbon reduction targets (from 40-90% in CFH through to CSAM) give a corresponding rising price of carbon and the model ranges in 2050 from £20-300/tCO_2. In the runs with the same cumulative emissions and discount rates (CEA, CCP) the carbon prices in 2050 are £173 and £360t/tCO_2 respectively, with the latter illustrating the extra price incurred by delaying decarbonisation. For comparison, at current rates the Climate Change Levy amounts to an implicit carbon tax of £8.6/tCO_2 for electricity and gas, and £37.6/tCO_2 for coal. Duty on road fuels in 2008 was about 50p/l. If this is all considered as an implicit carbon tax (i.e. ignoring any other externality of road travel), this amounts to about £208/tCO_2. This means that in the optimal market of the MARKAL model, rates of fuel duty would need to be about doubled in real terms by 2050, while taxes would need to have been imposed on other fuels at about the current fuel duty rate by the same date, in order for the targets to be met. While these tax increases seem large, they are actually a fairly modest annual tax increase if they were imposed as an annual escalator over forty years.

In addition to reduced energy service demands from the price effect, MARKAL delivers reduced final energy demand through the increased uptake of conservation and efficiency measures. The relatively high uptake of the measures across scenarios indicates their cost effectiveness compared to other measures. Such savings would require strong and effective policy measures. It may be that the Carbon Reduction Commitment, an emission trading scheme for large business and public sector organisations due to be implemented in 2009, will provide the necessary incentives for installing these conservation measures.

One example of the uptake of efficiency technologies in buildings is heat pumps, which play a major role in all the 80% and 90% carbon reduction scenarios. At present the level of installation, and of consumer awareness, of heat pumps is very low indeed, and their installation in buildings is by no means straightforward. To reach the levels of uptake projected in these scenarios, policies for awareness-raising and training for their installation need to begin soon.

In the transport sector the model runs give a detailed breakdown of the uptake of different vehicle technologies, including those with greater energy efficiency. Energy service demands (in billion vehicle km) in the transport sector in 2050 are only moderately reduced as the carbon targets become more stringent, but the energy demand required to meet those energy service demands falls by considerably more, (from 2130 PJ in the Reference to 1511 PJ in CAM). This results from a more than doubling of the efficiency of fuel use, combined with a range of electric, bio-fuel and hydrogen zero carbon fuels networks depending on scenario and transport mode. The development of these new vehicle types, and of more efficient existing vehicle types, will be partly incentivised by the carbon price. It is also likely to require an intensification of energy efficiency policies, such as the EU requirements to improve vehicle efficiency, and demonstration and technology support policies to facilitate the penetration of the new vehicle types and networks.

The model runs reported here reveal the single most important policy priority to be incentivising the effective decarbonisation of the electricity system, because low-carbon electricity can then assist with the decarbonisation of other sectors, especially transport and household. In all scenarios, major low-carbon electricity technologies are coal CCS, nuclear and wind. All the low-carbon model runs have substantial quantities of each of these technologies by 2050, indicating that their costs are broadly comparable and that each of them is required for a low-carbon energy future for the UK. The policy implications are clear: all these technologies should be developed.

The development of each of these technologies to the required extent will be far from easy. Most ambitious in terms of the model projections is probably coal CCS, which is taken up strongly from 2020 to reach an installed capacity of 12 GW by 2035 in CSAM and 37 GW in 2035 in CLC (the residual emissions from coal CCS are a problem in the most stringent scenarios). At present, even the feasibility of coal CCS has not yet been demonstrated at a commercial scale. There would seem to be few greater low-carbon policy priorities than to get such demonstrations on the ground so that commercial CCS can be deployed from 2020 (as the MARKAL model currently assumes). However, the required mechanism has yet to be agreed, the demonstrations may reveal unexpected technical problems, and although it is hoped that the auctioning of EU-ETS permits in Phase 3 of the scheme will generate much of the very considerable funds that will be required, the current weakness of the carbon price makes such funding uncertain. The timescale for near-term CCS deployment is therefore beginning to look extremely tight. The availability and uptake of CCS as projected by the model runs are therefore optimistic.

The UK Government believes that energy companies should build new nuclear power stations, and be able to with the measures it has put in place to reduce regulatory and planning risk. However, the underlying investment costs, and expectations of future electricity and carbon prices are all matters of considerable uncertainty. The scenarios envisage later deployment (compared to CCS) of significant investment in new nuclear plant (4 - 30 GW from 2035). The 2035 carbon prices in these scenarios could provide the kind of price required for these investments, but the higher levels of deployment will require that the new generation of nuclear plants are economically and technically proven by about 2015.

It is only in the third area of low-carbon energy supply, renewables, that the UK Government has firm targets for deployment, in the form of the 15% of final energy demand (probably requiring around 35% of electricity) to come from renewables by 2020 to comply with the EU’s overall 20% target by that date. This amounts to a ten-fold increase in the share of renewables in UK final energy demand in 2006.

In the MARKAL scenarios, only 15% of electricity is generated from renewable sources by 2020, and this is if existing policies (Renewables Obligation) are met Current uptake is much lower than required. Even with 15% renewable electricity, the maximum share of renewables in 2020 final energy demand (also including transport and heat in buildings), in the model runs is 5.77% (in

CCSP) which is obviously well short of 15%. There is therefore a very great policy challenge to increase the deployment of renewables over the next ten years. It is worth noting that the slow development of UK renewables to date, has been due to non-price issues, notably planning and grid access problems. These 'non-economic' problems are not likely to be easy to resolve.

The policy analysis here has focused on the scenarios with increasing carbon targets. In addition to changes in timing of decarbonisation, the main areas in which a cumulative constraint scenario (CEA, CCP, CCSP) shows a marked difference in technology choice are in respect of vehicle technology and biomass use. CCSP in 2050 prefers electric hybrid, battery and hydrogen vehicles, so that its use of bio-fuels is very small. This is in contrast to CCP, which makes very high use of bio-fuels in transport modes and bio-pellets in commercial buildings applications. The policy message again is that there is a wide range of developing vehicle technologies, and technologies in other sectors, which become preferred depending on the carbon abatement pathway. It should be the objective of policy at this relatively early stage to give strong encouragement to the full range of technologies, to help to bring them to the point where private companies will invest the very substantial sums required to achieve their commercial deployment.

As stressed by Lord Stern in the Stern Review, a robust, and rising, carbon price is an absolutely essential requirement for this technology development and deployment. The MARKAL model generates such a price as a necessary consequence of the carbon constraint. The Government has yet to find a way of doing so. Until it does, these scenarios and their associated carbon reductions are likely to remain beyond its reach.

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3. A Resilient Energy System

Key Messages

- A resilient energy system provides energy security by being able to recover from shocks and continue to provide energy services to consumers
- Without policy intervention, resilience and security goals will not be met
- Creating resilience requires more focus on reducing energy demand, establishing diverse sources of supply and reinforcing infrastructure, rather than simply decarbonisation of energy supply
- Policies focusing on climate change will help improve resilience but will not by themselves achieve energy security. Conversely, measures aimed at enhancing resilience will lead to lower CO_2 emissions but will not by themselves achieve current CO_2 reduction targets
- Electricity is key to the resilience of the energy system overall because alternative sources of supply are available at broadly similar costs making diversity cheap
- Considerable new gas infrastructure relating to storage and LNG imports will be required to maintain reliability of gas supplies in light of increasing dependence on imported gas and declining domestic supply
- Major shocks impacting on gas supply, going beyond traditional reliability concerns but within the range of historic events, could have impacts measured in £billions, mainly through lost supplies to industrial consumers
- Shocks would also require re-dispatching of electricity supply
- The main measures that would mitigate the impacts of major shocks are further connections to European and international gas markets and investment in storage
- Such mitigation measures are unlikely to be implemented purely through market-driven investments
- Whether government should act to promote such mitigation measures requires a careful consideration of the costs (upfront and certain) versus benefits (realised only in unusual circumstances), and whether interventions will discourage market-driven investments

Introduction

This chapter assesses what constitutes resilience in an energy system and how an energy system with different degrees of resilience can withstand various kinds of ‘shock’, focusing mainly on disruptions to gas infrastructure. The chapter describes how Resilient and Low-Carbon Resilient energy system scenarios have been constructed based on diversity of supply, energy dependence and infrastructure considerations. Through comparison with the Reference and Low-Carbon Core scenarios of Chapter 2, the benefits of building resilience into the system in the event of shocks are described and quantified, through the simulation of various price and supply shocks to the energy system. We focus on the year 2025, just beyond the immediate concerns

of policymakers but well within the lifetime of current investments. Finally, policies for realising energy system resilience in practice are discussed.

What is Resilience?

Anxieties about the vulnerability of the energy system are generally framed in terms of 'energy security' or more restrictively 'security of supply'. For example, DECC (2008a) identifies three elements of energy security: physical security, price security and geopolitical security. This focuses primarily on supply security and resilience and specifically the adequacy of capacity:

> *"Our analysis suggests that the single most important influence on expected energy unserved*[1] *is the overall balance, the margin, between demand and physical supply capacity".*

We have chosen to use the concept of 'resilience' to frame our analysis. The advantage is that resilience can be seen as an intrinsic characteristic of the energy system itself. It does not require us to think about the underlying causes of a particular shock, for example a prolonged interruption of gas supply. We only need to know that a particular kind of shock is possible. Our approach is more analogous to that of the EU (CEC, 2008) whose Energy Security and Solidarity Action Plan has five elements:

- Infrastructure needs and the diversification of energy supplies
- External energy relations
- Oil and gas stocks and crisis response mechanisms
- Energy efficiency
- Making the best use of the EU's indigenous energy resources

As discussed in the introduction, we established a working definition of energy system resilience which draws heavily on the characterisation of resilience in other fields, especially in the ecological sciences:

> *"Resilience is the capacity of an energy system to tolerate disturbance and to continue to deliver affordable energy services to consumers. A resilient energy system can speedily recover from shocks and can provide alternative means of satisfying energy service needs in the event of changed external circumstances."*

This definition identifies energy system resilience as a multi-aspect concept, with at least the following aspects:

- Energy intensity: for resilience the lower the intensity of energy use, the less energy of any kind is required to sustain economic activity
- Diversity: this has three components (Stirling, 2007): variety (the number of energy sources contributing to the system), balance (the share of the various energy sources contributing to the system) and disparity (the difference between the various energy

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[1] The key security of supply indicator under UK policy

sources contributing to the system). The desirability of diversity for energy system resilience may be applied to end-use technologies as well as energy supply

- Reliability: for resilience the equipment installed in the energy system needs to have a high and predictable probability of functioning at its designed capacity. Reliability also implies some element of redundancy – for resilience the energy system capacity needs to be somewhat above the level of maximum expected demand (the 'capacity margin'), so that there is the unused capacity to respond to unexpected failure of energy system components.

Constructing Scenarios for a Resilient Energy System

There can be no single measure of the resilience of an energy system. Instead we have developed a set of indicators reflecting the aspects above that point to the capacity of an energy system to tolerate disturbance (Table 3.1). The criteria for selecting the indicators were: relevance to the working definition of resilience; pedigree in terms of past or existing energy security strategies; and the practicality of implementation in the modelling tools available to UKERC. The indicators were quantified and implemented as constraints in our models. Quantification took place with reference to

Table 3.1: Resilience indicators

Indicator	**Quantified assumptions**
Macro indicators	Final energy demand falls 3.2% pa relative to GDP from 2010 onwards.
	No single energy source (e.g. gas) accounts for more than 40% of the primary energy mix from 2015 onwards
	No single type of electricity generation (e.g. gas, nuclear) accounts for more than 40% of the mix from 2015 onwards
Reliability indicators: gas and electricity	Value of lost load: • £5/kWh (residential electricity) • £40/kWh (industrial electricity) • £5/therm (industrial gas) • Lost load not allowed (residential gas) Loss-of-load expectation (LOLE): • 4 hours per year (0.05% of year)
Infrastructure enhancement	Range of options: • Natural gas storage • Additional LNG import facilities • Additional gas interconnector • Storage of back-up distillate oil at combined cycle gas turbine (CCGT) plant

policy ambitions, current energy planning practices and sensitivity testing of the constraints.

Reducing energy demand is a key element of EU energy security strategy. It will reduce vulnerability to all types of insecurity – physical, price and geopolitical. The 3.2% decoupling of final energy demand from GDP (see Table 3.1) is equivalent to an annual reduction of 1.2% in absolute terms (assuming GDP growth of 2% p.a.). DECC's most recent carbon and energy projections (DECC 2008b) adopt different assumptions about the impact of policy measures set out in the 2007 Energy White Paper through to 2020. Our assumptions about constrained final energy demand correspond roughly to the assumption of the high impact of energy efficiency measures up to 2020 and we assume that the same pace of improvement will continue thereafter. This Resilient scenario can therefore be said to be at the upper end of the plausible range in terms of energy demand reduction. However, it is less ambitious than the 'lifestyle' scenarios developed in Chapter 6.

The diversity constraints were formulated in terms of maximum market shares because: a) this is a simple and intuitive characterisation; and b) such constraints are easily implemented in our models. The quantification was intended to prevent any single energy source from dominating the market but it was subject to some sensitivity testing in order to ensure that the constraints acted in a meaningful way. Generation mix was constrained because the electricity sector was found to play a key role in shifting the primary energy mix. The availability of alternative generating options at similar costs means that diversity can be achieved at a relatively low cost in the electricity sector. The generation mix constraint helps guarantee security of electricity supply and prevents the electricity sector being used to compensate for imbalances elsewhere in the energy sector.

The reliability indicators are used to ensure adequacy of capacity in the gas and electricity sectors. This ties in closely with DECC's approach to energy security which balances the value of energy unserved as a result of statistically predictable fluctuations in demand and plant availability against the cost of providing extra capacity. The capacity margin – the amount by which installed capacity exceeds peak demand – is often taken as an indicator of reliability for electricity supply, as is the loss-of-load probability (LOLP) – the number of winters per century in which demand will not be fully met. There are no formal reliability requirements in the UK privatised electricity markets but markets are routinely monitored to assess indicators such as capacity margin and LOLP. Capacity margins and LOLP were developed as 'rules of thumb' based on more fundamental analyses using the concept of 'value of lost load' (VOLL) at a time when the electricity system was dominated by large fossil and nuclear plant. A capacity margin of around 20% and a LOLP of nine winters per century were the standards used by the former Central Electricity Generating Board (CEGB).

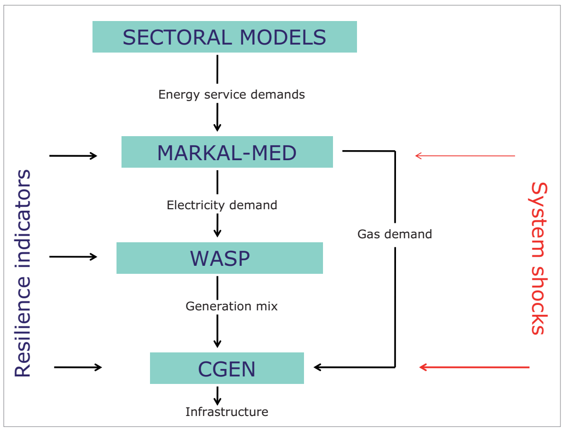
If new types of plant, particularly intermittent renewables, take a large share of the electricity market then the old relationships between VOLL, LOLP and capacity margin will break down. When demand is not fully met, periods of interruption may be longer and more load may be lost. The MARKAL model uses a capacity margin approach, but captures some of the impacts of intermittency by assigning a modest capacity credit (10% of maximum rated capacity) to wind at times of peak demand. Our more detailed network models use the more sophisticated loss-of-load expectation (LOLE) approach – the number of hours per year in which demand is expected not to be met – and also work with predicted values of unserved energy (lost load) to determine capacity levels. Using the LOLE and VOLL constraints increases the capacity needed to meet reliability standards.

Finally, we explore the implications of large 'abnormal' events to which it is difficult to attach statistical probabilities, focusing entirely on disruptions to gas infrastructure. Building up infrastructure through diversity and redundancy and storing more energy can help to mitigate these events. We explore a number of specific options in the following sections.

Modelling Approaches

The analysis has been undertaken by linking a number of the UKERC energy models as shown in Figure 3.1. The sectoral models described in Chapter 6 are used to establish energy service demands that feed into the MARKAL-MED model described in Chapter 2. The electricity demands from MARKAL-MED are then fed into a more detailed model of the electricity system, WASP (the Wien Automatic System Planning model), described below. Finally, the national generation mix from WASP, and gas/electricity demands from MARKAL-MED, then form inputs into CGEN (the Combined Gas and Electricity Network model). The resilience indicators are used to constrain the models. Each representation of the energy system at a given point in time can be subjected to 'shocks' to assess the costs and benefits of building in resilience.

Figure 3.1: Modelling resilience



The WASP Model

The WASP model (IAEA, 2006) is designed to determine a medium to long-term economically optimal expansion policy for a power generation system within user-specified constraints. The model minimises total discounted costs within the specified system reliability constraints. System reliability is evaluated on the basis of three indices: loss-of-load-probability/expectation, unserved energy and reserve margin. The cost of each possible combination of power generating units added to the system that meets the constraints is evaluated. Costs include capital investment, salvage value of investment, fuel, fuel inventories, non-fuel operation and maintenance and the value of energy not served.

System production costs and costs associated with unserved energy are assessed probabilistically. The model relies on detailed assumptions about the load duration curve, generating unit characteristics (i.e. minimum and maximum output levels, availability, efficiency, reserve providing capability, maintenance requirements), the loading order of units and the output of energy limited plants. Linear programming is used to determine an optimal dispatch policy that satisfies constraints on emissions and fuel availability. Dynamic programming is then used to compare and optimise the costs of alternative system expansion policies that would serve the future electricity demand given the required level of system reliability.

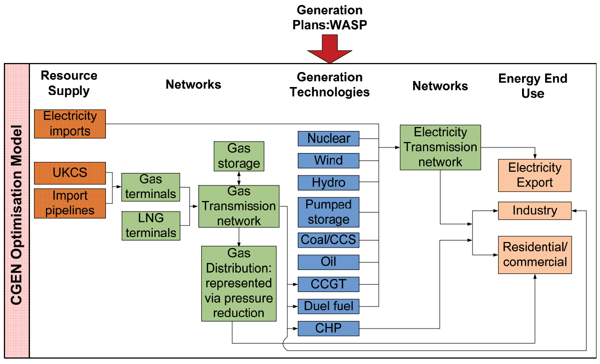
The CGEN Model

CGEN is an optimisation tool for the gas and electricity infrastructure. It minimises total discounted costs related to the combined operation and expansion of the gas and electricity networks whilst meeting demand requirements over the planning horizon. CGEN is a geographical model, thus the connection of gas pipes and electricity transmission wires in a network is explicitly modelled. This geographical element allows a realistic depiction of the physical constraints present in both networks. CGEN can be used in *planning mode* – i.e. it determines new investments so as to minimise the cost of meeting final demand for gas and electricity subject to operational constraints. It computes the cost of energy unserved in a manner similar to WASP. CGEN can also be used in *operational mode* where the network and generation assets are specified by the user. We have used CGEN in planning mode to model the Core scenarios and in operational mode to assess the impact of shocks and mitigating measures.

The components covered by CGEN are arranged into distinct categories as shown in Figure 3.2. These include resource supply, energy transportation (networks), generation technologies and energy end use. Resource supply includes bounds on the availability of primary energy supplies (gas, coal, oil etc) and electricity imports. Detailed modelling of the gas network includes facilities such as pipelines, gas storage and compressor stations. Gas import interconnectors are modelled as gas pipes with maximum transport capacities. The model carries out a DC load flow analysis for the electricity network. The interaction between the two networks is through gas turbine generators connected to both networks (Chaudry et al, 2008).

Generation plans from the WASP model are used as an input into the CGEN model. CGEN locates new generation plants around the electricity network in order to

Figure 3.2: Structure of the CGEN Model



minimise costs. Gas and electricity energy demand is fed into CGEN from MARKAL-MED. The demand is split into residential and industrial/commercial components for gas and electricity. Gas used for electricity generation is determined endogenously within CGEN.

Resilience and CO_2 Reduction

In this section we systematically compare key macro-level indicators from the Resilient and Low-Carbon Resilient scenarios with the Reference and Low-Carbon Core scenarios focusing on the year 2025. Table 3.2 sets out how the indicators move between 2000 (the base year for the model runs) and 2025 in each of the four scenarios.

Although there are synergies between the low-carbon/resilience agendas they are far from being synonymous with each other. The key theme in the Low-Carbon scenario is de-carbonisation of electricity supply with demand reduction making a modest contribution. The key theme in the Resilience scenario is demand reduction with only a modest reduction in the carbon intensity of electricity generation by 2025. The Low-Carbon scenario contributes to reduced energy dependence, but does not

Table 3.2: Resilient energy systems: key macro indicators for 2025 with respect to a 2000 baseline

REFERENCE (REF)		**RESILIENT (R)**	
Primary energy demand:	-7%	Primary energy demand:	-20%
Final energy demand:	+2%	Final energy demand:	-16%
Electricity demand:	+14%	Electricity demand:	+1%
Residential demand:	+5%	Residential demand:	-23%
Max primary share (gas):	38%	Max primary share (gas):	38%
Max generation share (coal):	54%	Max generation share (coal):	40%
CO_2 emissions[1]:	-12%	CO_2 emissions[1]:	-19%
CO_2 intensity power:	513g/kWh	CO_2 intensity power:	464g/kWh
Energy system costs:	£0bn	Energy system costs:	-£2bn
Welfare costs:	£0bn	Welfare costs:	-£19bn
LOW-CARBON (LC)		**LOW-CARBON RESILIENT (LCR)**	
Primary energy demand:	-13%	Primary energy demand:	-20%
Final energy demand:	-2%	Final energy demand:	-16%
Electricity demand:	+6%	Electricity demand:	-8%
Residential demand:	0%	Residential demand:	-20%
Max primary share (gas):	41%	Max primary share (gas):	38%
Max generation share (gas):	31%	Max generation share (coal):	40%
CO_2 emissions[1]:	-36%	CO_2 emissions[1]:	-36%
CO_2 intensity power:	188g/kWh	CO_2 intensity power:	360g/kW
Energy system costs:	+£2bn	Energy system costs:	-£2bn
Welfare costs:	-£4bn	Welfare costs:	-£19bn

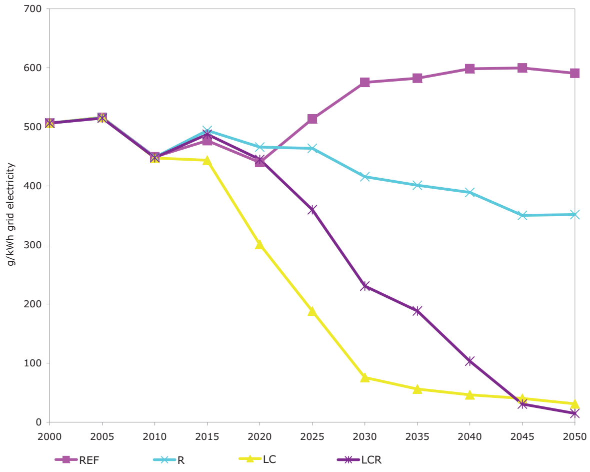
Note 1): CO_2 emissions reductions are measured with respect to 1990

go far enough to meet overall security goals as defined in the Resilient scenario; the Resilient scenario reduces CO_2 emissions, but does not go far enough to stay on the pathway to the 2050 80% reduction goal.

Figure 3.3 shows how the carbon intensity of grid electricity moves through to 2050 in each of the scenarios. In the Reference (unconstrained) scenario, carbon intensity increases due to a switch from gas and nuclear to coal, partly compensated for by increases in renewable generation. In the Resilient scenario, carbon intensity declines gradually because of investment in nuclear and renewables which is, however, partly compensated for by a switch from gas to coal.

The dramatic, and early, reduction in carbon intensity in the Low-Carbon scenario is the result of large-scale investment in coal plant fitted with carbon capture and storage (CCS), nuclear and wind generation. Carbon intensity declines significantly in the Low-Carbon Resilient scenario but lags about a decade behind the Low-Carbon scenario. Electricity demand is lower in the Low-Carbon Resilient scenario. Nuclear's market share is similar to that in Low-Carbon while there is a significant switch from coal CCS to renewables.

Figure 3.3: Carbon intensity of grid electricity



The residential sector is critical to the energy demand reductions that take place in the two resilient scenarios. Residential demand in the Resilient Scenario is almost 30% below that in the Reference scenario by 2025 while demand in the Low-Carbon Resilient scenario is 20% lower than in the Low-Carbon scenario.

The diversity constraints that we have applied to primary energy share and generation mix bite more strongly in the Resilient scenario than they do in Low-Carbon Resilient. In 2025, the Low-Carbon scenario broadly delivers diversity goals. Primary energy meets the diversity constraint in the Reference scenario. However, the large investment in coal results in the generation mix constraint being breached by a large margin. Coal fired generation is constrained off in the Resilient scenario. In the Low-Carbon scenario the constraint on primary energy mix bites mainly because of gas use in the residential sector. Moving to the Low-Carbon Resilient scenario reduces residential energy demand significantly and results in the primary energy mix constraint ceasing to bite. However, coal fired electricity generation, with a mixture of CCS and unabated plant, is then constrained off.

It appears from Table 3.2 that the costs, in terms of welfare loss, associated with building in resilience are much higher than

those associated with pursuing the low-carbon economy. This needs to be interpreted carefully. The largest component of the welfare loss in the two resilient scenarios is associated with reduced energy demand in the residential sector. As noted in Chapter 2, demand reductions in the residential sector are modelled entirely through a price response (rather than, for example, the implementation of conservation measures), leading inevitably to high estimates of welfare loss. To the extent that demand reduction can be secured through relatively low-cost conservation measures, the welfare losses would be reduced, so that those associated with the LC and LCR scenarios in Table 3.2 are very much upper bounds.

Reliability of Electricity Supply

Applying the reliability indicators in Table 3.1 to the electricity system shows that the conventional capacity margin approach will lead to increasingly unreliable supply if significant amounts of intermittent renewable capacity comes on to the system. Figure 3.4 shows how the required system capacity margin (the fraction by which installed capacity exceeds peak demand) changes between 2005 and 2050 under the Low-Carbon scenario if the more formal reliability approach based on VOLL and LOLE is applied. The difference relates mainly to the degree of renewables on the system. With growth in intermittent renewables, the frequency of electricity shortage conditions increases leading to higher levels of unserved energy. However, the average duration of such events generally remains unaffected.

Figure 3.5 shows how, in the same Low-Carbon scenario, the loss of load expectation (LOLE) exceeds accepted norms if the conventional capacity margin approach is adopted. Accepted loss-of-load expectations under current conventional systems range between 2 and 8 hours per year. With more intermittent renewables on the system, the conventional approach could lead to loss of load as high as 150 hours per year by 2040 under this scenario. In the later part of the projection, nuclear forms an increasing part of the mix and LOLE falls off.

The additional capacity and electricity system costs associated with the more formal reliability approach is shown in

Figure 3.4: Capacity margin using different reliability approaches, Low-Carbon scenario

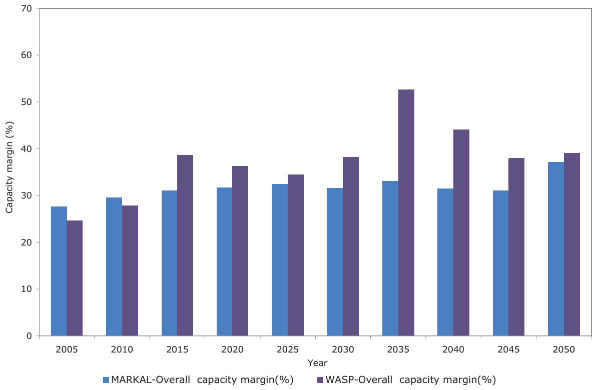


Figure 3.5: Loss-of-load expectation using capacity margin approach, Low-Carbon scenario

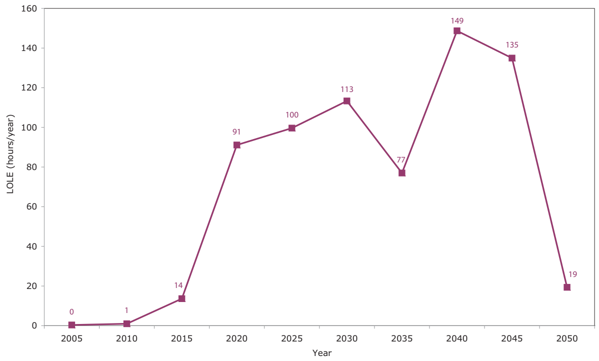


Table 3.3. Beyond 2020, the additional capacity required on the system to maintain reliability is in the range 5-10 GW depending on the scenario and the precise point in the projection. The cost of maintaining this capacity, which would be seldom used, is largely associated with capital costs and could run into several hundreds of millions of pounds per year. As an indicator, the £354m incurred in the Low-Carbon Resilient scenario in 2020 is equivalent to £1.03/MWh of all electricity generated and £9.85/MWh of wind energy generated. The modelling suggests just over 12 GW of wind on the system at this point.

Reliability of Gas Supply

When the UK was self-sufficient in gas supplies, the response to uncertainty in the gas market largely came down to turning the tap on and off. With the prospect of the UK becoming largely dependent on imports, other measures are required to ensure reliability of gas supplies. These include greater interconnection with Europe, opening up to global LNG markets and investing in storage.

We have operated the CGEN model using the indicators from Table 3.1 to assess the investments needed to ensure reliable gas supply through to 2050 under each of the four core scenarios. After taking account of current and committed projects, the CGEN model chooses between additional pipeline interconnectors, LNG terminals and gas storage facilities. Table 3.4 shows investments selected under the four core scenarios in addition to current and committed capacity. New interconnectors are not selected but there is considerable investment in new LNG terminals to compensate for declining domestic supply. This is largely driven by assumptions about

Table 3.3: Additional capacity and zystem costs to ensure reliability

	Additional System Capacity (GW)			**Additional System Cost (£m pa)**		
	2020	2035	2050	2020	2035	2050
Reference	1.3	5.5	5.5	67	274	277
Low-Carbon	3.7	11.5	4.4	187	575	219
Resilience	6.8	5.9	9.1	341	296	457
Low-Carbon Resilience	7.1	5.4	6.2	354	269	312

Table 3.4: Gas infrastructure investments

	Reference (REF)	**Low-Carbon (LC)**	**Resilient (R)**	**Low-Carbon Resilient (LCR)**
Interconnectors	No additional	No additional	No additional	No additional
LNG terminals	40 mcm/d 2015 20 mcm/d 2020 60 mcm/d 2025 40 mcm/d 2030	40 mcm/d 2015 20 mcm/d 2020 60 mcm/d 2025 40 mcm/d 2030	40 mcm/d 2020 40 mcm/d 2025 60 mcm/d 2030	40 mcm/d 2020 40 mcm/d 2025 60 mcm/d 2030
Storage	1000 mcm 2015	1000 mcm 2015	No additional	No additional

the relative cost of continental gas and gas available through LNG markets. New, additional storage is selected in the Reference and Low-Carbon scenarios but not in the resilient scenarios where final gas demand is much lower.

Figure 3.6 shows the gas market balance out to 2030 under each of the four core scenarios. This illustrates starkly the degree to which the UK will become import dependent. The broad pattern across all scenarios is that LNG capacity substitutes for UK domestic production and, in the 2020s, for Norwegian imports. In the two resilient scenarios, where gas demand is lower, Norwegian imports are reduced more quickly.

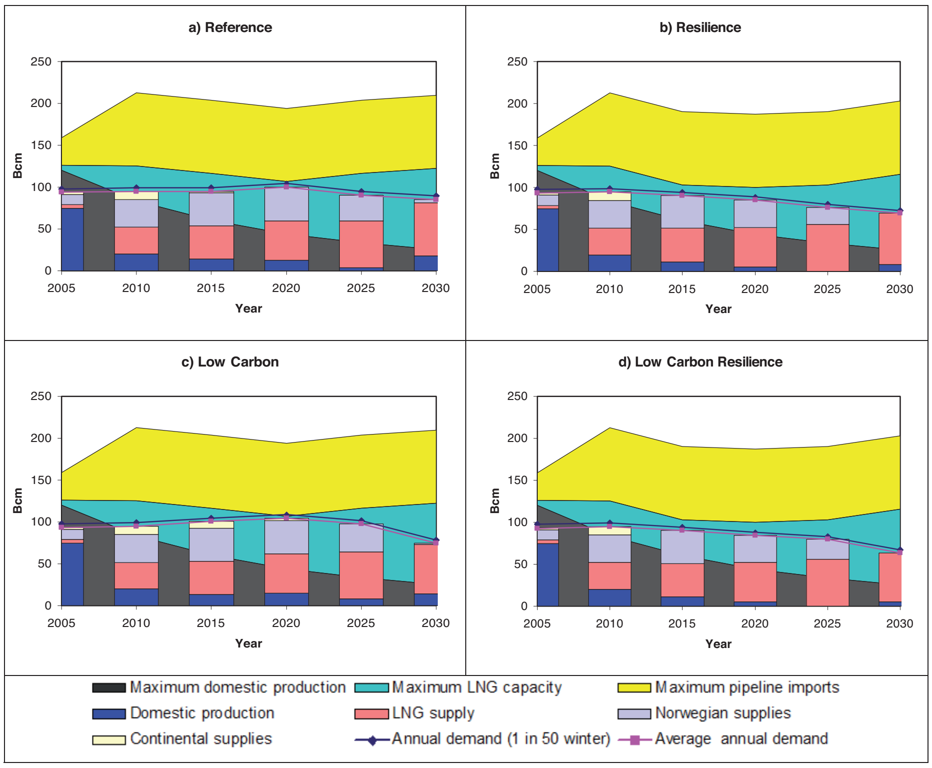
System Shocks

We have hypothesised three possible 'shocks' to the UK energy system that impact on gas supply facilities (Table 3.5). We have assumed that the impact of each shock is experienced over three different durations - 5, 40 and 90 days. In each case we have assumed that the shock occurs in mid-winter, nominally 1 January 2025, during a period of 'average cold spell' demand. These are deliberately severe events. However, they are within the range of recent experience. An explosion at the Bravo rig in the Rough field took the storage facility out of service for two months in 2006. Gas supplies through Easington were interrupted for five days after it was struck by lightning in 1999.

Table 3.6 shows the impact of the three events against the background of each of the core scenarios. The key messages are:

- The loss of the largest terminal, Bacton, which affects both imported

Figure 3.6: Gas supply/demand balance in the four core scenarios



and domestic gas supplies, has the largest impact

- The energy system can 'ride through' the loss of Easington or Milford Haven under the Resilient and Low-Carbon Resilient scenarios – and the impact of losing Bacton is much diminished. This is because these two scenarios are characterised by lower levels of residential gas demand which is strongly seasonal. The system can cope better when demand is less 'peaky'. Demand reduction demonstrably contributes to energy system resilience
- The imputed value of unserved energy (in £bns) is an order of magnitude larger than the changed system costs. System costs generally rise as more expensive gas is sourced and coal substitutes for gas in electricity generation. This however does not take account of the response in energy spot markets that would be expected following such events, which would tend to increase costs further
- The patterns of response are complex because the facilities play different roles in the gas network. In none of the scenarios is it necessary to curtail electricity supplies. Response is taken up entirely by exercising interruptible gas contracts, re-dispatch of the electricity system, use of distillate oil at certain CCGTs and non-contracted industrial gas interruptions

Table 3.7 assesses how different lengths of interruption could affect outcomes. The loss of Easington is taken as an example. The clear message is that shorter periods of interruption, of the order of days, can be accommodated through system adjustments with very little loss of load. Beyond a certain threshold, the costs increase rapidly, but they are less than linearly related to the length of the interruption.

Mitigating Shocks

The analysis above is based on the assumption that investment takes place to

Table 3.5: Description of facilities

Facility	**Description**	**Size**
Easington gas terminal	Connects the UK gas system to the Rough storage facility and the Langeled pipeline from Norway	Can deliver 120 mcm/day (equivalent to 35% of UK annual demand). Rough can store 3.3 bcm of gas, equivalent to 10 days average winter demand
Bacton gas terminal	Connects the UK to continental Europe via Zeebrugge and Balgzand. Also links to some domestic production	Can deliver 144 mcm/day (equivalent to >40% of UK winter demand). Also used for export
Milford Haven LNG terminal	Two terminals being commissioned in 2009	Each can process 55 mcm/day of gas delivered by LNG tankers (equivalent to 15% of winter demand)

Table 3.6: Impact of 40-day shocks in the four core scenarios

	Energy unserved (mcm)	Value of energy unserved[1] (£m)	Change in system operating costs[2] (£m)
Reference (REF)			
- Bacton	1839	3404	-7
- Easington	1049	1942	+137
- Milford Haven	866	1604	+104
Low-Carbon (LC)			
- Bacton	1718	3179	+29
- Easington	1155	2138	+144
- Milford Haven	1015	1878	+89
Resilient (R)			
- Bacton	244	452	+203
- Easington	-	-	-
- Milford Haven	-	-	-
Low-Carbon Resilient (LCR)			
- Bacton	704	1303	+135
- Easington	-	-	-
- Milford Haven	-	-	-

Notes: 1) using the values of lost load in residential and industry from Table 3.1; 2) this does not allow for the likely rise in spot prices for gas

Table 3.7: Impact of the loss of Easington for different periods

	Energy unserved (mcm)	**Value of energy unserved (£m)**	**Change in system operating costs (£m)**
Reference			
- 5 day	14	26	+29
- 40 day	1049	1942	+137
- 90 day	1857	3438	+294
Low-Carbon			
- 5 day	12	23	+32
- 40 day	1155	2138	+144
- 90 day	2127	3937	+242

meet the reliability standards set out earlier. It is also possible to undertake additional infrastructure investment that would help to mitigate the impacts of major shocks. This section investigates the benefits that such investment might bring in the event of such shocks and sets them against the costs. Table 3.8 shows seven alternative projects which would increase the resilience of the gas supply network.

We focus on the loss of Bacton, the most severe shock, for a 40-day period and

Table 3.8: Gas infrastructure projects

Project	**Capacity**	**Cost (£m)**
Storage facility similar to Rough	3000mcm delivering 40 mcm/d, located near St Fergus	475
Two storage facilities	Salt cavities each with a capacity of 500mcm delivering 40 mcm/d	550
Expansion at one LNG terminal	40mcm/d at Teesside	400
Expansion at two LNG terminals	20 mcm/d at each of Teesside and Isle of Grain	405
New gas interconnector	40 mcm/d through Theddlethorpe	340
Backup distillate storage at CCGTs	5 days storage at 6GW plant	15
Major distillate storage at CCGTs	40 days storage at 6GW plant	215

Table 3.9: Impact of mitigating investments: Bacton out for 40 days

			10% investor rate of return		3.5% regulated rate of return	
	Energy unserved (mcm)	Reduction in cost of shock (£m)	Additional annual costs (£m)	Return period (years)	Additional annual costs (£m)	Return period (years)
No investment	1718	-	-	-	-	-
Storage facility^1	1104	1093	52	21	17	63
Storage facility^2	832	1598	52	31	17	93
Two storage facilities	1246	832	60	14	20	42
One LNG terminal	786	1572	44	36	15	108
Two LNG terminals	789	1569	45	35	15	105
Gas interconnector	790	1600	37	43	12	129
Distillate storage	1685	53	2	32	1	96
Major distillate storage	1246	767	24	32	8	96

Notes: 1) facility half full in mid-winter; 2) facility completely full

assess the impact of these mitigating investments for the Low-Carbon scenario. The pattern of impacts is similar for other shocks, periods and scenarios. Table 3.9 shows the degree to which each individual mitigating investment would reduce the volume of energy unserved. The biggest impact comes from the expansion of import facilities, be they new LNG terminals or a new interconnector. Five days distillate storage has little impact (as might be expected for a 40 day outage) but dedicated gas storage and 40 days distillate storage have half to two thirds the impact of more import facilities.

The conclusion about the impact of gas storage is critically dependent on how much gas is assumed to be in store at the time of the shock. For the major storage facility we have considered two options: a) that the facility is half full in mid-winter; and b) that it is kept completely full for

emergencies. This has a significant effect on the conclusions. Note also that the analysis does not take into account changes in spot market process that might be expected to take place.

Making a mitigating investment can be regarded as taking out insurance against the eventuality of adverse events. If the event is expected to occur regularly, the investment might make sense. If it were extremely rare it might be better to forego the insurance costs and accept the consequences. The 'return period' in Table 3.9 refers to the frequency with which the event would need to take place for each of the mitigating investments to pay off in the long run. If the investor requires a market rate of return of 10% real, investing in two new LNG terminals might be expected to pay off in the long run if a 40-day outage at Bacton were to occur more frequently than once every 35 years. Given the severity of the event, and the improbability of its happening as frequently as this, it is almost impossible to conceive of this as a good investment in a market context.

On the other hand, investment in these mitigating measures could be regarded as being in the public interest for strategic reasons. At a rate of return on investment of only 3.5% real, the investment might still 'pay off' if the event were to occur as infrequently as once in 100 years. There might therefore be a case for the regulator allowing the costs of such an investment to be passed on to consumers, whereby companies would be prepared to accept a lower risk-free rate of return. The difficulty is that it is not possible to allow a risk-free rate of return on only one such asset. If this approach were adopted, there would be no market-driven investments, because infrastructure investments with guaranteed returns would effectively drive out investments that were exposed to normal market risks.

Adding up the Costs of Resilience

Ultimately, deciding how much to invest in and promote resilience in the energy system is a political decision that must be informed by evidence, albeit in the light of deep uncertainty. In this section we draw together evidence from the preceding analysis to assess the overall economic impact of investing in resilience.

Table 3.10 summarises how system costs and welfare costs change in moving from the Reference and Low-Carbon scenarios to the Resilient and Low-Carbon Resilient scenarios respectively. The high-level goals refer to the resilience constraints imposed on final energy demand and the energy mix. Electricity reliability costs refer to the additional system costs of maintaining capacity sufficient to meet reliability criteria over and above maintaining a conventional capacity margin. These costs are essentially associated with the greater use of intermittent renewables. Finally, infrastructure costs are those associated with mitigating the effects of major disruptions to the gas system.

Energy system costs change when the high-level constraints are applied, but so do welfare costs. It is important to note that the very high loss of welfare potentially associated with building in the high-level resilience goals (£15-19bn in 2025 – see Table 3.10) is very much an upper bound, and true welfare loss could be very much lower, or even non-existent. As discussed in Chapter 2, the response of residential consumers was modelled solely through a demand elasticity that caused them to reduce their demand for energy services, and did not allow conservation measures (which might be very low cost) to be chosen endogenously.

To get some insights into the possible effect of this assumption, we allowed certain residential conservation measures back into the model. As a result, a quarter of the demand reduction was achieved through conservation rather than a price-driven demand response. This lowered welfare losses by £2-3bn pa in 2025. If all of the demand reduction could be achieved through conservation then the welfare losses could be eliminated entirely.

The 'lifestyles' scenarios discussed in Chapter 6 achieve demand reductions even greater than those in the resilience scenarios discussed in this chapter. They are underpinned by both a greater adoption of conservation measures and a reduction of energy service demands, for example through turning down of thermostats in the home or reducing travel. In 2025, the energy system cost is £35bn pa lower in the LS LC (lifestyle change, low-carbon) scenario than it is in the Low-Carbon Scenario. This appears to be a classic win-win-win situation where energy conservation will bring economic, environmental and security benefits. However, the critical issue is whether reduced energy service demands are associated with welfare loss. If people are forced into discomfort through high energy

Table 3.10: Estimated costs associated with different aspects of resilience in 2025

	Reference ↓ **Resilient**	**Low-Carbon** ↓ **Low-Carbon Resilient**
High-level goals		
- Change in annual system cost[1]	-£2.0bn	-£4.6bn
- Loss of welfare[2]	Up to £19bn	Up to £15bn
- Change in system cost through 25% conservation[3]	-	£0.9bn
- Mitigation of welfare loss through 25% conservation[3]	£3.1bn	£2.3bn
- Reduced system cost through lifestyle change[4]	£33bn	£35bn
Electricity Reliability		
- Cost of additional capacity margin[5]	~£300m	~£300m
Infrastructure		
- Enhanced gas import or storage capacity[6]	£45m	£45m

Notes: 1) from MARKAL runs; 2) change in consumer and producer surplus from MARKAL assuming a price-induced response in the residential sector; 3) mitigation of welfare loss when conservation measures (which deliver about 25% of residential demand reduction) are allowed in MARKAL; 4) the reduced cost of the energy system when adding lifestyle change to the REF and LC scenarios respectively); 5) the cost of additional capacity determined by WASP as opposed to MARKAL. These additional costs vary considerably from one year to another; 6) annualised cost of two LNG terminals

prices the welfare loss is real. On the other hand, if thermostats are turned down though pro-active lifestyle choice then welfare might arguably increase.

A key point from Table 3.10 is that high-level resilience goals bring costs or benefits that are an order of magnitude higher than those associated with guaranteeing reliability of supply or insuring against infrastructure loss. The uncertainties associated with the costs of the high-level goals are equally large. However, as shown above, if the high-level goals are pursued then the case for infrastructure measures is considerably reduced.

Economic Vulnerability of Energy Dependence

The international price of oil has proved extremely volatile over the last few decades. Gas and coal prices tend to follow those of oil. This leaves any economy heavily dependent on fossil fuel imports economically vulnerable to price movements. By 2025, the UK will be importing most of the fossil fuels it uses, and it will almost certainly be imports that meet demand at the margin. Table 3.11 shows the level of primary demand for fossil fuels in each of the four core scenarios, illustrating that moving from the Reference and Low-Carbon scenarios to the Resilient and Low-Carbon Resilient scenarios would reduce total fossil fuel demand by 16% and 6% respectively.

The Table also considers the annual cost associated with oil prices rising by \$100/barrel and gas and coal prices moving proportionately. Although building in resilience makes a great deal of difference to the level of fossil use depending on whether the UK is on a low-carbon pathway, it makes remarkably little difference to the reduction in energy costs. This is because change in demand is for coal, the cheapest fossil fuel, while oil, the most expensive, changes least. In both the Reference and Low-Carbon scenarios, building in resilience lowers the increased energy costs by £5-6bn, or around 0.5% of current GDP levels. Most of this would be imported energy. The total impact of the \$100/barrel price increase would be around £42bn, or almost 4% of GDP in both the REF and LC scenarios, of which resilience

Table 3.11: Fossil fuel dependence in 2025 (PJ) and impact of a \$100/barrel oil price rise

	Oil	Gas	Coal	TOTAL
REF	2299	3112	2161	7572
R	1933	2706	1655	6294
Reduction in R	366	406	506	1278
Reduced economic impact	£3.0bn	£2.6bn	£0.9bn	£6.5bn
LC	2280	3262	1262	6804
LCR	1933	2725	1706	6364
Reduction in LCR	347	537	-444	440
Reduced economic impact (£bn)	£2.8bn	£3.4bn	-£0.8bn	£5.4bn

would save about 12%. This demonstrates the economic benefits of building in resilience.

Policies for Resilience

Resilience requires diversity of energy supply and therefore investment in a range of energy sources. It also requires investment in electricity and gas infrastructure over and above what might be required for decarbonisation alone. It also requires a greater emphasis on demand reduction than purely low-carbon scenarios, which tend to emphasise decarbonisation of energy supply.

The demand reduction points will be picked up in the final chapter of this report. Here the emphasis will be on the issue of investment, and the policies that are required to ensure that it is delivered in the quantity and form required for a resilient energy system.

The presumption underlying UK energy policy is that the first choice of delivery of energy services is through competitive energy markets (see, for example, DTI 2007, p.137: "We believe the UK's energy needs are best delivered by a liberalised energy market. The Government's role is to set the overall market and regulatory framework that enables companies to make timely investments consistent with the Government's policy goals on climate change and security of energy supplies.")

However, it is also clear that where there are market failures, Government intervention may seek to rectify these. Where the failures are in respect of inadequate competition, the intervention is likely to take the form of regulation. Where they involve externalities or public goods, public policy may seek to address them through regulation, economic instruments or some other intervention. To the extent that energy system resilience, or security, is a public good and Helm (2003, p.260), for example has written with regard to the electricity system: "Security of supply... is a *system* property with important public-goods characteristics.", then public intervention to provide it to the desired extent is clearly justified. This statement applies equally to the gas system. However, there is clearly room for debate over both the nature and extent of that intervention, the outcome of which will have a considerable influence on the institutional structure of the energy system and how public policy seeks to act through it.

Resilience and the network industries

In the UK energy system, the supply of energy-using equipment, from machinery to vehicles to household appliances, has long been left almost entirely to a market regulated only in terms of health and safety characteristics (though some equipment is now environmentally regulated too). The retail supply of energy carriers (fossil fuels, biomass and electricity) was the subject of privatisation in the 1980s and these markets have been progressively deregulated, so that there is now no formal price regulation, although energy prices can be subject to substantial and overt political pressure. However, energy supply is subject to regulatory oversight by the gas and electricity markets regulator, Ofgem. Ofgem has a direct role in price regulation of the gas

and electricity distribution and transmission companies, for whom competition is either very restricted or non-existent.

Ofgem's price regulation of gas and electricity distribution and transmission has important implications for energy system resilience because this resilience requires investment, on which the transmission and distribution companies need to make a return. This investment must be permitted by Ofgem in the regular price reviews relating to the companies, through which the companies are allowed to adjust their prices to generate the return. Ofgem (2009) has just initiated a consultative process to address fundamental questions about the existing regulatory framework and whether it provides enough encouragement for network companies to help deliver broader social and environmental objectives.

In relation to policy for investment for energy system resilience, there are three possible models:

1. Government provides the appropriate framework for the market to make the investment (the model through which electricity supply and gas storage and international pipelines are supposed to be provided)
2. The regulator permits the investment through price reviews, but the investment is provided by the regulated companies (this is the model for electricity and gas transmission and distribution)
3. Government carries out the investment itself (this was the principal model before privatisation)

Internationally, recent events have indicated two main challenges to energy system resilience from events outside the UK: physical supply disruption (as occurred recently with Russian gas) and energy price spikes (as occurred in 2007/08, and are widely predicted to occur again as and when energy demand picks up after the economic downturn).

Government policy to address these challenges to energy security (DTI 2007, p.35) consists of "promoting open, competitive energy markets" in the European Union (EU) and other regions; planning for unforeseen contingencies such as major disruptions (perhaps, in the case of gas, through ensuring that enough storage is available; "driving investment" in a diverse range of (low-carbon) technologies (although from the above it is clear that the investment itself will actually take place through market decisions); and "promoting policies to improve energy efficiency". The international approach is therefore very similar to that being pursued in the UK. This is the approach which will therefore be focused on here.

As discussed above, the core resilience issues of reliability and redundancy in the electricity system (given the very limited current electricity storage options) are reflected in the capacity margin (the gap between generating capacity and peak power demand), which is an important parameter in all the models used in the analysis in this chapter.

Current UK Government policy is to deliver an adequate capacity margin by having a licensing obligation on power companies to meet energy demands, and then relying on markets, through price signals, to deliver the capacity that may only be rarely used, but will then command a high price for power generated. One alternative to this approach is to make explicit capacity payments for plant that may not be much used. The desirability and efficiency of this is still the subject of debate and involves complex economic arguments related to the functioning of markets that are outside the scope of this paper (see Oren 2000 for some of these). Another approach is to allow the network companies to earn a regulated rate of return on generation plant that supports system stability. The current capacity margin appears to be adequate, but there are anxieties about the adequacy of current market arrangements to provide back-up capacity in the context of the large-scale expansion of renewable energy.

With gas and oil, storage capacity is key to resilience. As with the capacity margin, the current approach of the UK Government is to expect market signals to provide the incentive to invest in such capacity. For gas, the fossil fuel over which there is the principal security of supply concern, National Grid breaks down supply into UK Continental Shelf (declining), imports (increasing) and storage, while imports are distinguished by supply type (Norway, Continent and LNG) and import route (the various pipelines to Norway and elsewhere on the European mainland, and LNG), but not, interestingly, by country of origin. The market approach to the provision of supply infrastructure has had some success over the past few years, with new pipelines to Norway (Langeled) and The Netherlands (Balgzand-Bacton) opening in 2006, and two large LNG facilities at Milford Haven expected to open in 2009. While storage has been slower to increase, there is expected to be very substantial construction over 2010-14, such that by 2018 there will be storage space for some 10% of UK projected annual demand (DECC 2008a, p.72).

Efficiency and diversity

In contrast to gas storage and the capacity margin, which have long been a policy focus, the role of diversity and energy efficiency/productivity in promoting energy system resilience has been given less attention. These are the areas which have therefore been given particular attention in the analysis above. In particular it has been specified that a resilient energy system requires diversity in primary energy, diversity in the power sector, diversity in end-use technologies and lower energy intensity. Focusing here on supply, in a centrally-driven energy system it would be relatively easy in principle to ensure energy system diversity by building capacity of different types of plant. In a market-driven context, such as that currently in place in the UK, such an outcome may be more difficult to ensure. The key question is therefore how policy can ensure that the private sector comes forward with the required investment in diverse supply sources, which will also need to be low-carbon if they are to be consistent with carbon reduction targets.

Chapter 2 made clear that there is a range of (low-carbon) options for energy and electricity supply. Primary energy sources include the fossil fuels (coal, oil, natural gas), uranium, various renewables (of which onshore and offshore wind, biomass and possibly large tidal seem likely to play the largest role, although microgeneration technologies may also make a contribution). In transport, oil is dominant, but for the future it is possible that electricity will have a major role, either directly or through the production of hydrogen by electrolysis. For heat, natural gas plays the largest role (although biomass could substitute for this to some extent), so that the substantial use of natural gas also for power generation may present issues of diversity and security of supply. Electricity may be generated by any of the above primary energy sources, although in a low-carbon world the use of fossil fuels for this will require effective carbon capture and storage (CCS) technology to be deployed as well. As is seen in the next chapter, a carbon constraint in the absence of CCS very substantially reduces the electricity options available. This could lead to significant diversity issues.

There are therefore three broad policy priorities if the supply side of a resilient (and low-carbon) energy system is to be realised. The first is to prove the required technologies technically at a commercial scale. There is still work to be done here on all the large-scale centralised low-carbon electricity options that are closest to deployment (offshore wind, new nuclear and CCS), as well as much more to be done on less developed renewables such as marine technologies. There is a critically important role here for research, development and demonstration (RD&D) policy. Energy research funding in the UK collapsed in the 1990s, and has only recently been somewhat increased from very low levels. It is very important that it is not reduced again, but continues to increase, in the times of public spending constraint that seem likely to ensue because of current fiscal deficits.

The second priority is to ensure that the required financial incentives are in place for the private sector to make large-scale investments in technologies which are not yet competitive with fossil fuels. The carbon price established through the EU Emissions Trading Scheme (EU ETS) is currently far from robust enough to provide the required incentive. Clearly, with regard to renewable electricity, the Renewables Obligation did not do so either, and may or may not do so with the banding of the Renewables Obligation Certificates (ROCs) that is now being introduced. The success or otherwise of this must be very closely monitored, so that the incentive can be swiftly adjusted if it becomes clear that it is not sufficient, for example, for the very large and fast deployment of offshore wind turbines that will be necessary to meet the EU renewables target for 2020.

The third priority is to ensure that there are no non-financial constraints to the deployment of the different desired capacity options. Such constraints are neither easy to identify nor easy to remove, as is clear from the analysis of the UK's experience with onshore wind energy in IEA 2008 (p.17). Despite having among the highest remuneration levels for onshore wind in Europe, the UK has among the lowest deployment levels, and this is put down to non-financial constraints.

The policy conclusions on the supply and infrastructure aspects of energy system resilience are therefore broadly as follows. The current policy approach seems able to bring forward adequate investment for the private sector to build enough capacity and infrastructure to meet overall levels of UK energy demand, but is clearly struggling to ensure adequate diversity and adequate low-carbon sources in this new capacity – left to itself proposals for new electricity plant capacity could easily be dominated by coal and gas. The major delivery issues around the low-carbon technologies that are also required for energy system resilience are ensuring technical readiness for large-scale commercial deployment, adequate financial incentives for the private sector for that commercial deployment to take place, and the timely removal of non-financial barriers to that deployment so that it is not delayed or prevented. Resolving these delivery issues surrounding the major low-carbon sources of energy supply are the core policy imperatives for a low-carbon energy system, as was seen in Chapter 2. They turn out to be no less important for energy system resilience as well.

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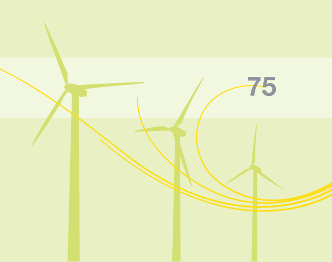
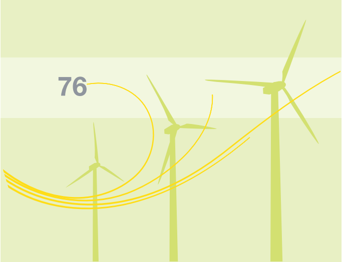


4. Technology Acceleration

Key Messages

- This chapter analyses the prospects for accelerated development of a range of emerging low-carbon energy supply technologies – and the possible impact of this on UK energy system decarbonisation
- The results suggest that technology acceleration could have a major influence on decarbonisation, by introducing new decarbonisation pathways with significantly increased contributions from renewables and hydrogen fuel cells in the longer-term
- 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. Raising the decarbonisation ambition from 60% to 80% does not mean doing 'more of the same' – it introduces new technology preferences and research priorities
- The 'learning potential' of emerging technologies over long timescales implies that short-term targets for technology deployment may be inconsistent with the most economically desirable long-term decarbonisation pathways
- Although it carries shorter-term implications for system planning and innovation support, supply side technology acceleration only has major impacts on deployment over the longer-term, especially after 2030. In the shorter-term, decarbonisation will require other responses, such as demand reduction, improved energy efficiency, and making best use of more mature supply technologies
- The analysis suggests that technology acceleration could substantially reduce the overall cost of decarbonisation, especially for achieving 80% 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
- The overall benefits to the UK of accelerated development appear to considerably outweigh the investment costs, suggesting that the UK should participate fully in global efforts at low-carbon technology innovation
- The results suggest that greatly expanded levels of spending on low-carbon energy supply RD&D (Research, Development and Demonstration) in the UK is justified, as part of wider international efforts. The suggested savings associated with technology acceleration could be translated into an annual budget for additional UK RD&D investment of around £1bn – an order of magnitude greater than current public spending levels – although much of this would need to be committed well before significant 'returns' start appearing after 2030



Introduction: Innovation and Decarbonisation

This chapter 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 decarbonising 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 research has involved bringing together detailed understandings of specific energy supply technologies, and insights on energy system change provided by system modelling and innovation studies. More specifically, the research 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.

Any comprehensive response to the decarbonisation challenge must consider how to best support the development of emerging low-carbon energy supply technologies. For many countries, however, these capacities have been eroded over recent history. As outlined in Chapter 1, levels of funding for energy RD&D 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.

More recently, growing concerns about climate change and energy security have prompted increased spending on energy RD&D, and global investment in sustainable energy technologies rose by over 50% in 2007 (UNEP, 2008). Although this upward trend is being affected by oil and gas price fluctuations and the general economic downturn, the challenge of climate change provides 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. There are many difficulties in systematically assessing this activity, and 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.

Energy systems tend to inertia and path dependency. This means that without major political, institutional or economic interventions, the UK energy system will 'lock-in' around existing technologies and fuels. Energy production in the UK has historically been highly dependent on fossil fuels, and this remains the case today. While coal use has declined steadily since 1970, gas and electricity consumption have substantially increased, and petroleum has been the single most significant end-use fuel throughout the past 30-40 years. In the electricity sector, coal-fired generation made up two-thirds of electricity produced in the UK as recently as 1990 (BERR, 2008). Since then, natural gas has also become an important fuel for electricity production, although conventional coal-fired generation remains significant, despite high levels of associated CO_2 emissions. Renewable energy technologies have only ever been a very minor contributor to energy production in the UK.

The Accelerated Technology Development Scenarios

The research summarised here has involved devising accelerated technology development (ATD) scenarios of UK energy system decarbonisation (which assume high levels of technological progress over time), and comparing these with non-accelerated equivalent scenarios. Given the uncertainties involved in the rate and direction of technological change, the results should be seen as illustrating the possible impact of supply side technology progress, rather than a detailed mapping out of system change over the next decade or beyond. The ATD scenario set is listed in Table 4.1 showing the specific technologies addressed, and the percentage CO_2 reductions involved, relative to 1990 emissions. A more detailed account of the ATD scenarios is provided in a UKERC research report (Winskel et al., 2009).

For each technology, the prospects for accelerated development were 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[1], and other

Table 4.1: Accelerated technology development (ATD) scenario set[2]

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

- LC Core 60, LC Core 80

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

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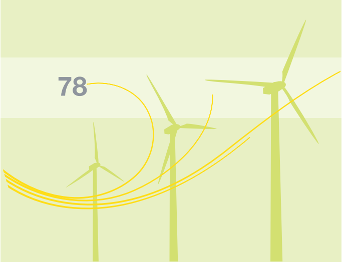
[1] The UKERC Research Atlas is available at http://ukerc.rl.ac.uk/ERA001.html

[2] This chapter uses variations on the core scenario names used in the rest of this report in order to distinguish between different accelerated development scenarios: LC-RCEP is called LC Core 60 and LC is called LC Core 80.



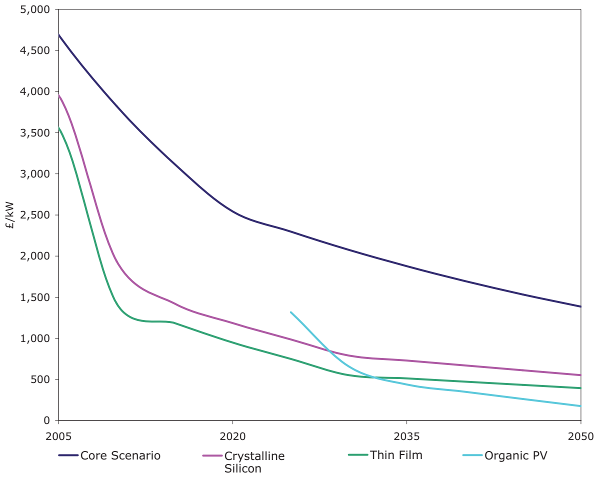
expert views and reports. For each narrative, a corresponding set of data was then devised to enable representation of technology acceleration in Markal energy system modelling, in terms, for example, of reduced capital or operating costs, improved efficiency, or earlier availability of advanced designs. The differences in input data between non-accelerated and accelerated modelling scenarios are discussed in detail in a UKERC 2050 research report (Winskel et al., 2009).

For each accelerated technology, assumptions were made about how accelerated progress in research and development might result in improved performance, lower costs, or earlier availability of more advanced designs. For example, Figure 4.1 shows how accelerated technology development was assumed to affect the capital costs for solar photovoltaics over time.

Impact of Accelerated Development on Deployment

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 only minor impacts on 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.

Figure 4.1: Revised capital cost curves for ATD-solar PV scenario



Different technologies contribute at different times in the ATD scenarios. Coal-fired generation using carbon capture and storage (CCS) plays a major part in the UK energy supply mix after 2020 in both accelerated and non-accelerated scenarios. Other technologies only show high levels of deployment in accelerated scenarios: 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 hydrogen 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 (Table 4.2). It is important to note that these results reflect, in-part, assumed progress incorporated in the non-

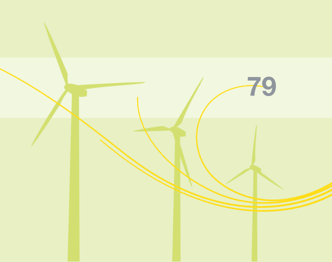
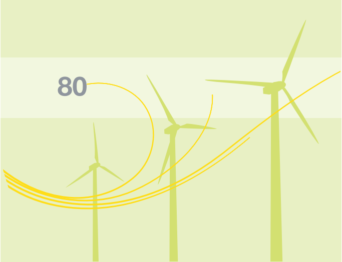


Table 4.2: Summary of technology specific impacts of acceleration

Overall Role in Accelerated Technology Development (ATD) Scenarios	**Specific Technologies Involved**
Wind power acceleration has major long-term impact (and moderate medium term impact) in single technology and Acctech 80 scenarios.	Offshore wind has a significant medium and major long-term role in ATD scenarios. Shorter-term deployment is relatively modest.
Marine energy (wave and tidal flow) acceleration has major long-term impact (and moderate medium term impact) in single technology and Acctech 80 scenarios. First deployment much earlier than in non-accelerated scenarios.	Initial deployment led by tidal flow, with wave energy becoming dominant after 2030. Longer-term deployment of both wave and tidal flow is constrained by resource assumptions.
Solar PV acceleration has major long-term impact in single technology scenario; moderate impact in aggregated scenarios.	Third generation organic solar cells have a significant long-term role. Earlier deployments of first and second generation solar cells are not represented in the ATD scenarios, but may be anticipated in practice.
Nuclear power acceleration has moderate medium and long-term impact in single technology scenarios; ATD assumptions are relatively modest, and long-term deployment reduces in aggregated accelerated scenarios compared to non-accelerated equivalent scenarios; much greater role if is CCS excluded.	Generation III Fission reactors have significant medium and long-term role. Later generations of fission reactors (III+ and IV) not represented in ATD scenarios, but their deployment may be anticipated over the longer-term. Fusion ATD assumptions are relatively modest; projected fusion deployment is post-2050.
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.	The ATD modelling assumptions do not explicitly distinguish between different forms of CCS technology. Long-term impact is sensitive to assumed capture rate.
Hydrogen fuel cells acceleration has a major long-term impact on transport sector decarbonisation. Fuel cell power generation has minor role with or without acceleration.	ATD modelling assumptions for transport fuel cells relate primarily to polymer electrolyte membrane (PEM) hydrogen fuel cells (HFCs), although other types are also included in the analysis.
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 80 (without fuel cells): transport - in LC Acctech 80 (with fuel cells): heat and transport.	Significant medium and long-term impact, arising from bioengineering improvements to energy crops and improved gasification technology; second generation ligno-cellulosic ethanol technology is also deployed in ATD scenarios.



accelerated Core scenarios. For example, there are relatively aggressive assumptions about the pace of CCS development in the core scenarios. (Additional scenarios were therefore produced to illustrate decarbonisation pathways in the absence of CCS, or delayed availability of CCS).

The impact of accelerated development varies for the different technologies analysed here. For example, in the non-accelerated LC scenario 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 one third of all power supplied in 2050 (Figure 4.2).

Similarly, much greater (and earlier) levels of deployment of marine energy are seen in the ATD Marine and Acctech scenarios (Figure 4.3). (Note that assumed resource constraints on marine energy mean that there is no increase in deployment as the overall decarbonisation ambition increases from 60% to 80%.)

Figure 4.2: Wind power installed capacity, aggregated scenarios (selected data, smoothed)

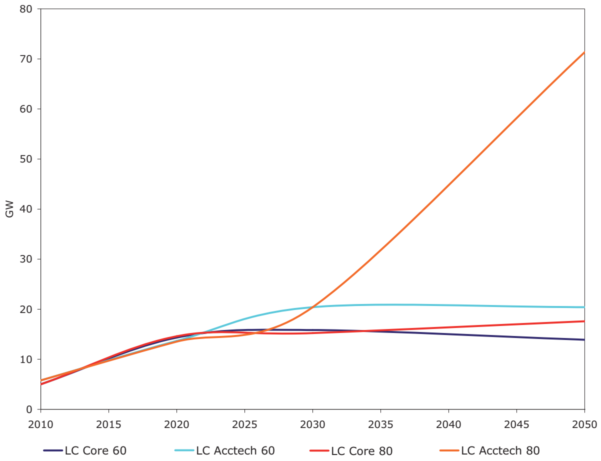
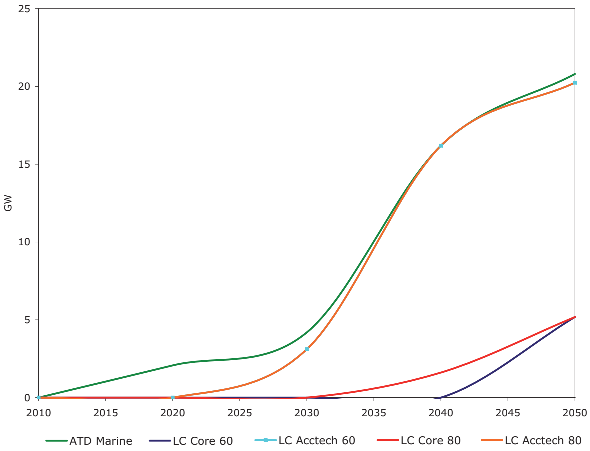
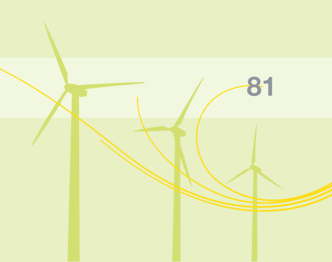


Figure 4.3: Marine energy installed capacity, single technology and aggregated scenarios



Wider Impacts of Accelerated Development on Energy System Decarbonisation

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 development of fuel cells changes the relative attractiveness of decarbonising different energy services, and the supply technologies (and associated research needs) involved. The most attractive supply technologies, and associated research priorities, 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.

In terms of decarbonisation by sector, the electricity supply sector decarbonises first and most thoroughly, and is substantially decarbonised by 2030 in all 80% scenarios, with or without accelerated technology development. Other carbon-intensive energy services (especially transport, but also residential demand) decarbonise in the medium and longer terms. 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.

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). 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. 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.

Final energy demand declines substantially after 2030 in both accelerated and non-accelerated scenarios, but 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. Accelerated fuel cells development has a major influence on these changes, increasing demand for hydrogen and reducing final demand for electricity and biodiesel in transport.

In terms of final energy demand by sector, accelerated technology development again makes a significant difference over the long term. In the non-accelerated LC scenario, residential energy demand almost halves between 2035 and 2050 – a key contributor to long-term system decarbonisation. In LC Acctech 80, however, residential energy demand declines much less steeply – only by around 20% between 2035 and 2050. The difference between accelerated and non-accelerated scenarios in terms of fuel mix 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 4.4).[3]

Costs and Benefits of Acceleration

The modelling results offer some indication of the overall advantages of supply side technology acceleration in energy system

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[3] 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.

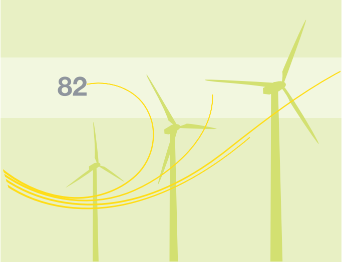
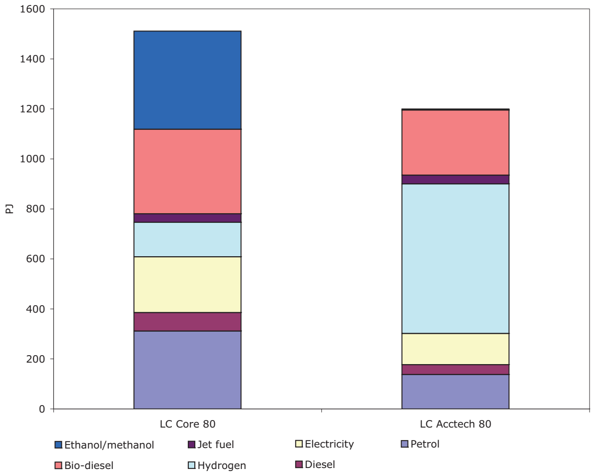


Figure 4.4: Transport sector energy demand by fuel, in 2050



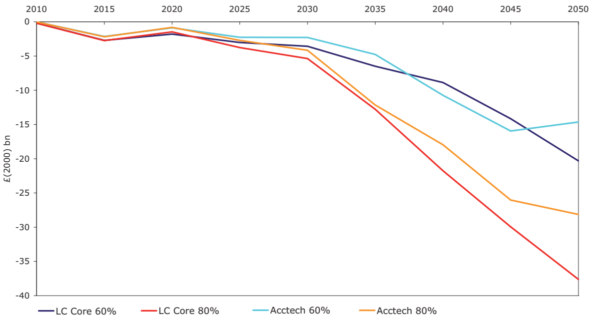
decarbonisation. These advantages accrue mostly in the long term, as accelerated development enables more affordable ways to achieve deeper decarbonisation. Two parameters – the marginal cost of CO_2 abatement, and the overall 'welfare cost' of decarbonisation – provide some quantification of this benefit. 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 under assumptions of high levels of progress.

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 – by 2050, the marginal cost of CO_2 abatement is around £130/tonne in accelerated development scenarios, compared to £170/tonne in the non-accelerated scenario.

The results suggest that technology acceleration may also substantially reduce the overall societal cost of decarbonisation, especially for 80% scenarios (see Figure 4.5). 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 accelerated performance improvements and cost reductions.

In practice, this comparison is far from straightforward, given that the investments associated with technology acceleration will be made internationally. However, research by the International Energy Agency on the international costs of accelerated technology development suggests that the overall benefits to the UK of accelerated development considerably outweigh the investment costs (IEA, 2008). 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

Figure 4.5: Change in welfare costs associated with decarbonisation



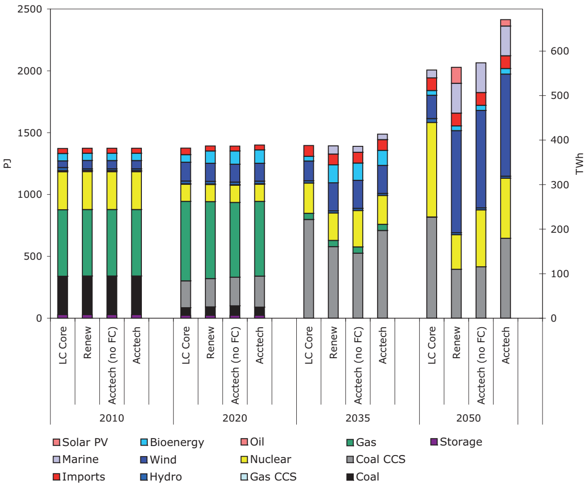
development of around £1bn per annum (an order of magnitude greater than current annual public spending levels) – although much of this investment would need to be committed well before significant 'returns' start appearing after 2030.

Electricity Supply Sector

For all 80% scenarios, the electricity supply sector undergoes near complete decarbonisation over the period 2010-2030. After 2030, low-carbon electricity is used to enable decarbonisation of 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 (Figure 4.6).

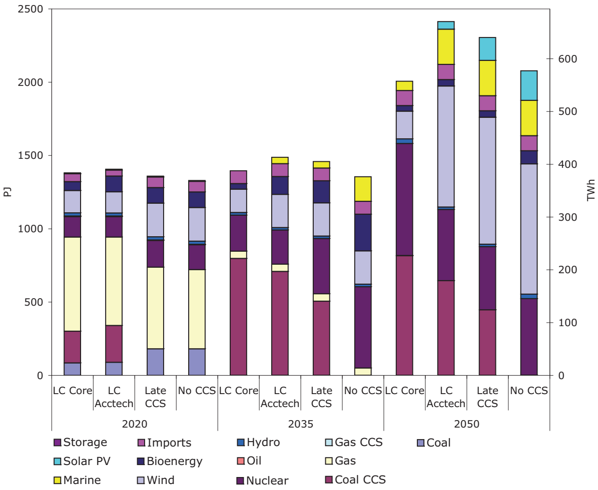
The results also suggest that achieving 80% decarbonisation ambition may involve the development a much larger UK power supply industry over the long term. While this expansion is seen with or without accelerated development, it is much more pronounced in accelerated development scenarios, with installed 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.

Figure 4.6: Power sector supply technology portfolios, aggregated scenarios, 80% decarbonisation to 2050



Given relatively aggressive assumptions about the cost and availability of CCS in the core scenarios, additional scenarios were generated to allow for delayed or non-availability of this still emergent technology. Because low-carbon electricity may be an important enabler of system-wide decarbonisation in the ATD scenarios, 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. 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 4.7). Delayed commercialisation of CCS (to after 2030) reduces its long-term market share as decarbonisation ambitions increase (and residual emissions from CCS become

Figure 4.7: Electricity generation in LC Core 80, LC Acctech 80 and LC Acctech 80 (no CCS and delayed CCS)



significant) and also as other low-carbon supply technologies mature.

Summary and Conclusions

The scenarios summarised 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 accelerated development of emerging technologies could allow for more affordable and diverse decarbonisation, especially over the longer-term. In attempting to map out desirable decarbonisation pathways for the UK, it is important to take this potential into account.

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: investing in longer-term supply options should be seen as a complement rather than replacement for shorter-term actions. Indeed, the results suggest that shorter-term decarbonisation and low-carbon technology deployment, over the next decade, require 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 procedures).

The results from the scenarios come nowhere near achieving the policy targets for renewables deployment, especially in the short term to 2020. In particular, realising the very high levels of renewables deployment by 2020 mandated by the EC renewables directive (CEC, 2008) 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, explored here, imply that short-term targets for technology deployment may be inconsistent with the most economically desirable long-term decarbonisation pathways, but may direct the energy system into less attractive pathways, from a longer-term perspective.

Managing possible trade-offs between short and long-term policy ambitions involves many uncertainties, including the interaction between technology development (to drive learning-by-

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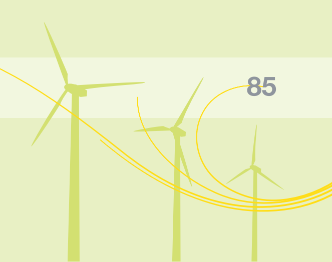

research) and technology deployment (to drive learning-by-experience). Large-scale deployment of more mature low-carbon supply technologies over the next decade offers significant improvement in their cost and performance. However, more mature technologies typically offer less scope for major cost reductions or performance improvements than more emergent technologies.

For policy, this suggests the need for parallel support of both deployment (market-pull) and development (technology-push), but with a much greater levels of spending on RD&D than at present. Expanded long term international support for low-carbon innovation should support diversity both across emerging technology fields (e.g. different types of renewables or low-carbon fossil fuels) and *within* technology fields (such as different types of PV cells or fuel cells). This investment promises substantial long term benefit to society in addressing the challenge of decarbonisation. For the UK, the results suggest than an order of magnitude increase on annual spending on energy RD&D (from £100m to £1bn) may be justified.

In the accelerated development scenarios, expanded and sustained international investment in RD&D has major long-term effects on the cost and performance of renewables and other low-carbon supply options, so that their longer-term deployment becomes much less dependent on market subsidies. As well as the specific investment needs associated with the technologies analysed here, there is a need for parallel support for enabling technologies and techniques not analysed here, such as innovative types of power storage, network management, distributed generation and demand side management.

In summary, accelerating the development of emerging low-carbon energy supply technologies promises significant long-term reward, in enabling alternative and more affordable decarbonisation. 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 a substantial return in the longer-term. Given the uncertainties involved here, there are no simple messages in terms of 'picking winners': most of the technologies analysed here – and many others not included – have a significant potential role. The need is for greatly expanded and 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.

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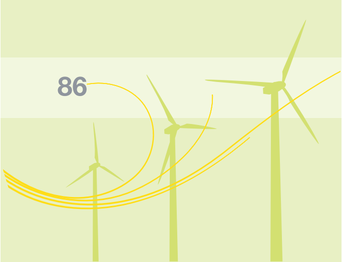

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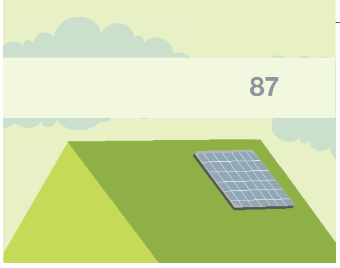


5. Environmental Sensitivities

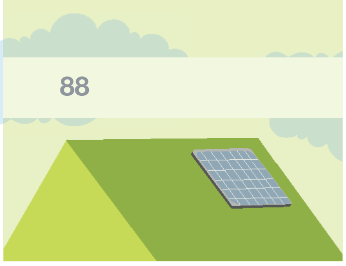
Key Messages

- Reducing CO_2 emissions leads, for the most part, to reductions in other emissions and pressures on the environment. The exceptions are radioactive releases, stress on water and land, and some aspects of air quality
- The development of bio-energy has a number of environmental implications, relating to air emissions, water availability and land use
- This is not a rationale for inaction on achieving a low-carbon economy, but signals areas in which further regulatory attention will be required
- Release of some pollutants, notably sulphur dioxide, will fall substantially
- A low-carbon strategy which emphasises energy efficiency and demand reduction will lead to considerably lower environmental impacts. Emissions of some pollutants could be halved in comparison to a supply-led strategy
- People's concerns about the environmental impacts of energy development can take several forms. They include concern about local impacts, fear of unfamiliar technological solutions, or concern about impacts on the natural environment and ecosystem services
- If people's concerns inhibit the development of certain technologies, then the costs of meeting CO_2 targets will increase. It will focus more attention on demand reduction policies
- The implications of a scenario where technologies are constrained if they are seen to harm ecosystem services could be particularly costly. A range of technologies and fuels (fossil, bio-energy, tidal barrages) would be affected. Globally, fossil fuel prices could rise as a result of certain extraction options being excluded

Environmental Impacts of Low-Carbon and Resilient Energy Scenarios

Energy systems, along with other human activities, interact with the environment in a number of well documented ways (Millennium Ecosystem Assessment, 2005). The interactions vary according to spatial and temporal scales and are dependent on both the magnitude of the driver and the ecosystem or organism being impacted. Within the first phase of UKERC a pragmatic approach was taken to make an initial examination of the environmental pressures generated by different energy scenarios.

The analysis summarised below aggregates the operational emissions of eight dominant pollutants (CO_2, CH_4, CO, N_2O, NO_x, SO_2, PM_{10} and radioactivity) from energy systems expected to be in operation between 2000 and 2050. Changes in pollutant emissions are described for each of the MARKAL Energy 2050 Core scenarios (Reference (REF), Low-Carbon (LC), Resilient (R) and Low-Carbon Resilient (LCR)). The total load for each pollutant was estimated by



aggregating the contributions from each of the energy generating technologies and uses for all sectors[1]. An important assumption is that emissions factors for each source and their associated abatement technologies perform as they do today, with a few exceptions relating to known emissions reduction policies such as the Large Combustion Plant Directive. As technology improvements are likely to lead to lower levels of emissions, the results may show a 'worst case' interpretation. Emissions from non-fuel sources and components not included in MARKAL were not considered here. In addition, a preliminary assessment of the altered water demand and land take and upstream carbon emissions for each scenario was conducted.

As the method adopted uses a comprehensive matching of specific technologies and activities to their emissions, the results can be used to compare changes in the environmental pressures associated with different energy generation and use strategies. This comparison reveals that there are some common trends across scenarios, but there are also divergences between values. With care, these can be interpreted as the implications of different energy decisions. Although changes in the magnitude of the pressures have been calculated, the impacts of the pollutants can only be described in general terms as the model has no spatial component and employs a coarse temporal representation (five-year time steps). Consequently, the analysis should be viewed as indicative rather than definitive.

Pollutant Emissions Under Different Energy Scenarios

Overall, emissions of the eight pollutants considered in this analysis decrease between 2000-2020 with little variation between the four Core scenarios. After 2020, the LCR scenario leads to significantly lower total pollution emissions, compared with the other Core scenarios. This demonstrates that the combination of a low-carbon pathway combined with a more resilient energy system has wider environmental and energy security benefits. The R scenario results in similar pollutant emissions to LCR for seven of the pollutants, but does not achieve the 80% CO_2 reduction target.

When the pollutants are considered individually it is also clear that there are key areas where LCR outperforms LC in reducing emissions. CO, N_2O, NO_x and PM_{10} emissions are significantly lower in the LCR scenario post 2020, mainly due to changes in the transport and residential sectors. The main differences between LC and LCR are that LCR has greater demand reduction particularly in the residential sector, and greater penetration of hybrid and electric cars. In contrast, LC has lower demand reduction in all sectors; greater biomass use for heating in the residential and service sectors (increasing PM_{10}, CH_4 and CO); and greater use of transport biofuels, as opposed to hybrid/electric cars in the LCR scenario. The analysis detailed below investigates these trends for each of the pollutants studied.

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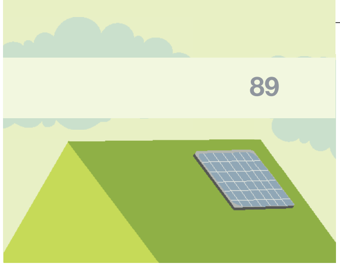
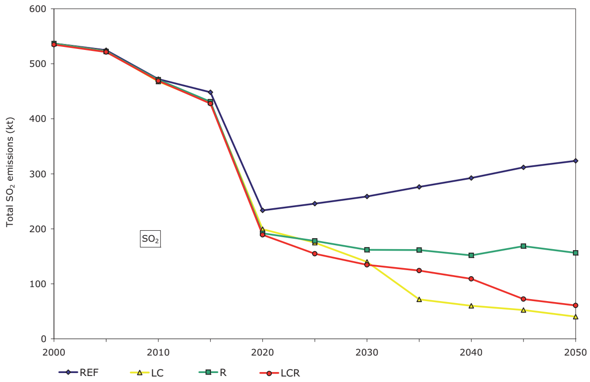
[1] Emission factors taken from NAEI (2006). Where unavailable, values were calculated from DUKES (BERR, 2008) and other scientific publications.



The combustion of coal releases sulphur dioxide (SO_2) and methane (CH_4). Consequently, SO_2 emissions are dominated by conventional coal-fired power stations; other sources include coal used in industry, and fuel oil and petroleum coke use in oil refineries. Coal power stations with carbon capture and storage (CCS) release very little SO_2 as it has to be removed to prevent it impeding the capture process. Consequently, emissions fall sharply in the LC and LCR scenarios (Figure 5.1) as coal CCS is introduced and becomes a dominant technology between 2020-2035. They fall, but to a lesser extent, in the REF and R scenarios, due to continued use of conventional coal-fired power stations. However, the requirement (from the EU Large Combustion Plant Directive) for flue gas desulphurisation (FGD) in conventional power stations after 2015, does reduce emissions by about 85%.

Initially in MARKAL, CH_4 emissions are dominated by the residential sector's use of coal and solid smokeless fuel for heating. In all four scenarios this use is phased out by 2025-30, resulting in a steady decline in emissions. However, it is important to recognise that only 2% of Britain's methane emissions are represented in MARKAL (NAEI, 2006), with 80% of existing emissions from waste decomposition and livestock. There are also other energy related methane sources not represented in this assessment, including gas leakage and methane from coal mining.

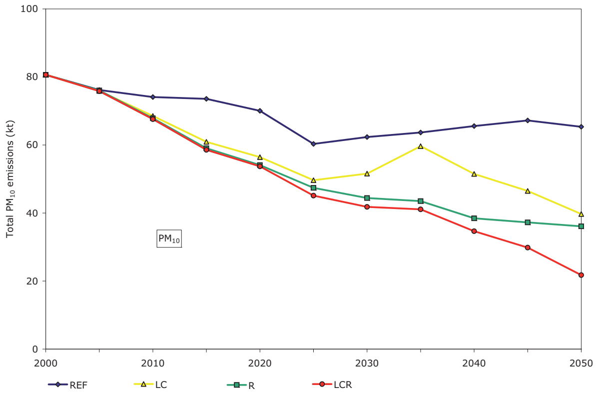
Figure 5.1: Total emissions of sulphur dioxide (SO_2) over time in the Core scenarios

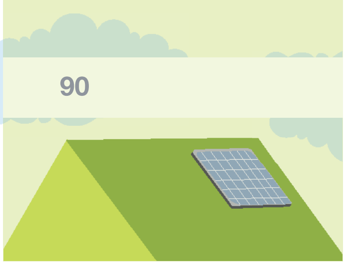


Most particulate (PM_{10}) emissions are from the transport and residential sectors; within transport, diesel vehicles are the main source of emissions. In LC, R and LCR scenarios, total PM_{10} emissions halve by 2050, in part through reduced diesel consumption (Figure 5.2). However, in all scenarios future technology developments may decrease particulate emissions further.

In the residential sector PM_{10} emissions fall in all scenarios, by approximately 95% between 2000-2030, due to the phasing out of coal, oil and wood for heating. However, in the LC scenario increased use of biomass fuel in the residential sector causes total emissions to rise by around 15% between 2030 and 2035 (Figure 5.2).

Figure 5.2: Total emissions of particulates (PM_{10}) in the Core scenarios





The extent of this rise will depend on the specific technologies used to reduce health impacts in modern biomass boilers or stoves.

Energy use in transport generates a number of different pollutant emissions and is the dominant anthropogenic source of carbon monoxide (CO) and the oxides of nitrogen (nitrous oxide (N_2O) and NO_x). However, each transport mode and fuel type has its own distinct footprint, so for example CO is mostly from petrol cars whilst NO_x splits more evenly between all liquid fuel cars and HGVs. The increasing use of catalytic converters in petrol cars caused an initial decrease in CO emissions in 2000-05 in all scenarios. The trend continues through the addition of bioethanol to the petrol fuel mix (Figure 5.3).

The residential sector provides another source of CO emissions (approx 20% in 2000). Phasing out coal and solid smokeless fuel use between 2000 and 2025-30 reduces CO emissions in all the Core scenarios (Figure 5.3). Only the LC scenario shows any reversal in the trend due to the use of wood in the residential and service sectors in 2035-2050. The lowest CO emissions are found in the two resilient scenarios (R, LCR), due to the introduction of hybrid and plug-in cars, and transport sector demand reductions.

Nitrous oxide (N_2O) emissions increase initially by the uptake of catalytic converters in cars, the inverse of the effect seen with CO (Figures 5.3, 5.4). Demand reduction and the use of hybrid and plug-in cars reduces emissions in the R and LCR scenarios by 2025. The same factors produce a later and smaller fall in emissions in the LC scenario through the increased use of hybrid and plug-in cars; the REF scenario shows a continuing rise. However, energy (as represented in MARKAL) is only responsible for 20% of the UK's N_2O emissions (NAEI, 2006), with over half of UK emissions derived from agricultural fertilisers.

Emissions of the other oxides of nitrogen (NO_x) are also dominated by the transport sector (~50% of emissions), particularly cars and HGVs. In all cases the emissions show a decline, down to approximately 65% of 2000 emissions in LCR scenario by

Figure 5.3: Total emissions of carbon monoxide (CO) in the Core scenarios

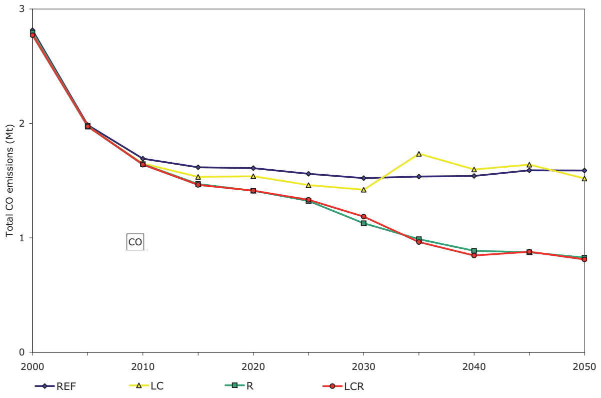
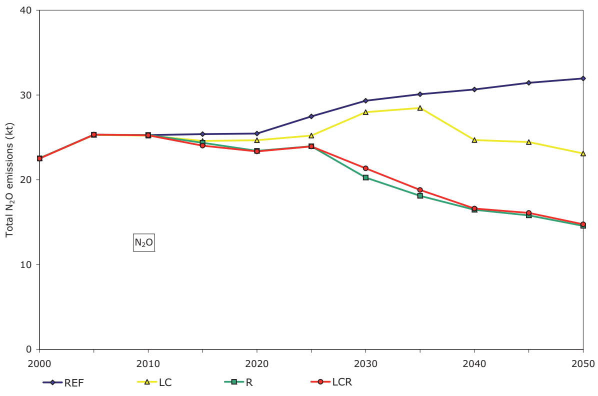
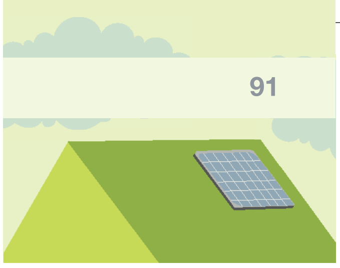


Figure 5.4: Total emissions of nitrous oxide (N_2O) in the Core scenarios

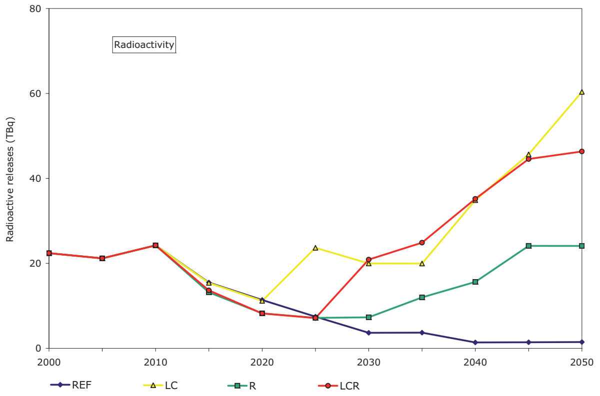




2050 and a smaller reduction of 20% in the REF scenario. Energy technologies and uses (in MARKAL) are responsible for 80% of our current NO_x emissions. Emissions not included in MARKAL are predominantly from international aviation and shipping.

Radioactive releases considered are from nuclear power stations, coal-fired power stations and other sources such as oil and gas platforms. Radioactive releases decline in the REF scenario, as nuclear power stations coming to the end of their life are not replaced (Figure 5.5). In the other scenarios, nuclear power stations are built so emissions rise to varying extents after a time lag due to the long planning and construction time required. The highest estimated discharge occurs in the LC scenario resulting in a nearly three-fold increase in discharges by 2050, matching its tripling of power generation. All new discharges would need to be assessed for exposure to both humans and the environment. Such increases may require quite detailed assessments, where appropriate, on the potential risk to wildlife, with a focus on reducing current uncertainties in the habitat assessments.

Figure 5.5: Total radioactive releases in the Core scenarios



The need for such assessments will depend upon where these increased discharges are occurring and the extent to which protected Natura 2000 sites are potentially impacted.

Relationship Between Pollutant Emissions and Energy Demand

If there is a strong and robust relationship between individual pollutant emissions and total energy demand, then a simple rule of thumb could be applied to describe changes in environmental pressures from different energy strategies. Although there are strong positive correlations between all of the pollutants and energy use, i.e. greater demand creates more pollution; the precise form of the relationship varies between pollutants and scenarios.

To investigate this relationship, total annual energy demand was plotted against estimated pollutant emissions, with each year represented as a point on the graph. Values for CH_4 (Figure 5.6) show a generally tight curvilinear fit across all scenarios, indicating that CH_4 emissions are strongly related to energy demand, regardless of the scenario. In contrast, for CO_2 (Figure 5.7), there is a strong correlation between energy demand and emissions within individual scenarios, but the trends of scenarios are significantly different from each other. In the LC scenario, technologies are selected with the aim of minimising CO_2 emissions, so on the graph this scenario has the steepest slope, due to large reductions in CO_2 emissions over time, despite little change in energy demand. In the R and LCR scenarios there is a greater reduction in energy demand over time, which means that less

Figure 5.6: Relationship between emissions and energy demand between 2000 and 2050 for methane (CH_4) in the Core scenarios

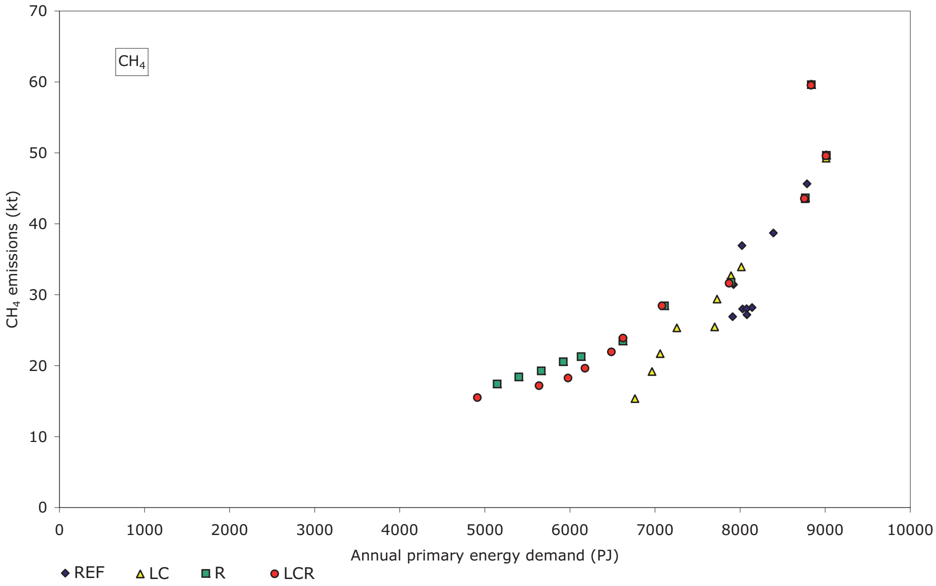
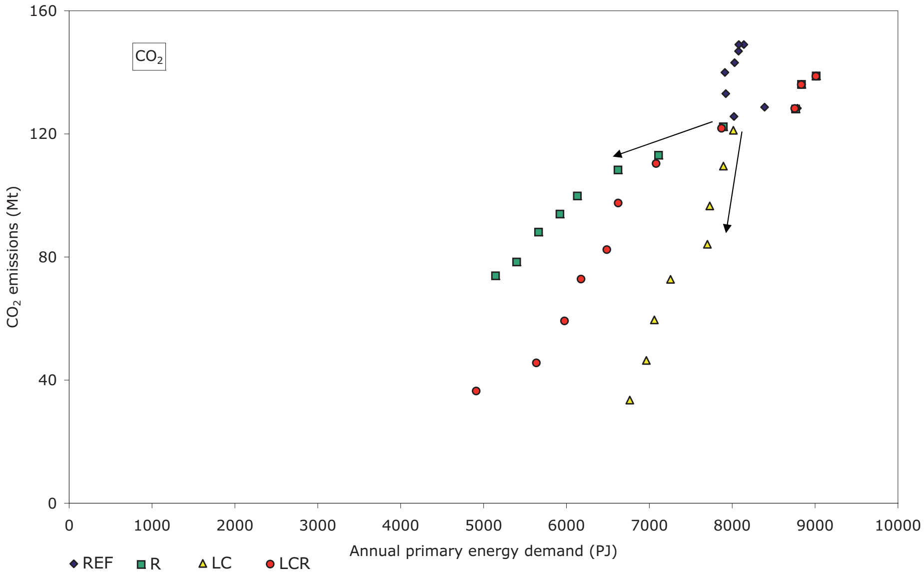


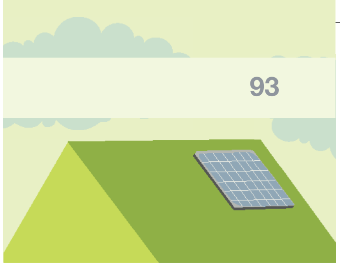
Figure 5.7: Relationship between emissions and energy demand between 2000 and 2050 for carbon dioxide (CO_2) in the Core scenarios. Arrows indicate the direction of change in demand over time.



investment is required in low-carbon technologies. Therefore, in these scenarios, each PJ of energy used will produce higher CO_2 emissions than a PJ of energy used in the LC scenario.

Wider Environmental Pressures

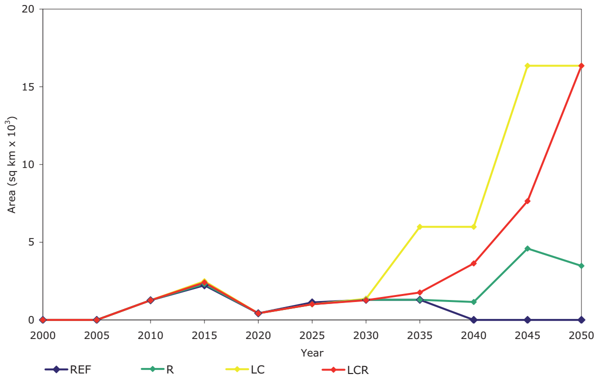
Further environmental pressures relate to changing demand for water and land where resource depletion and change in condition are issues. Water is a power source (hydro



and pumped storage), and is used for cooling in power stations and for agricultural and forestry production of energy crops and biofuels. A preliminary analysis suggests that the LC scenario will result in the largest increase in water demand, driven by increased electricity generation from coal CCS and nuclear power, as well as the extensive production of biofuels and energy crops. Water demand for the agricultural production of energy crops also increases in the LCR scenario, while the REF and R scenarios show the smallest increases in water demand.

The current perception of energy generation systems is of a limited number of power stations, refineries and mines which only cause local environmental impacts. New technologies can be far more demanding in terms of area in which to operate. Some technologies, such as wind power, are capable of operating with other land uses in a multi-functional way, whilst others, such as bioenergy, can become monocultures. The land take for bioenergy in the Core scenarios is shown in Figure 5.8. The scenarios show similar trends through to 2030 where bioenergy starts to be significantly deployed in the LC and LCR scenarios, both rise to eventually use about 8% of the British land area – around a third of our current arable land or more than 10% of our total agricultural area (including semi-natural extensive grazing area). The impact of this change will be dependent upon the location, condition and habitat history of the land replaced.

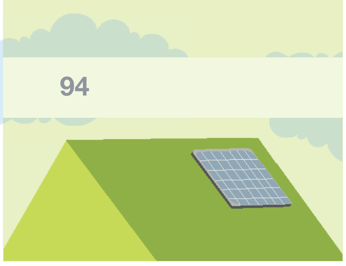
Figure 5.8: Land take for bioenergy in the Core scenarios



Energy Scenarios with Socio-Environmental Constraints

The environment is central to all future energy scenarios; it supplies the resources and receives the impacts of energy capture and use. However, the environment has another more subtle but equally powerful influence over future energy systems; public and stakeholder perceptions and evaluation of the socio-environmental risks and benefits of activities provide powerful constraints and drivers of change. The UKERC Energy 2050 Core scenarios demonstrate how low-carbon and or resilient energy systems can develop in the UK to meet specific targets, but these scenarios will require public buy-in and acceptance if they are to become established. In this study, three variant scenarios were developed, in which some aspect of this public buy-in is missing, imposing an extra constraint on the evolution of the energy system. The variant scenarios (DREAD, ECO and NIMBY) use the 80% Low-Carbon Core scenario (LC) as a baseline. Thus, like LC all the socio-environmental scenarios are constrained to deliver an 80% reduction in carbon emissions by 2050.

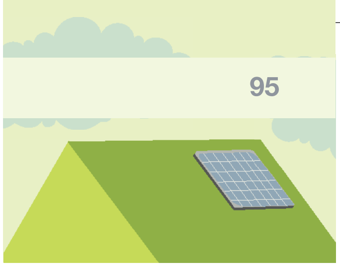
In the most extreme scenario, DREAD, the deployment of certain technologies is



halted by public fears about how those technologies could pose unknown but potentially catastrophic dangers which could threaten human life. In part reinforced by the prospect of catastrophic climate change, there is a general mistrust of Government, regulatory bodies, the scientific community and big business, rooted in the assumption that all of these have some cynical or self-interested motive. Within this scenario novel and 'threatening' technologies are not deployed, so there is no new nuclear build, no CCS and no use of hydrogen for power or transport.

The second scenario variant, called ECO, represents considerable public concern for the conservation of ecosystem goods and services with a consequence that there is a financial cost for a sustainable lifestyle. Peoples' acceptance of energy systems is built around a wider perception of environmental costs of operation, including imported feedstocks. In the ECO scenario, fossil fuel prices are increased due to concerns about the ecological impact of certain types of fossil fuel extraction. For instance, in this scenario, oil is not taken from oil sands or other ecologically sensitive areas. This leads to increased global prices. Domestically, open-cast coal mining is deemed to be too environmentally damaging and is thus not allowed after 2010. Bioenergy is only seen as an option where the ecological impacts can be minimised. Therefore, liquid biofuel for transport is not allowed in the UK, as it is considered to be inefficient and requires intensive agricultural management to deliver. Imported biomass and biofuel are also banned because the public is unconvinced about the sustainability merits of overseas production and thus rejects it in an attempt to protect rainforest and threatened habitats. Further, in response to ecological concerns about land use change, the growth of crops is heavily constrained to only 11% of the total capacity considered to be available in the LC scenario. There is also a 25% constraint on wind power (onshore and offshore) and wave and tidal power due to concerns about the environmental impact of those technologies in certain areas. In addition, a tidal barrage is not allowed at all in this scenario due to concerns about potential damage to the environment.

NIMBY, or Not In My Back Yard, is the third variant scenario. In this scenario the public objective is to preserve the local environment, lifestyle and systems. The public rejects new developments when they have a high visual impact, while existing facilities are allowed to continue at their current levels because they are already accepted aspects of the landscape. Consequently, nuclear power is allowed, but no new nuclear sites are permitted, there can only be redevelopment at existing commercial reactor sites. Coal CCS is a less familiar technology with no existing plants. However, a limited number of CCS plants are allowed in certain locations where existing power plants and infrastructure can be modified without major aesthetic impacts. Onshore wind is only permitted where windfarms are already established or planning consent has been awarded. Offshore wind is only permitted where it has minimal visual impact. Therefore, in the NIMBY scenario,



offshore wind farms are only allowed to be built beyond a 12 nautical mile coastal buffer zone. Bioenergy production is accepted so long as it maintains the appearance of the existing landscape. Consequently, energy crops such as Miscanthus and short rotation coppice are not allowed because they are unfamiliar and would alter the character of the landscape. The production of traditional crops such as wheat and oil seed rape for biofuel is constrained to 37% of the potential production available in the LC scenario due to the public's resistance to changing non-agricultural land to produce more crops. Tidal barrages are not allowed because of the way that they would change the character and visual aesthetics of an area.

These environmental constraints are summarised in Table 5.1.

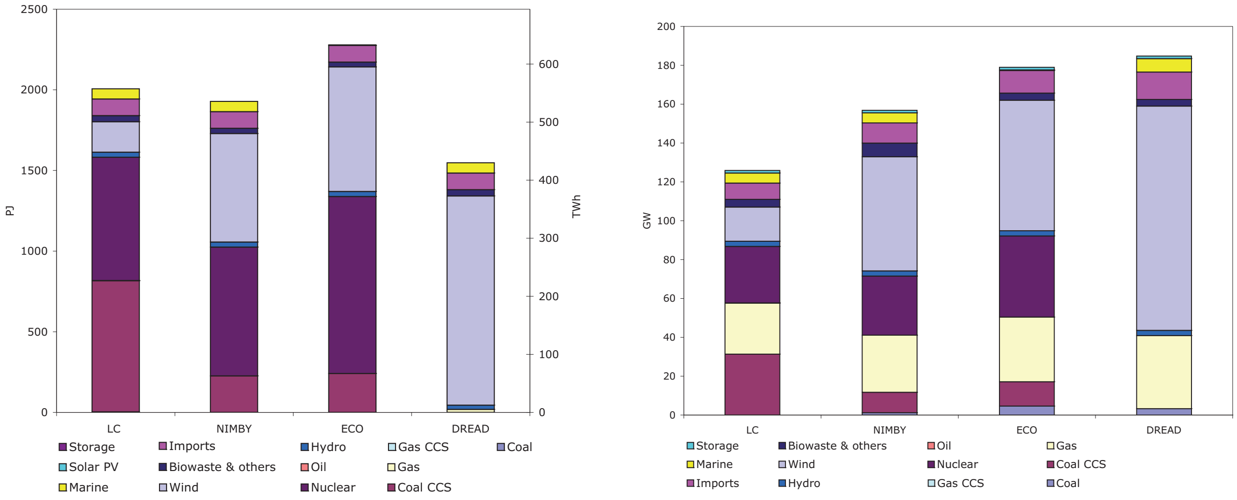
Implications of the Socio-Environmental Constraints

The energy systems developed within the three socio-environmental scenarios offer different strategies to meet the 80% decarbonisation target and address their additional wider concerns. While all scenarios initially decarbonise the power system they employ different supply side technologies which carry wider implications across the entire energy system. As a consequence of the additional socio-environmental constraints, each scenario then takes its own approach to decarbonisation of different sectors. The strategies employed are predominantly reducing demand and making alternative technology selections. The difference in demand reduction strategies can be seen in their electricity generation (Figure 5.9).

Table 5.1: Summary of the additional constraints over those set in the LC scenario on the energy sources for the socio-environmental scenarios. Empty cells indicate no additional constraint

	DREAD	**ECO**	**NIMBY**
Nuclear	None allowed		Only existing sites allowed
Fossil fuel price		Increased cost	
Coal CCS	None allowed		Limited sites
Hydrogen	None allowed		
Renewables			
Wind		Limited onshore & offshore	Only far offshore allowed; No new onshore planning consent given
Bioenergy		No imported biomass allowed; No biofuels allowed; Limited crop production	No energy crops allowed; Limited crop production
Marine		No tidal barrage allowed; Limited tidal stream and wave	No tidal barrage allowed

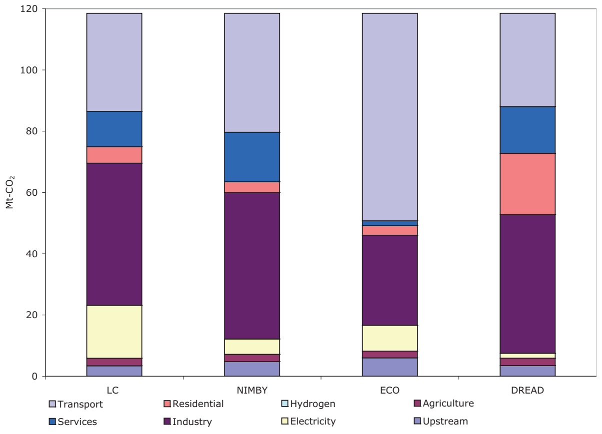
Figure 5.9: The electricity generation in 2050 for the 80% low-carbon Core scenario (LC), NIMBY, ECO and DREAD variants broken down by (a) electricity generating type and (b) the installed capacity delivering the power in 2050


(a)

(b)

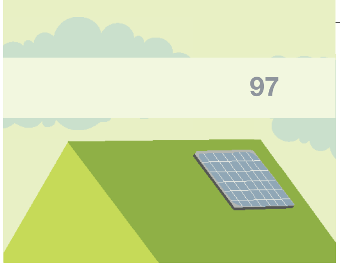
As a result of the different pathways to decarbonisation, the sectoral emissions of CO_2 show dramatic differences by 2050 with the ECO and DREAD scenarios showing greatest divergence from both one another and LC (Figure 5.10). For instance, within ECO, the limits on transport set by increased costs of fossil fuel and lack of biofuel availability, counter-intuitively forces the continuation of use of diesel and petrol which produces higher transport sector emissions and pushes other sectors to reduce their emissions more than in the other scenarios.

Figure 5.10: Total emissions of CO_2 in 2050 for the 80% low-carbon Core scenario (LC), NIMBY, ECO and DREAD variants broken down by sector. Emissions in millions of tonnes of CO_2



DREAD Scenario

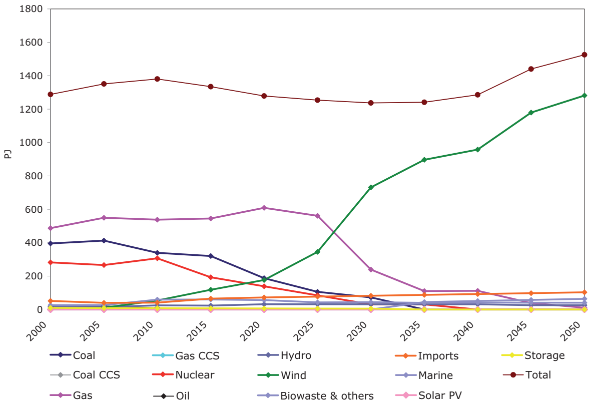
To achieve the 80% reduction in carbon emissions, each of the variants shows the same general strategy employed in the LC scenario of decarbonising the electricity sector and then targeting transport and the residential sector. The additional constraints produce novel mixtures of power generating sources, but also bring about reductions in demand. The most stringent constraints were applied in the DREAD variant and that shows the greatest demand reduction. Primary energy demand is reduced by 19% of the LC scenario,



nearly to the level in the low-carbon resilient (LCR) Core scenario.

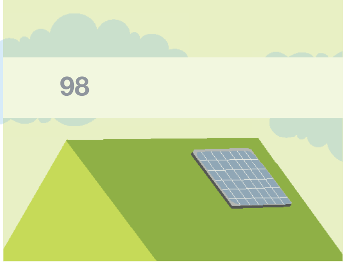
Not surprisingly, power generation under the constraints imposed by DREAD is very different than the LC Core scenario. The power sector is not very diverse in the DREAD scenario and is dominated by wind power (offshore, onshore and microgeneration); 84% of electricity is generated by wind in 2050 with the bulk of it offshore (Figure 5.11). As a consequence, the system has a very low base load (less than 10%) which is balanced with back-up gas capacity. By 2050 over 60% of the installed capacity is wind. This installed capacity of wind is three times the size of gas capacity which is installed as back-up. Achieving this type of power sector would pose a substantial challenge to society and would necessitate advances in storage technology and smart grids. This scenario therefore illustrates that if a number of energy supply technologies were constrained it could become much more difficult to achieve the UK’s 80% decarbonisation target.

Figure 5.11: Changes in the electricity generating mix 2000-2050 in the DREAD scenario variant



A power supply system that is dominated by a single generating source such as is the case in DREAD is less likely to be resilient. In this case the system is built around high levels of wind power. Although the operation is predominantly under UK control, it risks both periods of still air and threats of altered resource due to changes in climate. Storage sounds to be an attractive solution, but within this variant less storage is employed than in the low-carbon Core scenario (LC). Initially both DREAD and the Core scenario use the same quantity and type (storage heaters and a little pumped hydro) but then after 2035, the level of plug-in hybrid vehicles in DREAD is only about 60% of the total used in the LC scenario. Here we have to question the capability of the model adequately to capture the opportunities of supporting intermittent power sources; the decrease in plug-in hybrid storage is probably because electricity becomes so expensive that there are better options for transport.

To deliver the power needed, the model employs two approaches: using power more effectively (by getting better returns for the energy used) and using less (by reducing demand). The DREAD scenario has a rapid increase in electricity generation after 2040 yet this increase is of a much lower magnitude than the increase in the LC scenario after 2035. Agriculture and industry maintain similar levels of electricity demand in both scenarios, but demand from the residential, service and transport sectors all fall. By 2050 in the DREAD scenario, a quarter less electricity is used than in the LC scenario.

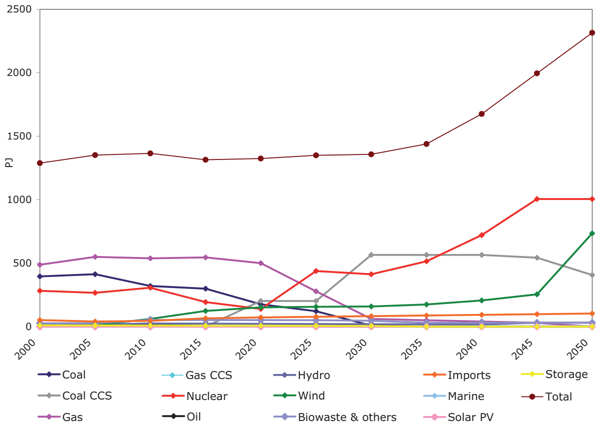


Transport fuel demand is similar between DREAD and the LC scenario until 2035, after which both show a decline as diesel and petrol use drop. The total transport fuel demand decrease is greater in LC as DREAD uses bio-diesel to deliver more of its transport needs. The greater uptake of biofuels is divided between the heavy and light goods vehicles and the introduction of bio-kerosene into the aviation sector after 2040. The strategy is, in part, targeted at reducing electricity demand while maintaining a low-carbon performance. The additional increase in biofuels is predominantly sourced within the UK and diverges from the LC scenario after 2035.

ECO Scenario

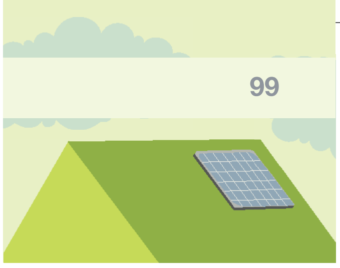
The ECO scenario illustrates a very different energy system to the LC or DREAD scenario. Primary energy demand in the ECO scenario is lower than the LC scenario; it is only around 80% of the LC primary energy demand in 2050. The ECO scenario has a very high level of electricity generation compared to the LC scenario and the other socio-environmental scenarios. Electricity production in the ECO scenario is primarily from nuclear power, which is the dominant source of electricity, coal with CCS and wind power, the latter rapidly increasing in the 2040s (Figure 5.12).

Figure 5.12: Changes in the electricity generating mix 2000-2050 in the ECO scenario variant



The removal of domestic open-cast coal and the increased global costs of fossil fuels have a noticeable impact on the development of the electricity mix over the 50 year period. Existing coal generation continues at a moderate level for slightly longer in the ECO scenario than in the LC scenario. However, in the ECO scenario, the uptake of coal CCS is significantly lower than in the LC scenario; in 2050 there is less than a third of the coal CCS seen in the LC scenario. This reduction in the use of coal CCS for decarbonisation in the ECO scenario reflects the reduced availability of domestic coal resources and the increased global price for imported coal which make coal CCS less cost effective than it was in the LC scenario. This is just one example of how public attitudes towards energy technologies could have a significant impact on the deployment of certain technologies and the overall energy system mix.

In the ECO variant, there is a rapid rise in electricity demand following 2040, with industry and hydrogen production taking the lion’s share of the increase. Up until that point the industrial sector had shown a decline similar to that in the Core scenario. Both the residential and transport sectors in both ECO and LC also have increasing electricity demand, yet the increases start earlier in the ECO variant and are relatively more gradual in these sectors.



The installed capacity of the power sector in the ECO scenario rises to almost 180 GW by 2050 compared with 120 GW in the LC scenario. The increased installed capacity in the ECO scenario is largely due to the installation of wind capacity in the last 5-year time step; high levels of wind must be installed to meet the demand for electricity and further, when more wind capacity is built it has to be balanced by additional gas generating capacity.

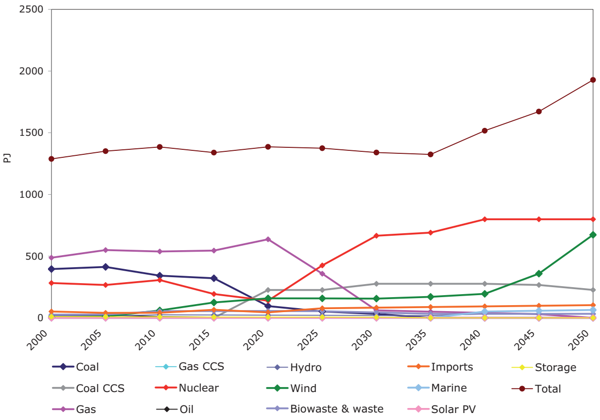
The total constraint on all transport biofuels in the ECO scenario leads to increased difficulties in decarbonising the transport sector. Whereas the Core scenario partly decarbonises the transport sector by utilising bioethanol, biodiesel, hydrogen and electricity as transport fuels, the ECO scenario cannot use either of the biofuels. The scenario continues to use some electricity for transport but it does not dramatically increase from the LC scenario, most likely because there are other more cost-effective measures to decarbonise the energy system. Hydrogen fuels are introduced 5 years earlier in the ECO scenario than in the LC scenario. As a result of the changes to transport fuel availability and costs, the ECO scenario retains higher levels of fossil fuels (petrol and diesel) than the LC scenario. This causes emissions from the transport sector to be significantly higher than the LC scenario. To balance out these transport emissions, there are significant emission reductions in the service, industry and electricity sectors in the ECO scenario.

NIMBY Scenario

In the final scenario variant, NIMBY, while the primary energy demand drops by about 18% of that in the LC scenario, the primary demand breakdown by fuel type and sector remain close to the LC baseline. NIMBY remains the most similar to the LC scenario, with the only major divergence being in the selection of dominant electricity sources in the electricity mix. In primary energy, the major difference is a reduced use of coal, by 2050 being less than a third of LC scenario. Although biomass and waste also show a lower demand, other energy sources, namely nuclear and renewables show earlier uptake; nuclear levels off at its capacity limit by 2030.

The electricity demand in NIMBY matches that of the LC, but the generation mix has nuclear growing rapidly through the 2020s, to replace the role that coal with CCS has in the LC (Figure 5.13). The selection of power sources, with the exceptions of nuclear and coal CCS, show similar trends in both NIMBY and LC, through to the 2040s, when NIMBY shows a dash for wind; surprisingly, there is only marginally more gas installed to balance the

Figure 5.13: Changes in the electricity generating mix 2000-2050 in the ECO scenario variant



intermittency. As a consequence of expanding wind power, the final total installed capacity in NIMBY is greater than in the LC (~160 GW as opposed to 120 GW).

Transport fuel use in the NIMBY variant shows very similar trends to the LC, with both dominant fossil fuels (petrol and diesel) showing declines at equivalent rates. In LC, diesel declines slightly more in the last decade (2040 to 2050) and is balanced by an increase in bioethanol and biomethanol. In NIMBY, there is less biofuel available than in the LC because crops are restricted to landscapes where they are already established. Interestingly, despite crop limitations, aviation does take up bio-kerosene in the NIMBY variant.

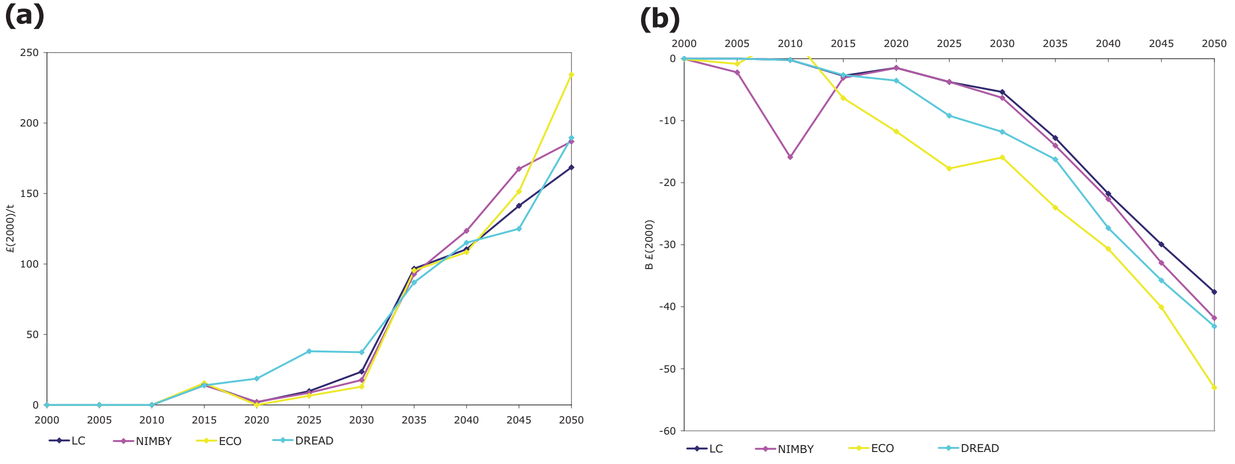
Overall Impact of Public Acceptance of Energy Technologies

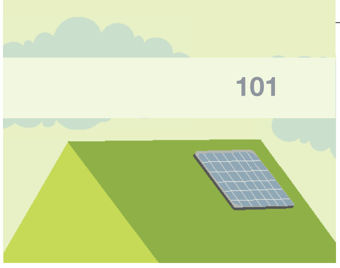
The ECO scenario has the highest cost implications for society. By 2050 the marginal cost of CO_2 is the highest in ECO as seen in Figure 5.14a. Further, using consumer and producer surplus as a measure of societal welfare, the ECO scenario shows a significantly greater decline in welfare from 2015 onwards than in the LC, DREAD or NIMBY scenarios (see Figure 5.14b).

Although the marginal cost of CO_2 in 2050 is highest in the ECO scenario, the marginal cost of CO_2 in the DREAD scenario is the highest in the middle period (2015-2030). In all three of the scenarios costs are higher than in the LC scenario. This illustrates that public acceptance of energy technologies can have a substantial impact not only on the make-up of the energy system but on the cost of decarbonisation. When the public rejects certain technologies for any of the various reasons explored in this report, decarbonisation becomes more costly and more challenging.

Yet this consideration seems to be widely neglected in discussions of decarbonisation; there is even less public discussion about how the carbon reduction

Figure 5.14 (a) The marginal costs of CO_2 (in £$_{2000}$ /tCO_2) and (b) Societal welfare expressed as consumer and producer surplus (in £$_{2000}$). Shown for 80% Low-Carbon (LC) Core, NIMBY, ECO and DREAD scenarios





targets should be met than there is of the targets themselves. If public attitudes towards UK decarbonisation strategies continue to be neglected then there may be some unexpected and unpleasant surprises in the quest to reach 80% decarbonisation, including failure to achieve the target. This is not to suggest that public attitudes should be overridden in order to reach 80% decarbonisation; rather, these socio-environmental attitudes must be understood and considered when planning the transition to a decarbonised economy.

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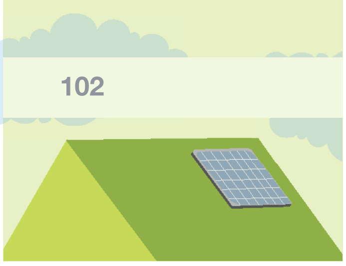


6. Energy Lifestyles

Key Messages

- Society and human behaviour change over time, sometimes in unpredictable directions, and therefore there is a wide variety of possible future levels of energy service demand and end use technology choice
- We have explored a scenario in which social change is strongly influenced by concerns about energy use and its environmental implications, and therefore energy service demand is at a significantly lower level by 2050 than in the 'business as usual' assumptions of other scenarios
- Social and lifestyle change principally affects energy use in the residential and transport sectors, but has wider implications
- In the residential sector, the main drivers of energy service demand are internal temperature, consumption of hot water and use of lighting and appliances. In the transport sector, the main factors are mobility itself, the choice of mode and the uptake of more efficient vehicles. The efficiency of energy use is important in both buildings and vehicles
- In these sectors a combination of energy service demand change and efficiency improvement could reduce energy demand by more than 50% from baseline levels by 2050
- In both sectors, lifestyle change alone will increase the share of electricity in final demand, but reduce the need for massive electrification to meet tough carbon targets
- Social and lifestyle change has the potential to reduce national energy use, energy system cost and carbon emissions by 35% and 30% below baseline levels
- In an energy system constrained to 80% carbon emissions reduction, the main effect of social and lifestyle change is to reduce the costs of delivering a low-carbon energy system, by up to £70 billion

The Lifestyle Scenario

There is considerable interest in the possibility of a cultural shift affecting people's lifestyles. This chapter speculates about the nature, extent and implications of this shift. Lifestyles are more than just attitudes but are reflected in the meaning attached to consumption as well as consumption patterns, societal values, acceptance and use of time and space.

All scenarios necessarily include lifestyle assumptions even if these are unstated and implicit. For example in the Core scenarios of chapters 2 and 3 the assumption is explicit – that preferences do not change significantly over the period to 2050. This implies that lifestyles continue to change along the same lines as the recent past and are driven by price and reflected in elasticities of demand for energy services.

Of course, in practice lifestyles will change in other ways and for other reasons. If Government is pursuing ambitious carbon emissions, this is likely to be consistent with social acceptance, and therefore it is probable that attitudes and personal behaviour will change. Also, what is judged to be acceptable or desirable changes with technical possibility. The 'lifestyle' scenario describes a world in which personal action and socio-political goals within society are consistent. Carbon emissions reduction is delivered not merely through public policy, prices and technical change, but also through socially led change, i.e. through individuals and communities choosing to live in a way that has lower environmental impact.

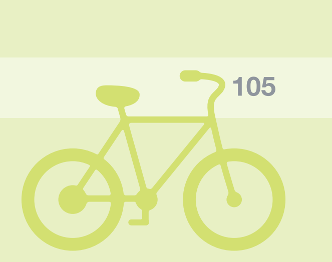
Social values and public attitudes do not change overnight (except under conditions of external shock which we do not seek to describe). However, over a 40-year period, history shows that some social norms do change. So the scenario is designed to be distinct from other scenarios, but to remain within the realms of what is plausible. We judge plausibility with reference to historical rates of changes and current differences across OECD countries. The aim is not to set a utopian vision for future buildings and travel patterns, but to look at what might be reasonable changes to expect in the future. The primary focus of the scenario is household energy use and personal transport – i.e. the forms of energy most directly controlled by the individual. In both cases we examine changes to both choice of energy using technology and use of that capital stock.

The basic storyline of the scenario is of steadily changing social attitudes to the environment, with increasing understanding leading to a widely held belief that human activity is having a serious impact on the global climate. This is followed by a broad social consensus that personal consumption is a key driver and needs to change. We do not assume complete social agreement, nor widespread frugality, but majority support geared to improving quality of life without increased material consumption in rich countries. Starting with some key opinion leaders, social norms emphasise 'green housing'; and 'community living' and 'accessibility' replace 'mobility' as aspirations.

Lifestyle Change at Home

A combination of increasing energy awareness, higher prices and improved real time information increasingly allows attitudes to be reflected in behaviour. The key changes in behaviour that affect residential energy use are those that affect the major uses of energy in the home. In the Lifestyle scenario energy using practices change as follows:

- Insulation of the building stock to a high standard becomes a social expectation. Refurbishment to passive-house standard is adopted progressively, initially through low-income focused programmes in cities and then to rural solid-walled properties
- Over-heating of buildings becomes socially unacceptable, so that the long-term trend in rising internal temperatures ends and they decline modestly. Hot water use also declines, but only to the levels found in many other European countries. New low-carbon heating systems enter the market after 2010 and take a large market share around 2020, allowing building regulations to prevent the use of current inefficient heating technologies after 2030



- The phase out of incandescent lighting in 2011 is successful, with a wide range of solid-state lighting systems rapidly gaining mass consumer markets
- Cold appliance labels and standards prevent markets for US size appliances developing. Typical appliance efficiencies continue to improve up to 2050, especially in cold appliances and consumer electronics. Every home is internet connected, as part of changes to mobility, but growth in electricity use for home computing ends, as remote processing of data with low-power clients for home access is introduced. The 1 Watt initiative for standby is widely implemented. With increased use of 'all off' switching for unoccupied property and automatic low-power modes, standby electricity use decreases
- Smart meters are universally deployed after 2010 with rapid improvements in future generations of technology to provide information on information on energy use by individual devices, in real time. These provide comparisons with historical data for the houses and similar households accessed in a variety of ways to suit consumer preferences, including dedicated displays, TV, SMS and internet, as well as with warnings of non-standard use patterns
- The use of air conditioning in housing remains very limited and is increasingly unacceptable as alternative passive cooling techniques become the norm. Social reaction to conspicuous consumption also prevents any significant growth in markets for new high energy devices such as patio heaters, hot tubs and large plasma screens, initially through peer pressure and then by regulation
- Initial market growth in micro-renewables is highly dependent on the core of committed green energy innovators. Starting with some key influential groups and influenced by zero carbon new-home trends, microgeneration becomes increasingly popular – first solar water heating, then photovoltaics and micro wind
- Consumption patterns also change in food. Increased concerns about health, animal welfare and climate lead to meat consumption halving by 2050

Lifestyle Change and Mobility

Transport energy demand is a function of mode, technology and fuel choice, total distance travelled, driving style and vehicle occupancy. Distance travelled is itself a function of land use patterns, destination and route choice and trip frequency. The 'lifestyle' consumer is more aware of the cost of travel and the energy and emissions implications of travel choices and is sensitive to the rapid normative shifts which alter the bounds of socially acceptable behaviour. Consequently, the following changes take hold:

- The focus shifts to the quality of the journey experience rather than the quantity and speed of travel. Social norms elevate active modes and low-carbon vehicles in status and demote large cars, single-occupancy car travel, speeding and air travel

- Efficient, low-energy and zero energy (non-motorised) transport systems will replace current petrol and diesel car-based systems. The increased uptake of slower, active modes reduces average distances travelled as distance horizons change. Localism means people work, shop and relax closer to home and long-distance travel will move from fast modes (primarily air and the car) to slow-speed modes covering shorter distances overall (local rail and walking and cycling). However, capacity constraints limit the pace of change so that mode shift to buses and rail will be moderated
- The new modes will result in a new spatial order towards compact cities, mixed land uses and self contained cities and regions. There are no large-scale shifts in the spatial distribution of the population between urban and rural. Some services return to rural areas, but it becomes more common to carry out personal business by internet
- New models of car ownership are embraced. This includes car clubs and the tendency to own smaller vehicles for every day family use and to hire vehicles for longer distance travel. These are niche markets in which new technology is fostered. Lower car ownership is correlated with lower car use
- Small-scale technology facilitates relatively rapid behavioural change. Information and Communication Technology (ICT: telematics, in-car instrumentation, video conferencing, smartcards, e-commerce) makes cost and energy use transparent to users and changes everything from destination choice, car choice, driving style and paying for travel, including in the freight sector
- A more radical change takes place through changes in work patterns and business travel. The impacts of teleworking and video conferencing are known to be complex, but potentially important (Gross et al., 2009). Teleworking particularly affects the longer commute trips and thus has a disproportionately large impact on average trip lengths. Combined with the shifts towards active modes and different models of car ownership, this amounts to significant lifestyle shift. It also becomes socially unacceptable to drive children to school
- The novelty of air travel wanes as not only does it become socially unacceptable to fly short distances, airport capacity constraints mean it becomes less convenient. Weekends abroad are replaced by more domestic leisure travel but this is increasingly carried out by low-carbon hired vehicles, rail and luxury coach and walking and cycling trips closer to home
- There is increasing acceptance of restrictive policies in the context of more choice for local travel as the alternatives are improved. These restrictions include the general phasing out of petrol/diesel vehicles in town/city centres through low emission zones, increased parking charges and strict speed enforcement. Generally,

however, the policy environment is one of 'push and pull' as fiscal and regulatory sticks are combined with the carrot of infrastructure investment (e.g. in car clubs, public transport, cycle infrastructure, railway capacity)

- Increased internet shopping and restrictions on heavy goods vehicles, particularly in town centres, increases the use of vans. There is some shift towards rail freight

Modelling the Lifestyle Scenario

Modelling the energy implications of lifestyle change is challenging. It involves detailed assumptions about both the demand for energy services, as well as technology choice, and how these interact with other decisions with the energy system. We have addressed this challenge using three models with different capabilities, as follows:

- The UK Domestic Carbon Model (UKDCM). This is a heat balance model of the UK housing stock. It allows us to model the detailed energy service demands as a function of house type, as well as the implications of different scenarios for installation of insulation and microgeneration
- The UK Transport Carbon Model (UKTCM) (Brand *et al*, 2002; Brand, 2009). This is a highly disaggregated, bottom-up model of transport energy use in the UK. It allows us to model the energy service demands of different assumptions about transport service demand, modal choice and vehicle choice
- The MARKAL energy system model. This allows us to model the impacts of system wide changes in energy and carbon prices on users' decisions, e.g. choice of fuel in homes and vehicles, as well as the effects of demand changes on the wider energy system

We have modelled two additional 'lifestyle scenarios' (LS REF and LS LC) as variants of the Core scenarios REF and LC, as shown in the Table 6.1. Both LS REF and LS LC include similar lifestyle changes; the difference is the inclusion of a (price driven) 80% carbon constraint in LS LC.

The commentary below largely focuses on the difference between REF and LS REF; and between LC and LS LC.

Modelling Household Energy

The lifestyle changes described above were modelled as follows in the LS REF and LS LC scenarios. The assumptions reflect analysis undertaken previously in a low-carbon scenario for the Royal Commission on Environmental Pollution (Palmer et al,

Table 6.1: The Lifestyle scenarios related to the Core scenarios

		System wide carbon constraint in 2050	
		None	- 80%
Social/lifestyle assumption	Business as usual	REF	LC
	'Lifestyle'	LS REF	LS LC

2006), except that the specific assumptions of the lifestyle scenario imply some differences (e.g. for low internal temperature and hot-water use, less building demolition), and more recent information implies a higher realistic potential for heat pumps and lower for district heating and microwind turbines.

- Internal demand temperature peaks at 20C in 2010, then falls back at 0.2C/year to 17C in 2025 and stabilises there. Temperatures are the same in old and new dwellings
- Demolition rate remains at a low rate of 17,000 per year, reflecting a desire to reuse, whilst new build reaches a peak of 255,000 per year in 2016 and stabilises at 120,000 per year
- Energy demand for air conditioning remains negligible (in homes)
- Hot-water use falls linearly by 1.25% annually from 2010 to 2050
- Electricity for lights and appliances increases until 2014 and then decreases to 58% of this value in 2050
- There is full penetration of cavity wall insulation by 2020 and loft top up by 2040. Increased use of external wall insulation both for solid wall insulation (35%) and cladding walls (37%). Wall insulation delivers U-values of 0.25, windows 0.8, implying performance broadly equivalent to current best available
- Purchase of conventional heating systems, i.e. solid-fuel, gas and oil boilers and direct electric heating constrained out after 2030
- District CHP take up reaches between 10% and 25% by 2050
- Single-dwelling CHP reaches between 10% and 60% by 2050
- Heat pump take-up reaches between 10% and 60% by 2050
- Single-dwelling biomass take-up is limited to a maximum of 20%
- Solar thermal on 50% of dwellings providing 25% of domestic hot water by 2050
- Solar PV panels are installed on 15 % of dwellings by 2050
- Microwind turbines are installed on 5 % of dwellings by 2050

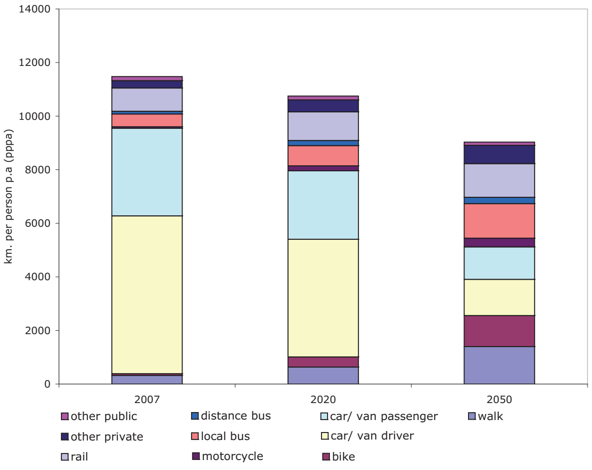
Modelling Transport Energy

The lifestyle changes described above were modelled as follows in the LS REF and LS LC scenarios.

The first set of assumptions related to distance travelled and mode shift. In terms of mode shift, the major reductions in energy demand from the transport sector (see below) are a result of a 74% reduction in distance travelled by car by 2050 as a driver and a passenger. The use of all other surface transport modes increases, apart from a 12% fall in distance travelled by Heavy goods vehicles (HGVs). The reduction in car travel comes about as a result of significant mode shifts, particularly to bus travel towards the latter half of the period (184% increase in vehicle kilometres) and cycling and walking. Mode shift is combined with destination shifting as trips are either totally abstracted from the system through virtual travel or shorter as a result of localisation.

Figure 6.1 shows how people become progressively more 'multi-modal' by the end of the period in the LS REF scenario. In 2020, the car is still used for the majority of distance travelled as a driver or passenger (67%), but this drops to 28% by 2050. However, 'other private', (which includes taxis, hire cars and car club cars) increases from 2.4% of distance in 2007, to 7.5% so that, combined with being a car passenger, 36% of all distance is still undertaken by car in 2050. At the same time, cycling goes from accounting for less than 1% to almost 13% of distance travelled. This surpasses levels seen today in countries regarded as demonstrating best practice in this area: in 2006 an average Dutch person cycled 850km per year, corresponding to around 8% of total distance travelled (SWOV, 2006). We have chosen to push this further over 40 years on the basis that the Dutch have achieved this level so far without comprehensively restricting cars from urban centres and increasing the cost of motoring, which this lifestyle scenario assumes. If cycling and walking are added together, 'slow modes' account for 28% of travel in 2050. Implicit in the assumptions made here is the fact that cars are increasingly banned or priced out of city/ town centres.

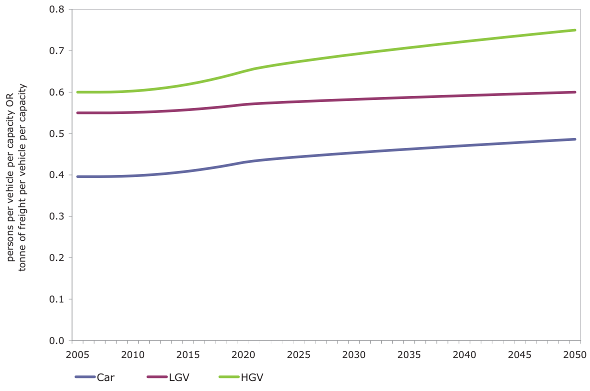
Figure 6.1: Surface passenger transport by distance and mode split in different years in the LS REF scenario



Specific load factors also increase relative to the reference case for cars, LGV and HGV, see Figure 6.2. By 2050, car load factors will have increased by about 23% from the 2007 situation. Similarly, load factors increase for HGV (higher rate than cars) and LGV (lower rate).

There is also an effect of lifestyle change on driving style. Changes to on-road fuel efficiency as a result of speed limit compliance and eco-driving was modelled by assuming that in any given year a certain proportion of car and LGV drivers (includes new drivers) are practicing eco-driving with an average 8% improvement in fuel efficiency for each mile affected (Figure 6.3). However, not all drivers are practicing eco-driving, and even for those who are, not every mile they drive is

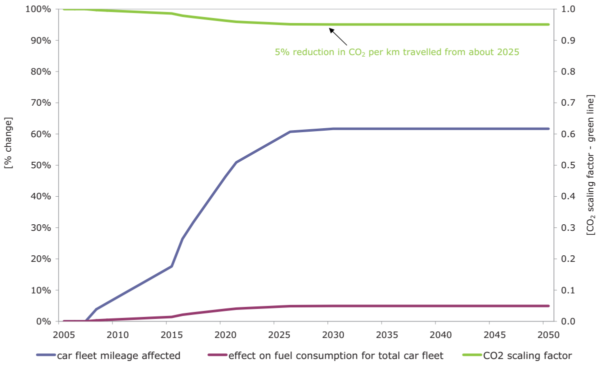
Figure 6.2: Lifestyle projections of specific load factors for cars, LGV and HGV in the LS REF scenario



affected. Speed limit enforcement and in-car instrumentation is assumed to be introduced to augment the behaviour change from about 2015. There are incentives to practice eco-driving as the cost of motoring increases and enforcement penalties are steep. Speeding becomes socially unacceptable as it is seen as wasteful. Penetration through the HGV fleet is the same as for LGVs but the savings per mile are lower (4%) as these vehicles are already speed limited and fuel efficiency training has already taken place in some industry sectors.

With respect to car choice, the higher uptake of lower and zero carbon vehicles has been modelled in UKTCM by assuming more favourable preference and performance parameters (but keeping purchase prices and other cost factors the same) for Battery Electric Vehicles (BEV), Hybrid Electric (HEV) and Plug-in Hybrid Electric (PHEV). The scale and timing of these changes have been modelled on the high to extreme technology scenarios of the recent scoping exercise commissioned by BERR and DfT (2008). The scenarios were reproduced in UKTCM by assuming that, at equal annualised costs, consumers show *equal preference* for conventional and EV/HEV/PHEV vehicles and, in some cases, prefer the latter by a ratio of 2-to-1. Note that equal preference implies equality in perceived market potentials (availability of infrastructure), perceived risk (fuel type, 'proven' vs. 'new' technology) and performance (range, speed, acceleration, etc.).

Figure 6.3: On-road fuel efficiency of cars – assumptions made in the lifestyle scenarios



In addition, no changes in investment and operation and maintenance costs were assumed, as consumers of tomorrow choose to buy greener vehicles not on the basis of reduced purchase prices but on the basis of changed preferences for and perceived risk of a low-carbon vehicle. Car buyers – whether private, fleet or business – choose smaller cars instead of larger ones. This is simulated in UKTCM by phasing out the sale of new large cars (engine size >2.0 litres) by 2020 – starting in 2010, with linear interpolation between 2010 and 2020. This general shift in consumer preference was further modelled in MARKAL MED by assuming lower 'hurdle rates' (discount rate for capital expenditure) for energy-efficient and low-carbon vehicles such as PHEV cars (12.5% instead of 15%, from 2020) and BEV motorcycles (15% instead of 25%, from 2015).

Implications for UK Energy

Energy use in the residential sector

The combined effects of substantial improvements in building fabric (insulation and glazing) coupled with modestly lower internal temperatures have a significant effect on the demand for space heating, see Figure 6.4. The recent (post-2004) trend of a decline in energy use continues, so that energy demand falls by approximately 50% in LS REF compared to REF (and current use). The demand for hot water follows a broadly similar pattern.

The dominant heating technologies also change radically, see Figure 6.5. The predominance of the gas boiler is challenged by several alternatives – biomass, CHP at various scales and heat pumps. Heat pumps (ground source and air source) take a significant share, but gas-fired-technologies (district heating, in urban centres and mixed use developments, and fuel cell micro-CHP in smaller suburban properties) develop and retain a bigger share. This remains the case even in LS LC when national CO_2 emissions are reduced by 80%, although heat pumps and wood have bigger markets in this case. The much larger role of heat pumps in the LS scenario leads to the lower final energy demand, even with less behavioural change than in LS LC. Solar water heating becomes an accepted part of the built environment after 2010 in LS scenarios, providing 50% of water heating demand by 2050.

Figure 6.4: Household energy demand in the LS REF scenario

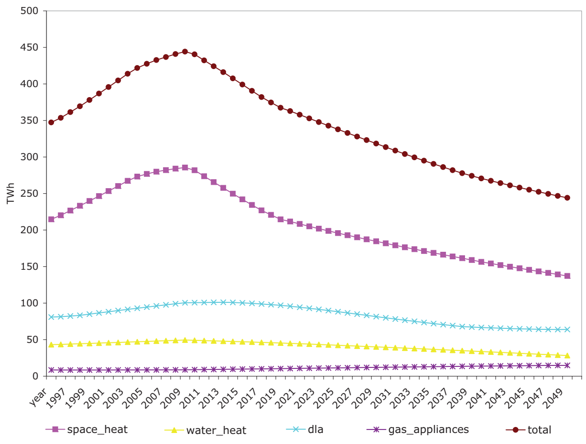
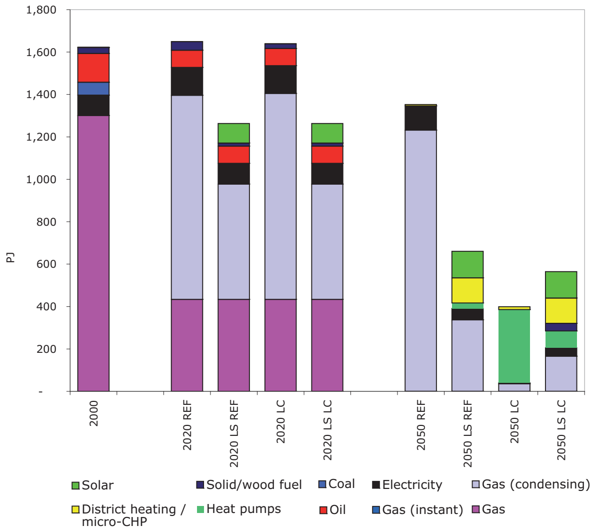


Figure 6.5: Residential heating by fuel type, different scenarios

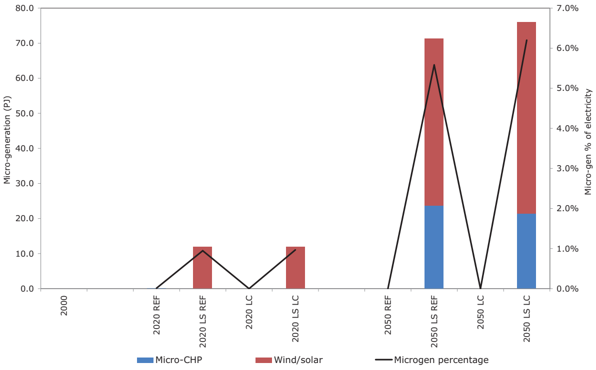


The decline of traditional incandescent lighting accelerates in the period of the voluntary phase-out. They are initially replaced by compact fluorescent lamps (CFLs), but low-cost Light Emitting Diodes (LEDs) rapidly enter the market after 2010 in LS scenarios and become the norm by 2020. With modestly increased levels of illumination, lighting energy use falls by 90% by 2030.

Trends in appliance electricity use prove more difficult to reverse. However, by 2020, continuing improvements in energy efficiency, the saturation of the most intensive uses and the absence of important new sources of demand combine to reverse the trend of increasing use. In LS scenarios, demand then falls by about 1% annually to 2050.

Electricity-generating micro-renewables remain expensive in the early part of the period under consideration. Markets grow,

Figure 6.6: Residential microgeneration in different scenarios



but only slowly until 2020 (see Figure 6.6), by which time the costs have fallen, a viable installation industry has developed and the technical potential is better understood. In LS scenarios, market penetration reaches five million homes for PV and two million homes for wind by 2050. Microgeneration possibilities are discussed in more detail in Chapter 7.

Energy use in the transport sector

The higher uptake of lower and zero carbon vehicles combined with mode shifts and significant alterations to work, shopping and leisure travel patterns result in final energy demand being halved from this sector by 2050 compared to the unconstrained reference case (REF).

In the lifestyle reference (LS REF) case, by 2020 market shares (in terms of vehicle km, not energy use) for hybrid electric (HEV) cars and battery electric (BEV) reach 21% and 9% respectively, compared to zero penetration in the REF and carbon ambition (LC) cases (Figure 6.7). From 2020 petrol plug-in hybrid electric (PHEV) cars become more popular, reaching market shares in 2050 of nearly 50%. In total, HEV, BEV and PHEV cars have a 77% market share in 2050 albeit of a significantly smaller market overall (car use is 74% less than in the REF case). Diesel PHEVs, Hydrogen cars and methanol do not appear in any of the scenarios.

Vehicle end-use efficiencies increase moderately as a result of downsizing of cars and the on-road fuel efficiency programme. The entire petrol and diesel car fleet uses 5-6% and 11-12% less energy per km driven in 2020 and 2050 respectively. Similarly, the LGV and HGV fleets use 2% and 3% less in 2020 and 2050 respectively.

As a result of demand reduction, fuel switching and efficiency gains, the demand for conventional transport fuels (petrol and diesel) decreases by 57% in the unconstrained lifestyle scenario (LS REF). By comparison, electricity demand grows steeply, up by 67% compared to the REF case, particularly in the second half of the period, accounting for 18% of total fuel demand in the unconstrained lifestyle scenarios by 2050 (Figure 6.8). Bio-fuels

Figure 6.7: Car vehicle type by distance driven in different scenarios and years

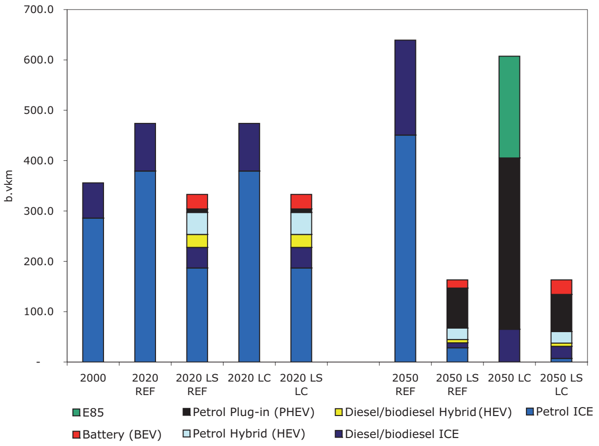
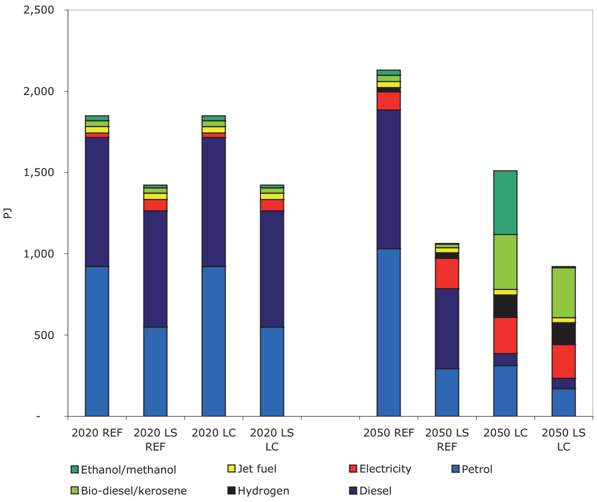


Figure 6.8: Transport fuel demand in different scenarios for different years



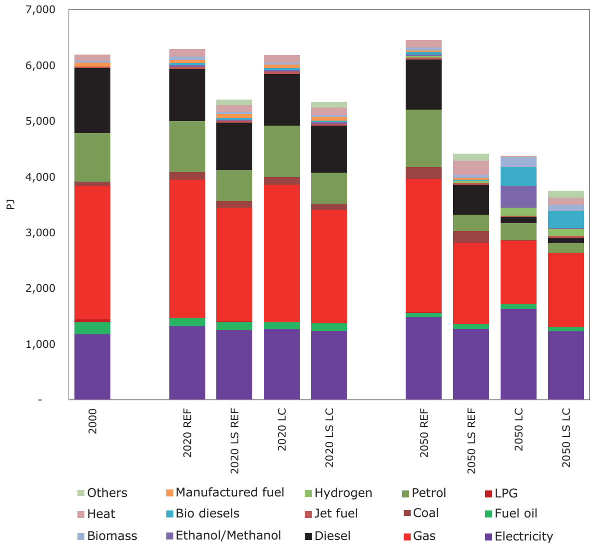
and hydrogen play a major role only in the carbon-constrained cases. For bio-fuels, this is a result of the availability of unlimited blending of second-generation bio-diesel, while in the unconstrained REF and lifestyle scenarios, demands decrease in line with petrol and diesel demands. A high-level blend of bio-ethanol and petrol (E85) used in flex-fuel road vehicles only appears in the Core constrained case (LC) where it accounts for 26% of total fuel demand. In the related lifestyle scenario, lower demand and greater preference for efficient vehicles means that bio-diesel hybrids are preferred.

Implications for the Wider Energy System

The most significant impact of lifestyle change on the wider energy system, compared to the Core scenarios, is due to reductions in demand, particularly for gas in households and oil derived fuels in transport (see Figure 6.9). In LS REF scenario, gas use is 34% lower and oil use 54% lower than in REF. Total energy demand is at approximately the same level as in the LC scenario without any system wide carbon constraint being applied. Carbon emissions are reduced by 30% in LS REF compared to REF. This in turn makes the achievement of radical carbon reductions such as 80% easier, with fewer changes required to the energy system. This is apparent in Figure 6.9 from the much smaller changes between LS REF and LS LC in 2050, than between REF and LC.

Final demand for electricity is reduced by less than other fuels, only 14% (LS REF compared to REF), as lifestyle change includes some fuel switching to electric technologies, notably plug-in hybrid vehicles and heat pumps. In carbon-constrained scenarios, the reduction is bigger (25% reduction from LC to LS LC) as the LC includes more electrification driven by carbon prices. This leads to a lower rate of growth in construction of centralised zero carbon electricity technologies – CCS, nuclear and wind – in LS LC than in LC, see Figure 6.10.

Figure 6.9: Final energy demand by fuel in different scenarios for different years



The much reduced dependence on oil is due to a combination of reduced demand, modal switch, improved efficiency and increased use of electricity. In LS LC this also results in a halving of use of biofuels (principally wheat-derived ethanol) compared to LC. A significant hydrogen sector develops to meet HGV demand in LS LC as in LC, whereas in REF and LS REF, hydrogen only plays a minor role later in the period to power rail transport.

The increased use of electricity in heat pumps in households in the LS scenarios is more than offset by reductions in demand by lights and appliances and by much increased electricity output from microgeneration (see Figure 6.6). Implications for the low voltage grid are also affected by the market for electric vehicles if these are charged at home. Power demand on the grid is broadly unchanged from year 2000 levels in 2050 in LS REF compared to a rise of over 50% in REF. The effect is more significant in the LC scenarios, where lifestyle change prevents any significant increase in demand in LS LC from year 2000 levels. This compares to a 170% rise in electricity demand from households plus light vehicles in LC, with potentially serious implications and/or investment requirements for the low voltage grid.

Figure 6.10: Electricity generation mix in different scenarios for different years

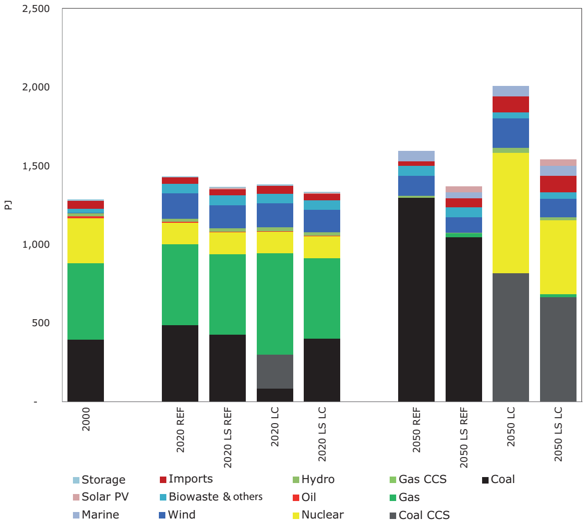
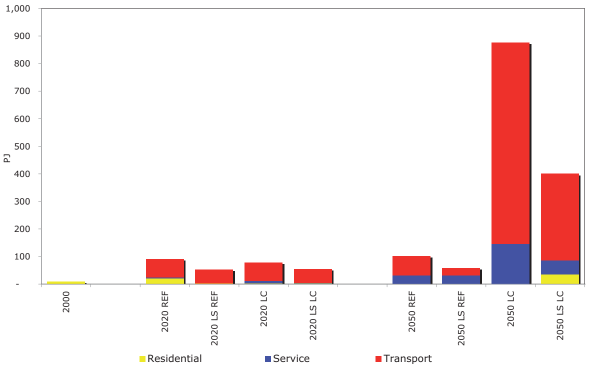


Figure 6.11: Demand for bioenergy in different scenarios for different years



The electricity from increased use of PHEV cars and vans is assumed to come mainly from night charging. This allows the PHEV fleet to act as effective electricity storage, enabling base load centralised generation plants to run better (and more cheaply). The implications of transport fuel differences between REF and LS scenarios is also huge for reliance on biofuels, with lifestyle change leading to far lower use of biofuel (see Figure 6.11).

Economic Implications

It is not meaningful to do a welfare comparison between the Core (REF and LC) and LS scenarios (LS REF and LS LC) as the underlying consumer preferences differ. Total energy supply system costs fall by more than 25% as lower investment is required in a smaller energy system. In both LS (compared to REF) and LS LC compared to LC REF, the energy supply investment costs to 2050 are reduced by £90 billion. The additional costs of demand side investment in households are £20 billion. The difference in transport sector costs is difficult to estimate, but almost certainly lower in the LS scenarios due to reduced travel. We therefore estimate the lifestyle scenario costs are at least £70 billion lower than the reference comparators.

The marginal cost of carbon abatement in 2050 in the carbon-constrained scenarios falls, but only modestly from £169/tCO_2 to £163/tCO_2.

There are also implications for public finances, largely from reduced demand for transport fuels. If tax rates were to remain unchanged, annual revenues in 2050 would fall from £27 billion in REF to £11 billion in LS REF. This is likely to be offset by greater acceptance of environmental taxation in general, including increases in carbon tax (or permit auction) revenues, income from road user charging and parking charges.

Policy Implications

As in the carbon reduction scenarios described in Chapter 2, the key focus of energy policy in the LS scenarios is carbon emissions reduction. However, in the LS scenarios some of the policy pressures are eased. In particular, increased social acceptance of the need for change makes a high carbon price (or alternative carbon control policies) politically sustainable earlier, reducing the marginal cost of carbon emissions abatement in 2050 and particularly the scale of energy supply sector investment.

The greater use of social change implies a broadening of the focus of energy policy. In particular, there is greater scope for housing and transport policy to facilitate changes to technology in these sectors. In turn, this implies that more energy policy objectives are delivered at sub-national level (devolved, regional and local) than in other scenarios. Education and training also change to reflect attitudinal shifts and high requirement for new skills and training in the building and transport sectors.

There is a significant investment shift to the demand side – particularly the buildings, vehicles and public transport infrastructure required for systemic change. This has implications for the type of low-carbon investment required from the finance sector, i.e. a greater emphasis on mass market and decentralised technology (including the microgeneration technologies described in Chapter 7). This implies a bigger role for District Network Operators (DNOs) (to deliver metering, microgeneration and real time demand response), Passenger Transport Executives (PTEs) (to increase mass transit capacity) and social housing providers in energy policy. New business models, e.g. for energy service and car clubs, and new ways of paying for fuel (e.g. using smart cards and differentiated tariffs) will play a larger role. In contrast, the very strong reliance on energy suppliers to deliver low-carbon goals, e.g. through upstream emissions trading, the Renewables Obligation and CERT, declines.

The greater role of individual citizens and communities in energy policy is a scenario assumption. It also has policy implications if it is to occur. In this scenario people will expect household energy suppliers to provide metering and feedback, product suppliers of all types to label products. Carbon reduction achieves the status of a social norm, in a similar way to the role of health and safety today. This leads to an expectation of Government leadership and tough environmental regulation. In transport, there is increasing acceptance of restrictive policies in the context of more choice for local travel as the alternatives are improved. And in buildings, there is general acceptance of tighter building regulations, including where these require improvement of existing homes.

The changes to transport systems lead to significant other benefits, such as better health (much more regular walking and cycling), reduced congestion, noise and accidents, and better local air quality. These are often key drivers of the case for change at a local level.

The social acceptability of carbon pricing will be relatively high, though never unproblematic, resulting in carbon pricing being extended to the whole economy, but with a downstream focus. The concomitant is that policy will be expected to provide a social contract between Government and citizen, with consistent support for decentralised low-carbon investment and behaviour change, whether through better quality public transport, vehicle-free zones or clear incentives for new vehicle and household technologies. Regulation of the market to eliminate unnecessarily high-carbon technologies, e.g. high-emitting vehicles in cities, will be expected to be increasingly tough.

Market-based instruments will continue to have a strong role, not only to price carbon, but also to support innovation. This will probably be through fixed-price or consistent capital subsidy mechanisms, designed to reduce risk for citizen and community involvement in innovation. This applies most obviously to small-scale renewable generation, but probably more importantly to building insulation and vehicles.

Similar principles will be applied to support for social innovation, recognising the importance of social entrepreneurs and community projects. As with technology support this will require a portfolio approach, but with support for 'roll out' where success is evident. There will be significantly higher levels of engagement of local government in area-based initiatives, driven by a combination of community pressure and central Government incentives.

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7. Microgeneration

Key Messages

- Microgeneration offers a unique set of opportunities along with a commensurate set of challenges for its further introduction into the energy system. These relate to the scale and demand-side nature of these generation technologies, and their potential to be disruptive to the incumbent energy system

- Capital costs are a key barrier for all of the main microgeneration systems, resulting in a high implied cost of the CO_2 reduction they provide. Furthermore, technical performance and durability of some of the systems needs to be improved before significant market entry will become viable and aid in meeting energy policy aims

- Choice of reference system against which microgeneration is compared is crucial for accurate performance assessment. Given the possibility of radical energy system change in some UKERC scenarios, research is required to investigate the nature of the 'marginal' energy system and subsequently demonstrate if/how interventions may ensure emissions reductions. Without a convincing base of evidence, credible mitigation technologies may be ignored by industry or denied government support

- Policy has developed rapidly in the UK to support microgeneration, but until recently has focused on uptake rather than appropriate application of systems. Additionally, some policy instruments could support technologies that are unlikely to perform well. These issues and regulatory/institutional factors surrounding appropriate balancing and settlement of micro-generated electricity means that achievement of a level playing field with centralised generation is still a long way off

- The interface between demand-side technology, policy and behaviour could be a key element in the success of future energy policy. Existing underlying incumbent structures of energy production and delivery could be altered from a consumption-based model towards deeper engagement from individuals and corresponding knock-on behavioural changes. It could help to bring about the lifestyle change required for a resilient low-carbon energy system

Introducing Microgeneration

The current UK electricity system is based on relatively few large-scale power plants and a transmission and distribution grid to carry their power across the country to consumers. Decentralised energy production, which contrasts with centralised approaches, involves deployment of a large number of energy generators at or closer to the point of final demand, with associated benefits including efficiency advantages where combined heat and power can be employed, the possibility of reduced transmission and distribution losses for electricity, and a reduced requirement for centralised infrastructure investment, to name a few. One important category of decentralised energy technologies is microgeneration, which for the purposes of this chapter is defined as electricity and/or heat generation systems suitable for installation and use in residential dwellings.

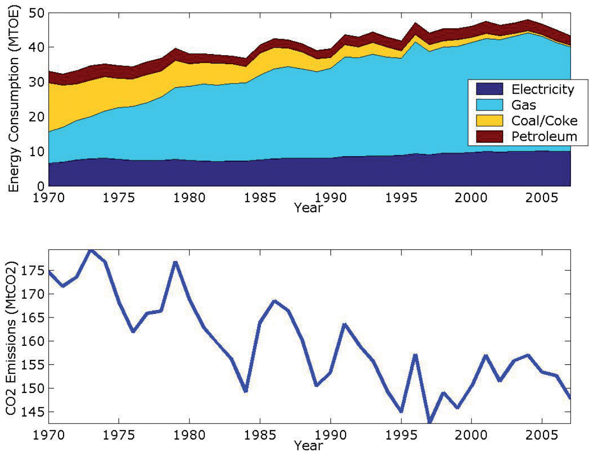
Microgeneration is a class of technologies of the smallest scale in stationary energy supply, installed on the customer side of the meter in residential dwellings, and hitherto typically owned and operated by the dwelling owner/occupier. These key features distinguish microgeneration from other methods of energy supply and provide a unique and challenging set of circumstances for their wider introduction. This chapter explores the status and prospects of the main microgeneration technologies, investigates aspects of appropriate performance assessment, and discusses the interface of policy, behaviour and demand-side technology in terms of its potential to bring about fundamental change to the way energy is produced and consumed.

Microgeneration has recently benefited from the attention of a broad range of energy system stakeholders, from technology developers through to policy makers. The primary overarching driver of this attention is a perceived ability to contribute to greenhouse gas (GHG) reduction in the residential sector. In the UK the residential sector is responsible for more than a quarter of national greenhouse gas emissions, making it a focus of mitigation-related attention, and whilst its contribution has broadly been diminishing since the 1970s, trends beginning in the mid 1990s were less encouraging, as per Figure 7.1. This lack of progress can be attributed to the reduced potential to switch away from solid fuels such as coal to natural gas for dwelling heating, and a stall in a broad downward trend of GHGs embodied in grid electricity, rather than changes to the rate of improvement of energy efficiency. Microgeneration may aid in restoring the decarbonisation trend for the residential sector, and thus enable it to assist energy efficiency in contributing to long-term GHG reduction targets.

In 2004 there were approximately 82,000 microgeneration installations in the UK according to DTI (2006). The technology type by far dominating this installed base was solar thermal systems, accounting for more than 95% of the total. However, projections of future uptake of microgeneration published by the government in Element Energy (2008) suggest that under a baseline scenario 3 million installations could be in place by 2030, rising to more than 9 million under a more favourable policy scenario. They found that preferred technology types in future scenarios varied according to the prevailing policy mix; fuel cell based micro-combined heat and power (micro-CHP) was important in all scenarios, and various combinations of solar photovoltaics (PV), heat pumps and biomass boilers could also be strongly represented. Whilst these overall figures seem optimistic, they may be defensible on the basis that further decarbonisation of residential heat supply is problematic without some kind of microgeneration, with the only alternatives being direct electric heating using low-carbon electricity or district heating schemes, each of which faces its own distinct and comparable challenges. Overall, these market size projections indicate that microgeneration could play an important part in the future low-carbon energy system, with some studies suggesting they could contribute between 15% and 40% of UK electricity supply in 2050[1] (Energy Saving Trust et al. (2005)). This is one of the main reasons for the increased commercial and policy attention for microgeneration.

Another broad foundation of the increased interest in microgeneration is the relatively recent availability of small-scale generation technologies at a cost that is becoming competitive with their large-scale counterparts. These cost reductions serve to bolster the economic case for microgeneration, bringing a variety of established and new technology developers and integrators to the sector.

Figure 7.1: Trends in energy consumption, fuel mix, and CO_2 emissions for the UK residential sector adapted from BERR (2008)



Further to the climate-related, market size, and technology availability drivers, a key element of the interest in microgeneration revolves around the potential the technologies offer to alter the fundamental structures that underlie conventional energy production and consumption. They present opportunities for the lifestyle changes in energy use in the home that may be required to achieve a resilient low-carbon future via engagement of the general population with their energy system, as explored in Chapter 6. However, the prospect of every dwelling becoming an energy producer as well as a consumer creates a tension with the traditionally centralised, structures in place in the incumbent energy system. This tension between centralised and decentralised approaches is a key question for stakeholders, and a deeper understanding of synergies and conflicts between approaches will be crucial for informing future energy policy.

The precise definition of microgeneration varies through the literature, with some studies suggesting that systems up to $50kW_e$ or $100kW_e$ should be included. Here the following definition is adopted; microgeneration is any type of generation (i.e. electricity and/or heat) that is suitable for installation and application in a single residential dwelling. In the UK this typically limits the capacity of microgeneration systems to just under $4kW_e$ electrical (due to provisions in modification G83/1 in ENA (2003) where connection current is limited to 16 Amps per phase), or around $30kW_{th}$ thermal.

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[1] Assuming 2050 electricity demand is equal to that of 2005.

Microgeneration Technologies: Status and Prospects

Microgeneration technologies can be broadly categorised as either low-carbon heat, renewable energy generation, or micro combined heat and power (micro-CHP), although technologies frequently blur the boundaries between these classifications as described in Staffell et al. (2009). Systems can produce electricity, heat, or both. They are installed on the customer side of the meter, and those that generate electricity are usually (but not universally) connected in parallel to the electricity distribution network, enabling interchange of electricity with the incumbent system. A summary of typical basic characteristics, status and issues associated with examples of selected technologies is displayed in Table 7.1. Capital cost is a major barrier for all microgeneration technologies. General awareness of the existence of some system types is also important, in addition to an array of technical, location, and fuel-chain concerns.

Another key discriminating factor between microgeneration technologies is their ability to provide cost-effective greenhouse gas emissions reductions. Bergman et al. (2009) reviewed policy and behaviour related to microgeneration and reported that a very wide range of CO_2-related outcomes exist across the technologies. Using estimates of current capital costs and assumptions regarding performance, reference system and lifetime, it was shown that the cost of existing government support mechanisms for CO_2 reduction via microgeneration could be between £55 (biomass boilers) and £320 (solar PV) per tonne CO_2. These relatively high public costs of mitigation could be justifiable on the basis that some of the supported technologies, notably solar PV, have excellent long-term potential if cost targets are met. Consistent with Table 7.1, Bergman et al. also found capital cost to be a key barrier for microgeneration, with estimated payback periods of the order of several decades in some cases. Micro-CHP is an exception to this (including fuel cell micro-CHP as discussed in Hawkes et al. (2009)), with paybacks as short as 5 years with government support, assuming aggressive near-term capital cost targets can be met.

Importance of the Reference or Baseline System

The nature of the reference or baseline system – defined as the system that microgeneration is replacing or displacing – is vital in determining its performance. Specifically, carbon dioxide reduction afforded by mitigation actions (such as microgeneration) in the UK is typically measured via characterisation of the conventional energy system and calculation of impact by assuming that system will be replaced by the alternative. However, a precise definition of this reference system is problematic; interventions act on the margin of the energy system, implying that system-average statistics such as grid-average CO_2 rates are less relevant for comparison. Furthermore, rapid changes in the conventional system are expected in coming decades. As such, appropriate choice of reference system is a key controversy relating to microgeneration,

Table 7.1: Comparison of metrics for micro-generation technologies. adapted from Staffell et al. (2009). Abbreviations: el – electrical, th – thermal, HP – heat pump, HPR – heat-to-power ratio.

	Typical Capacity	Current Estimated Efficiency / Annual Yield	Current Approx. Installed Cost	Market Status	Main Issues
Low-Carbon Heat Technologies					
Biomass Heater Biomass Boiler	<5kWth 10-20kWth	70-80% 80-90%	£2,000-3,000 £6,000-10,000	Small commercial	Cost, Fuel supply chain, Awareness
Air Source HP Ground Source HP	5-15kWth	3.0-3.7 3.4-4.4	£2,500-7,500 £10,000-15,000	Large commercial (small in UK)	Awareness, Cost
Micro-CHP Technologies					
Stirling Engine (High HPR)	1kWel 5-13kWth	4-8% el 75-80% overall	£3,000 (with subsidy)	Late Demonstration	Electrical efficiency, Cost
Internal Combustion Engine (Intermediate HPR)	1kWel 3kWth	20% el 80-85% overall	£3,500 in Japan	Small commercial	Cost, Few developers for household scale
Fuel Cell (Low HPR)	0.7-1kWel 0.5-3kWth	25-45% el 80-85% overall	£15,000+ in Japan	Demonstration moving to commercial	Cost, Durability
Renewable Energy Generation Technologies					
Solar PV	1-2kWel	650-900 kWh/kW	£5,500/kW el	Commercial	Cost
Solar Thermal	1.5-3kWth	500-600 kWh / kW	£3,200, with wide variation	Large commercial	Cost
Micro-Wind	0.6-1.2kWel	50-500 kWh/kW urban 500-1000 kWh/kW rural	£2,000+	Small commercial	Lack of appropriate locations (i.e. energy output), planning permission

and an important topic for ongoing research.

For performance assessment of microgeneration the reference system in the UK is generally accepted to be the case where the dwelling consumes grid electricity, and domestic hot water and space heating needs are met via combustion of natural gas in a condensing boiler. In terms of CO_2 reduction, the heating reference system in this case is reasonably straight-forward; combustion of natural gas in the boiler produces approximately 0.19kgCO_2/kWh of gas used. Conversely, the CO_2 emissions avoided due to reduced use of the reference electricity system is much more complicated. Using grid-average emissions rates, which have been hovering above 0.5kgCO_2/kWh in the UK for the past few years, to estimate the fair credit to give to an intervention may not be the best estimate of the influence of an intervention. The actual CO_2 reduction afforded by an intervention is arguably a combination of:

1. The instantaneous response of generators on the reference system to a change in demand (e.g. which generator ramps down in response to a load reduction).
2. The near to medium term energy trading impact of a systematic change in demand caused by presence of a demand-side intervention.
3. The longer-term build margin, where the construction of the next generation of system capacity (e.g. new power stations) may be accelerated or deferred due to a set of interventions.

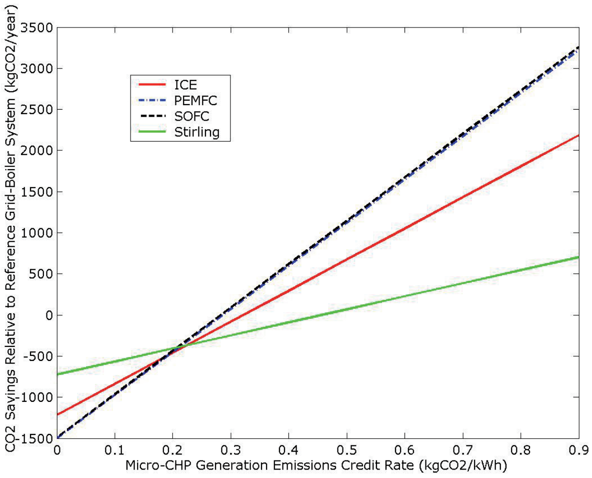
Further complicating matters is the questionability of the existing conventional or a specific future system as an appropriate reference in a time of energy system upheaval. For example, if long-term government targets are to be met, rapid decarbonisation of centralised electricity generation will be required over coming decades, as exemplified in the low-carbon scenarios of Chapter 2. This poses questions regarding the accuracy of any projection of the build margin described above, where conclusions are inevitably uncertain. This issue applies equally to the heating reference system, where choice of the condensing boiler as the marginal conventional technology is debatable where rapid decarbonisation may promote large-scale adoption of technologies such as heat pumps, district heating, and biomass boilers. Where the reference system presents such a moving target, fair evaluation of alternative technologies will pose challenges, obscuring identification of optimal pathways towards a low-carbon residential sector, and necessitating risk-aware assessment methods.

An example of the impact of definition of reference system on performance assessment is clear for the case of gas-fuelled micro-CHP. Figure 7.2 displays this dependency through a plot of modelled CO_2 reduction against the fair credit rate for displaced grid electricity. Micro-CHP does not provide emissions reduction when the fair CO_2 credit rate falls below approximately 0.3 kg CO_2/kWh. Given that low-carbon scenarios such as those in Chapter 2, consistent with long-term climate related targets, require rapid decarbonisation of the electricity grid, this result seems to cast doubt on gas-fuelled micro-CHP in a future low-carbon energy technology mix. For example, the average carbon intensity of the Low-Carbon Core (CAM) scenario described in Chapter 2 is 0.06 kg CO_2/kWh by 2035, and 0.037 kg CO_2/kWh by 2050 (see Figure 3.1), which is well below the 0.3 kg CO_2/kWh threshold figure given above.

However, to draw such conclusions would be premature given uncertainty regarding the reference system (i.e. uncertainty regarding the true fair CO_2 credit rate for onsite generation), and the potential for micro-CHP control strategies that ensure systems displace fossil fuelled centralised generation. The LS scenarios in Chapter 6 demonstrate the potential for a significant gas CHP potential to be consistent with 80% CO_2 reduction in some scenarios. Furthermore, potential exists for micro-CHP to employ alternative fuels, which would significantly alter the CO_2 reduction predictions of Figure 7.2. These considerations could have major implications for the relative quantity of CHP and heat pump installations.

Overall it is clear that further research is required to tackle the issue of definition of the reference system for performance assessment of demand side mitigation interventions. Such definition is required to ensure credible mitigation actions are not ignored by industry and denied access to government support.

Figure 7.2: Sensitivity of annual CO_2 emissions reduction (kg CO_2/year) to emissions credit rate granted for onsite generation (kg CO_2/kWh) for 1kWe micro-CHP systems in an average UK dwelling demand scenario. Abbreviations: ICE = internal combustion engine, PEMFC = polymer electrolyte fuel cell, SOFC = solid oxide fuel cell, Stirling = stirling engine.



Policy Development for Microgeneration

In recent years substantial effort has been directed towards development of policy instruments and regulation to support microgeneration in the UK. At the highest level these include broad indications of support such as provision in legislation to set microgeneration targets as per HM Government (2006), publication of a Microgeneration Strategy via DTI (2006), and numerous reports detailing the potential of technologies and impact of proposed incentives. An attempt has been made to underpin this overarching support by specific financial incentives, changes to regulation to remove technical barriers and streamline bureaucracy, and changes to fundamental instruments such as the building regulations to permit credit to be given for inclusion of microgeneration in dwellings as outlined in Bergman et al. (2009). The influence of these specific instruments on microgeneration has yet to be observed on any significant scale, and many are the subject of ongoing debate.

The existing financial policy instruments, which are dominated by the Low-Carbon Buildings Programme (LCBP), the Carbon Emissions Reduction Target (CERT), and Value Added Tax (VAT) reduction on energy-saving items, can provide significant economic support for microgeneration[2], but focus on uptake of technologies rather than their appropriate application. A new method of support – a feed-in tariff for microgeneration – has been put forward in the recent Energy Act (HM Government (2008)), and this could better incentivise utilisation of microgeneration of electricity in a way that can help to achieve the broader aims of energy policy. However, unconsidered application of instruments such as feed-in tariffs can also have negative impacts, and could even create perverse incentives as in the case of gas-fuelled micro-CHP:for example it has been shown (Hawkes and Leach (2008)) that where micro-CHP is incentivised via a feed-in tariff for electricity, gratuitous operation of the device[3] to benefit from the feed-in tariff can result in higher CO_2 emissions than the case where no support is offered. Examples like this show that care must be taken with the structure of such instruments to ensure they help to meet policy aims.

Debatably the most important policy instrument in relation to microgeneration in the UK is the proposal to mandate high levels of the Code for Sustainable Homes (CLG (2006)), notably to require all new dwellings to be zero carbon from 2016. The most practical way to achieve this at present is via high levels of energy efficiency and installation of multiple microgeneration measures in each dwelling, which would undoubtedly provide a strong boost to the industry. However, a serious doubt exists regarding the readiness of the construction and commercial sectors to provide the means to reach zero carbon status at a reasonable cost. In response to this issue, the government has recently consulted on the definition of zero carbon, suggesting that some sources of CO_2 may not be included in the implemented approach.

There are also a number of further policy and regulatory issues, many of which relate to the simplicity and logistics of microgenerator installation and operation. Many of these concern data flows within the Balancing and Settlement Code (OFGEM (2001)), in order to allow microgeneration export to participate in electricity system balancing effectively and to be fairly settled. Data flow issues should be resolvable, albeit at some expense. Arguably, metering etc. will cost more than the value of export for some microgenerators, although metering issues are also an important behavioural concern. Perhaps the most challenging issue regarding balancing and settlement is that of creating standardised profile classes for dwellings with microgenerators (and for microgeneration export). Standard profile classes are a tool used in balancing and settlement where half-hourly metered data is not available. They are expensive to create and, for microgeneration, may be inaccurate as generation profiles can vary significantly, even between technologies of the same type. This not only creates difficulty regarding fair settlement for each generator, but also has implications regarding effective low-cost balancing of the system in real time. In the future,

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[2] These three policy instruments, and particularly the LCBP, can provide several thousands of pounds of support for individual microgeneration installations. However, even with support, capital cost is an important barrier for system uptake.

[3] Via overheating of the dwelling to higher temperatures than would normally be required, deferral of insulation upgrade, etc.

these standard profile classes may be replaced by smart metering and IT solutions. If the amount of microgeneration increases significantly, it may become necessary for it to be controllable in order to maintain a stable electricity system. The roles of system balancing, local voltage control and phase balancing are particularly important. For these reasons, smart metering and two-way communication with the supplier could be necessary to enable microgeneration to meet the needs of the grid, and for householders to be financially rewarded for controlling microgeneration appropriately.

Overall the policy framework to support microgeneration has recently benefited from attention, but significantly more effort is required to ensure a level playing field between decentralised and centralised energy generation. Much of existing policy focuses on the uptake of measures, rather than performance after adoption, which could be a key element in unlocking further benefits of consumer engagement with their energy system. Indeed links between the behaviour, technology (e.g. smart metering, microgeneration), and the structure of policy and regulation could create opportunities for inducing the lifestyle change required for an enduring low-carbon society.

The Interface of Policy, Behaviour, and Demand-Side Technology

According to Bergman et al. (2009), maximising the energy and emissions savings from microgeneration requires both significant uptake of the technology among consumers and behavioural changes in domestic energy use. As discussed above, much of existing policy focuses on uptake only, which may not encourage appropriate behavioural changes. However, microgeneration can be considered in the context of energy related behaviour and the broader social and infrastructural measures which could shift domestic energy use to more sustainable patterns, as set out in Chapter 6. Consideration of these issues in policy instrument formulation and technology development could enable policy aims to be achieved more effectively.

Energy-related behaviour is often thought of simply as consumption. However, consumption is not just about satisfying needs, but is connected to identity and meaning creation; material goods play symbolic roles in our lives beyond their functional uses. Specifically, environmentally significant (consumer) behaviour is culturally embedded and includes social, moral and normative considerations (Jackson (2004)). For example, people see the government (and industry) as responsible for addressing environmental problems, and see themselves as having little effect. Indeed evidence exists that there is a lack of understanding of the influence of individual behaviour on energy use and related climate change. Stemming from these observations, there appears to be an opportunity to use microgeneration as a part of broader social change, greater use of demand-side technologies, and behaviour change (Watson et al. (2006)). This can be discussed in terms of the distinction between ‘energy consumer’ and ‘energy citizen’ as per Table 7.2. Judicious

Table 7.2: Qualities of consumption and citizenship, present and possible future scenarios. Adapted from Janda (2007)

	Consumer	**Citizen**
Business as Usual	Economic rights (& social opportunities) • more is better	Political rights • voting, earning, responsibilities
Microgeneration Scenario	Buy more microgeneration => smart houses, passive users	Wise use & sufficiency => smart houses, smart users

formulation of policy instruments combined with development of appropriately aligned technology and business strategy could result in actors adopting the microgeneration/citizen mentality. This is opposed to the existing model applied by the incumbent energy system where customers are seen as consumers, resulting in the focus on technology uptake rather than on context-setting for environmentally-aware behaviour, and leading to the microgeneration/consumer combination of Table 7.2.

Overall, the social and behavioural issues pertinent to microgeneration are a potent factor in dictating uptake and use. It is clear that research is required that considers the policy/behaviour/technology interface for successful uptake and application, in order to formulate a complete policy framework for accelerating the penetration of microgeneration into the energy generation mix. Successful uptake of the most appropriate installations with good information provision can maximise emission savings as well as increase citizen awareness of their energy usage and potential savings.

Conclusions

Microgeneration offers a unique set of opportunities along with a commensurate set of challenges for further introduction into the energy system. On one hand, as shown in Chapter 6, it could form an integral part of a low-carbon energy supply in the UK in coming decades, and indeed it is virtually indispensable for further decarbonisation of residential heat. On the other hand it faces a demanding set of technical, economic, and institutional obstacles.

Capital costs are a key barrier for all of the main microgeneration options, and technology R&D, learning-by-doing, and market scale-up is required to reduce these. Furthermore, some of the relevant technologies are immature, and technical performance must be improved before market entry will become realistic. Numerous additional barriers exist, including the structure of the incumbent energy system, lack of awareness or the existence or potential of technology options, and a broader techno-centric view that ignores possibilities to affect energy and climate-related attitudinal changes.

In terms of performance assessment of the technologies, it is apparent that choice of reference system against which to compare microgeneration is very important and not well understood. This is because any individual mitigation intervention is marginal in nature, and therefore average energy system statistics are unlikely to be appropriate in determining (for example) its greenhouse gas emissions reduction contribution. Moreover, in a period of energy system upheaval as is predicted over coming decades, the definition of which future generation plant to compare microgeneration against is problematic and requires research attention.

Despite these challenges, policy has developed rapidly in the UK to support microgeneration. Numerous mechanisms of upfront capital support exist, and a new feed-in tariff has been proposed. However, some of these developments have been ill-considered, and co-ordination between and within instruments is haphazard. As such, achievement of a level playing field with centralised generation is still a long way off.

Finally, it is suggested that the interface of technology, policy and behaviour is critical to the success of future energy policy. Existing modes of policy delivery and stakeholder business models in the residential sector favour passive energy consumption, but a shift of focus may motivate a more engaged response with ensuing knock-on benefits. Microgeneration is one technology that can help better engage individuals and the public as a whole, providing opportunities to leverage lifestyle change towards a resilient low-carbon energy system.

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8. Prospects and Policies for a Secure and Low-carbon Energy System

Key Messages

- Achieving a resilient low-carbon energy system in the UK is technically and economically feasible at an affordable cost
- There are multiple potential pathways to a low-carbon economy. A key trade-off across the energy system is the speed of reduction in energy demand versus de-carbonisation of energy supply
- There are also a large number of more specific trade-offs and uncertainties such as the degree to which biomass, as opposed to electricity and perhaps hydrogen, is used in transport and other sectors
- Deploying new and improved technologies on the supply side will require a substantially increased long-term commitment to RD&D, the strengthening of financial incentives and the dismantling of regulatory and market barriers
- Reducing energy demand is the key to a resilient energy system. This will reduce the UK's exposure to energy price shocks and could help us to ride out major disruptions to infrastructure
- A step change is needed in the rate of improvement of energy efficiency. This will reduce the welfare costs associated with demand reduction
- Changes will be needed to the design and regulation of energy markets to facilitate the move to a resilient low-carbon energy system, with, for example, much stronger incentives for transformational investments in supply and transmission infrastructures
- Lifestyle changes that reduce energy demand would enhance energy system resilience and reduce the costs of CO_2 reduction. Further work is needed to assess how such changes might be induced and the role that policy could play
- If public concern about specific technologies prevents their deployment, the cost of meeting CO_2 targets will significantly increase, and a greater burden will be imposed on demand side responses
- Reducing CO_2 will broadly lead to improvements in other environmental areas, but regulatory attention may be needed in some areas (air quality, water stress) where there are potentially adverse effects

Overview

The overall purpose of the Energy 2050 project was to provide insights into the policy choices, institutional structures, market regulation, and implications for consumers, energy companies and others, of the determined implementation of measures to achieve a low-carbon resilient energy system. It has sought to answer the question: How can the transition to a secure and low-carbon UK energy system be achieved over time, and how can opportunities over short and long timescales, and between different parts of the system (production and consumption, technology and behaviour) be brought together and barriers overcome?

The Energy 2050 project has shown that the technical and economic potential for the UK to move systematically towards a resilient and low-carbon energy system is there and the prospects are encouraging. On the supply side there is a wide range of low-carbon options potentially available to deliver both the carbon reductions required by the UK Climate Change Act, and the diversity required for energy system resilience.

Achieving the 80% Target

A range of scenarios, all of which achieve the 80% CO_2 reduction goal, is summarised in Table 8.1. Although they have this in common, the mixture of technologies varies widely *demonstrating that there is no one pathway to a low carbon economy*. The route to 2050 depends on how we respond to options that are either opened up through technological development or behaviour changes, or closed down because of social choices or events beyond our control.

Figure 8.1 shows how the scenarios reported in Table 8.1 are clustered in relation to each other. The tree diagram has been created by analysing the degree of correlation between the scenarios in terms of a set of key indicators for 2035, roughly the mid-point of the projection period. The indicators are: level of final energy demand; carbon intensity of grid electricity; and maximum fuel share in the primary energy mix. These three indicators were selected because they capture the principal differences in system responses to decarbonisation and resilience imperatives across the different scenarios.

The degree of dissimilarity between two scenarios is measured by the distance from left to right before their two branches meet. If two scenarios are closely correlated, i.e. they are similar in terms of the key indicators, they will be close to each on the diagram and their branches in the tree diagram will meet after a short distance. The LC Acctech and LC Renew scenarios are examples of these. The branches of dissimilar scenarios converge further to the right of the diagram, for example LCR and LC.

Two scenarios - lifestyles (LS LC) and low-carbon resilient (LCR) – are quite distinct from the others. Both have much lower levels of final energy demand, and much higher CO_2 intensity of grid electricity, than the others. Although they are driven by different ‘storylines’ – reducing energy dependence in the case of LCR and a cultural shift in attitudes to energy usage in LS LC – the similarities in terms of outcome are striking.

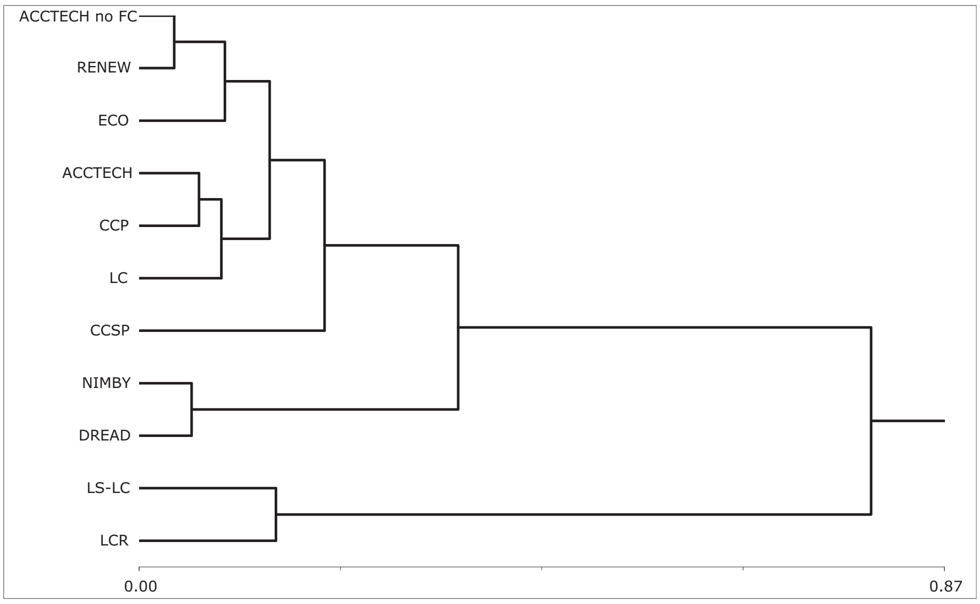
The key characteristic of the closely linked NIMBY and DREAD scenarios is that restrictions on electricity generating technologies have forced a reduced market share for electricity, and hence a continuing reliance on natural gas. Gas accounts for a significant share (above 40% in DREAD) of the primary energy mix.

CCSP, which has a least-cost carbon pathway based on a social discount rate, is also distinct, being characterised by early carbon reductions leading to both lowered final energy demand and decarbonised electricity.

Table 8.1 Summary of UKERC energy 2050 scenarios meeting 80% target

Group	Scenario	Notes
Carbon reduction scenarios	LC	80% reductions by 2050, 26% by 2020
	CCP	Least-cost path, 80% CO_2 reduction post 2050. 2010-50 carbon budget from CEA
	CCSP	Least-cost path, 80% CO_2 reduction post 2050. 2010-50 carbon budget from CEA. Social discount rate
A resilient energy system	LCR	Low-Carbon Resilient
Technology acceleration	LC Acctech	All seven supply technologies accelerated
	LC Renew	All four renewable supply technologies accelerated
	ACCTECH no FC	All seven supply technologies accelerated (except Fuel Cells)
Energy lifestyles	LS LC	Lower-carbon lifestyle changes in households and personal transport
Environmental sensitivities	DREAD	No CCS, new nuclear or hydrogen
	ECO	Constraints on wind, marine, nuclear, CCS and the availability of rape seed oil, straw and wheat. Energy crops disallowed
	NIMBY	Constraints on wind, marine and domestic bio-energy resources

Figure 8.1: Clustering of scenarios in 2035



The two scenarios which involve technology acceleration (LC Renew and LC Acctech) are similar in that they both address mainly the decarbonisation of electricity. They are also quite similar to the core low-carbon LC scenario and the least-cost path CCP scenario. The ECO scenario, which is particularly restrictive in terms of electricity generating options and bio-energy development is mid-way between the CCSP scenario and the technology acceleration cluster.

The electricity sector has to be effectively decarbonised to meet the 80% target by 2050 in all the scenarios. In most of the scenarios we have looked at, electricity is well on the way to decarbonisation by 2030. However, in the LCR and LS LC scenarios decarbonisation runs about a decade behind the others.

Scenario Comparison

Looking out to 2050, the end of the projection period, Tables 8.2 and 8.3 compare the major scenarios reported in earlier chapters. Table 8.2 compares energy and carbon outcomes. Table 8.3 focuses on economic variables.

With regard to Table 8.2:

- In respect of carbon reduction (column 3), REF (which contains UK Government carbon reduction policies up to 2007) produces only 2% reduction from the 1990 level by 2050. Of the other carbon-unconstrained scenarios, LS REF and R produce 31% and 52% reductions respectively, indicating the carbon-reducing power of lifestyle change and a policy priority of energy system resilience. However, this is still well short of the 80% reduction target. Stringent additional carbon-reducing policies are clearly necessary if this target is to be achieved

- In respect of cumulative emissions (column 4), CCP and CCSP show that the same cumulative emissions (19 $GtCO_2$) can be achieved over different time-paths, although CCP, which delays carbon reduction, has to achieve 89% decarbonisation by 2050 in order to achieve this

- In respect of energy demand (column 5) all the 80% or more reduction scenarios (LC, LCR, CSAM, CEA,CCP, LC Renew, LC Acctech, DREAD, ECO, NIMBY, LS LC) reduce primary energy demand by 2050 by 31-45% below the REF level, and final energy demand by 29-39%. These reductions occur through the joint application of the carbon price, efficiency and conservation measures and, in LS LC, non-price related behaviour change. At present, policies do not exist either to establish the necessary carbon price across the economy, nor to stimulate the necessary uptake of efficiency and conservation measures

- Achieving the 80% target is also associated with considerable increases in electricity consumption (typically 50% over REF), or reductions in residential energy demand (typically around 50% below REF), or both (column 6). LCR, DREAD and LS LC have the smallest increases in electricity demand, for different reasons. LCR decarbonises more by reducing energy demand, because of the energy intensity constraint. DREAD uses less electricity in transport. LS LC has among the highest reductions in residential energy demand (57%), also uses less transport fuel and, like DREAD, uses more bio-fuels. CSAM, LC Acctech, and ECO all have increases in electricity above 70%: CSAM because of the high level of decarbonisation required (it has the lowest cumulative

CO_2 emissions of all the major carbon reduction scenarios); LC Acctech because the technology acceleration has left low-carbon electricity technologies relatively cheap; and ECO because there are no limits on nuclear and coal CCS

- Of the diversity indicators (column 7) only LS REF and CCSP breach the 40% maximum share of any primary fuel, with both of them using too much coal for power generation. The breach does not occur in REF because the primary energy demand is much larger. Far more scenarios breach the 40% maximum share in generation, with REF and LS REF outstanding as having too much coal-fired generation, and DREAD too much wind (see Figure 5.11), because of social concerns about the other major low-carbon electricity sources, nuclear and CCS

- Column 8 shows the extent of decarbonisation of the electricity system by 2050. The CO_2 intensity of the least decarbonised of the major carbon reduction scenarios (CCSP) is still only 7% that of REF by 2050. DREAD and CSAM are almost completely decarbonised. Most of those with relatively little power sector decarbonisation tend to use more biofuels (CEA, CCP, LS LC), allowing the power sector to take more of the carbon budget. CCSP uniquely goes for a mixture of demand reduction and hydrogen in transport

- The final two columns relate to EU targets for 2020. In the first column, it can be seen that by 2050 in no scenario does the UK come anywhere near the 15% of renewables in final energy demand by 2020, which is its mandatory EU target. The maximum achieved is just 6%. In the second column, it can be seen that the maximum reduction in primary energy demand by 2020 is 11% in the early-action CCSP scenario, and 10-11% in the two Core resilience scenarios, compared to the EU aspiration to reduce EU primary energy demand by 20% below the 'business-as-usual' level by that date. There is further discussion of these two policy positions below.

With regard to Table 8.3:

- Broadly the highest carbon prices occur in those scenarios that have the highest carbon reduction targets (CSAM), delay carbon reduction (CCP), or rely for decarbonisation on both high levels of power generation and demand reduction (ECO). For the rest, meeting the 80% carbon reduction target can be achieved with a carbon price of below £208/tCO_2 For comparison, if all the current rate of fuel duty in the UK (about 50p/litre) were considered to reflect a carbon price, this would be about £208/tCO_2.

- With regard to energy system costs, as discussed in Chapter 2, in MARKAL there are two opposing tendencies when a carbon or resilience constraint is applied. The use of more expensive low-carbon or other technologies tends to increase the energy system cost, while reductions in energy demand (from the higher energy price) tend to reduce it. It can seen that only in the resilient and lifestyle scenarios is the demand effect greater than the effect from more expensive technology, so that the energy system cost in R falls by £11 billion. In all other scenarios it increases, in the high-carbon reduction scenarios by £18-30 billion. For comparison, in 2050 the total energy system cost across the scenarios is £250-300 billion. The increase in energy system costs due to decarbonisation is therefore around 10% in most cases

- The energy system cost calculation in the lifestyle scenarios is not strictly comparable with that in the other scenarios, because of modelling differences. However, the intuition behind the result seems sound: people demand less energy because their preferences have changed, rather than because energy prices have been increased through the deployment of more expensive technologies. The energy system is therefore smaller, and cheaper. The reduced size (about 30%) is in line with the reduced energy demand
- Constraining MARKAL always reduces social welfare because its unconstrained run is defined as optimal. The reductions in social welfare in the 80% decarbonisation scenarios (excluding CCSP and LS LC, which change the discount rate or preferences) amount to £28-53 billion. The losses of social welfare due to gaining resilience or low-carbon resilience are higher at £49 or 59 billion. As noted in the text, this is an upper bound, because of the very pessimistic assumption that energy price increases cause reductions in demand rather than an increase in uptake of relatively low-cost conservation measures. There is no obvious comparator to this welfare cost. UK GDP is about £1.5 trillion. A £50 billion welfare loss as a proportion of UK current GDP is about 3%, but would be less than half that in 2050 if UK GDP were to grow at 2% pa, as is often considered likely

In the light of these results, some comments now follow on particular themes from the previous chapters.

Table 8.2: Comparative table of energy 2050 scenarios: carbon and energy

Scenario	Scenario name	Carbon reduction targets/ 2050 reductions if no targets (from 1990 level)	Cumulative emissions $GTCO_2$ (2000-2050) / 2050 emissions $MTCO_2$	Primary energy demand / Final energy demand %	Total electricity demand / Residential (all fuels) demand %	Max primary share / Max genmix % at 2050	CO_2 intensity of power g/kWh at 2050	Share of renewables in final energy demand at 2020 %	Primary energy demand reduction at 2020 (% from 2020 REF)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
CORE SCENARIOS				Difference from 2000 baseline at year 2050					
REF	**Reference**	**2%**	**30/583.0**	**-4/+4**	**-25/-2**	**38/81**	**592**	**5**	**0**
LC = CAM	**Low-Carbon (Ambition)**	**26% by 2020** **80% by 2050**	**20/118.5**	**-32/-29**	**+57/-55**	**32/41**	**31**	**5**	**1.3**
R	**Resilient**	**52%**	**23/285.3**	**-44/-38**	**+1/-50**	**31/40**	**352**	**5**	**10.6**
LCR	**Low-Carbon Resilient**	**26% by 2020** **80% by 2050**	**20/118.5**	**-49/-40**	**+17/-50**	**24/40**	**15**	**5**	**10.2**
CARBON REDUCTION									
CFH	Faint-heart	15% by 2020 40% by 2050	26/355.4	-5/0	+27/-6	39/74	110	5	1.6
CLC= LC-RCEP= LC 60	Low-carbon	26% by 2020 60% by 2050	22/236.9	-19/-14	+35/-19	34/57	44	5	3.5
CSAM	Super ambition	32% by 2020 90% by 2050	18/59.0	-41/-28	+73/-58	34/45	8	5	6.1
CEA	Early action	32% by 2020 80% by 2050	19/118.5	-32/-30	+56/-56	33/43	31	5	3.8
CCP	Least-cost path	Same cumulative as CEA 89%	19/67.1	-37/-30	+60/-58	30/49	22	5	3.3

CCSP	Socially optimal least-cost path	Same cumulative as CEA 70%	19/178.6	-29/-31	+59/-58	43/54	41	6	11.3
TECHNOLOGY ACCELERATION									
LC Renew	All four renewables	26% by 2020 80% by 2050	20/118.5	-36/-26	+60/-48	24/41	15	6	0.3
LC Acctech	All seven technologies	26% by 2020 80% by 2050	20/118.5	-31/-25	+89/-28	26/34	20	6	-0.2
ENVIRONMENTAL SENSITIVITIES									
DREAD	See Table 5.1	26% by 2020 80% by 2050	20/118.5	-44/-27	+17/-47	32/84	4	6	7.0
ECO	See Table 5.1	26% by 2020 80% by 2050	20/118.5	-45/-34	+78/-58	23/48	8	4	8.2
NIMBY	See Table 5.1	26% by 2020 80% by 2050	20/118.5	-44/-32	+51/-57	25/41	9	5	1.5
ENERGY LIFESTYLES									
LS REF	Reference lifestyle	31%	23/407.1	-33/-29	+2/-52	46/77	571	6	21
LS LC	Low-carbon lifestyle	26% by 2020 80% by 2050	20/118.5	-44/-39	+15/-57	31/43	32	6	21

Table 8.3: Comparative table of energy 2050 scenarios: economic variables

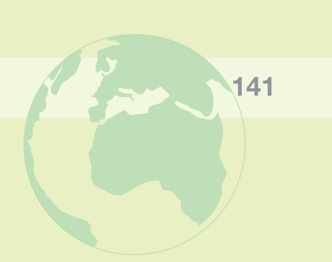
Scenario	**Scenario name**	**Carbon reduction targets/2050 reductions if no targets (from 1990 level)**	**Marginal cost of carbon abatement (carbon price) at 2050 £(2000)/tCO_2**	**Energy system costs £bn (change from REF at 2050)[1]**	**Welfare costs £bn (change from REF at 2050)[1]**
(1)	(2)	(3)	(4)	(5)	(6)
CORE SCENARIOS					
REF	**Reference**	**2%**	**0**	**0**	**0**
LC = CAM	**Low-Carbon (Ambition)**	**26% by 2020** **80% by 2050**	**169**	**17**	**38**
R	**Resilient**	**52%**	**0**	**-11**	**49**
LCR	**Low-Carbon Resilient**	**26% by 2020** **80% by 2050**	**20**	**2**	**59**
CARBON REDUCTION					
CFH	Faint-heart	15% by 2020 40% by 2050	20	3	5
CLC= LC-RCEP= LC 60	Low-carbon	26% by 2020 60% by 2050	85	8	20
CSAM	Super ambition	32% by 2020 90% by 2050	299	30	52
CEA	Early action	32% by 2020 80% by 2050	173	17	37
CCP	Least-cost path	Same cumulative as CEA 89%	360	23	48
CCSP	Socially optimal least-cost path	Same cumulative as CEA 70%	66	2	7
TECHNOLOGY ACCELERATION					
LC Renew	All four renewables	26% by 2020 80% by 2050	148	19	34
LC Acctech	All seven technologies	26% by 2020 80% by 2050	131	18	28

ENVIRONMENTAL SENSITIVITIES					
DREAD	See Table 5.1	26% by 2020 80% by 2050	190	20	43
ECO	See Table 5.1	26% by 2020 80% by 2050	234	28	53
NIMBY	See Table 5.1	26% by 2020 80% by 2050	187	20	42
ENERGY LIFESTYLES					
LS REF	Reference lifestyle	31%	0	-89[2]	-[3]
LS LC	Low-carbon lifestyle	26% by 2020 80% by 2050	163	-94[2]	-[3]

[1] Undiscounted costs are reported in order to compare the scenarios with different discount rates

[2] Because of differences in the modelling, these numbers are not strictly comparable with those in the rest of the column

[3] Because underlying preferences have changed in these scenarios, no meaningful welfare comparison can be drawn with REF or LC



Building in Resilience

The key elements of building in resilience are promoting reductions in energy demand and import dependence through efficiency; encouraging diversity of supply; and ensuring adequate investment in capacity and infrastructure.

It is imperative that reductions in energy demand are promoted, either through the take-up of cost-effective energy conservation measures or through lifestyle changes that reduce demand for energy services. If supply side measures that decarbonise electricity supply are not available, because of delays in commercialising (CCS) or deploying (renewable) technology, then greater levels of energy demand reduction will be required to stay on the trajectory towards an 80% reduction in CO_2. Seeking out cost effective efficiency is vital because there could be major welfare losses associated with forcing down energy demand through the price mechanism. A step change in policy delivery is required and the residential sector will be critical. Measures such as a new Supplier Obligation beyond 2012 and a careful look at the business models for delivering energy efficiency, particularly the role of the utilities vis-à-vis local authorities and others, are needed.

In general, our low-carbon resilient (LCR) scenario did not need to be constrained to obtain high levels of diversity in terms of either primary energy or electricity generation.

Ensuring adequate capacity and infrastructure is largely down to market design and regulation. The current system has achieved this since electricity privatisation, but the consequence of having large volumes of intermittent renewable energy on the system and the loss of indigenous natural gas supplies needs consideration. It is not at all clear that the current market arrangements will induce sufficient investment in back-up capacity to ensure system reliability. Options such as capacity payments or allowing grid operators to earn a regulated return on back-up capacity need to be considered.

Our analysis has shown that investment in gas storage, new interconnectors and LNG import facilities has taken and will take place on the basis of market incentives. However, the level of market investment could still leave us vulnerable in the event of catastrophic loss of infrastructure for days or weeks. There is a policy choice to be made about investment in 'strategic' storage or other facilities which could probably only be justified if developers could earn a risk-free regulated rate of return on the assets. Nevertheless, the cost of strategic investment is relatively modest compared to aggressive energy efficiency measures or back-up capacity for renewables.

The degree to which strategic storage is justified is also dependent on the level of effort in bringing down final energy demand, especially in the residential sector. Our analysis suggests that the gas/electricity system could ride out all but the worst infrastructure outages if demand levels fall.

Energy Demand

With regard to demand side issues, it is clear that a reduction in the demand for energy could play an important role both in achieving a more resilient energy system and in reducing the costs of carbon reduction, in terms of both welfare costs and the cost savings implied by needing a smaller energy system. In the Reference scenario, primary energy demand in 2025 is 7% below that in 2000, and, in the Resilient scenario, because of the imposed 3.2% pa reduction in energy intensity, is 14% below the Reference case. The objective of the EU Energy Efficiency Action Plan (CEC 2006) is to control and reduce energy demand and to take targeted action on consumption and supply in order to save 20% of annual consumption of primary energy by 2020 (compared to the energy consumption forecasts for 2020). The Resilient scenario is compatible with the EU energy efficiency objective, whereas the Reference scenario is not. Moreover, the resilience scenarios (R, LCR) achieve greater percentage reductions in primary energy than any of the decarbonisation scenarios (see Table 8.2, final column), with the exception of the lifestyles scenarios, and the CCSP scenario, which reduces demand early in order to avoid low-discounted heavy capital investment later on. It is clear that strategies for decarbonisation need to promote behaviour change as well as the uptake of low-carbon technologies if the UK is to be in line with EU energy efficiency aspirations.

In principle, the means of reducing the economy's energy intensity seem clear: a combination of rising energy prices and measures to enhance the development and deployment of energy efficiency measures in the various end-use sectors of industrial processes, electric motors, buildings, vehicles and appliances, and to induce more energy-conserving behaviours. Although many energy efficiency measures are cost effective, achieving a 3.2% pa reduction would be challenging, and any number of devils will lurk in the policy details.

Delivering improvements in energy intensity at rates that are economically attractive at prevailing prices has not often been achieved. Partly this has been because governments have been unwilling to increase energy prices above market rates to the extent that would be required. It has also been because of now well documented barriers to the take up of energy efficiency measures. People are unaware of the prices they pay for energy, the scale of their energy consumption and size or their energy bills; even with recent energy price increases (and certainly before them), energy bills are a low proportion of most people's expenditure; energy efficiency technologies have a low profile and are of little interest to energy consumers; people (both consumers and many installers) are unaware or sceptical of the technologies that would help save energy; consumers do not trust the expertise of the installers of energy efficiency technology or energy suppliers; the installation of some energy efficiency technologies is perceived to cause disruption to the household (see Sorrell et al. 2004 for a more detailed exposition).

Given this situation it is well established that a range of policy instruments is needed, including market-based instruments, information and advice and regulation. Governments in the UK have traditionally not favoured raising energy prices for fear of exacerbating fuel poverty, which adds to the priority of raising energy efficiency in existing housing to address this policy tension. A combination of advice, product regulation and increasingly large energy efficiency programmes (mandated via CERT) have been successful in raising the uptake of low-cost measures (e.g. insulation, condensing boilers and efficient lights and appliances).

The UK Government's Consultation on a Heat and Energy Saving Strategy (DECC 2009) recognises that continuation of the current policy framework will be insufficient to deliver long-term goals. Deployment of higher cost energy efficiency and microgeneration measures to further reduce demand will face all the familiar barriers as well as larger financing constraints. The need for a major shift in energy sector investment towards efficiency to address carbon goals is international, as recognised by the IEA and the UN Climate Change Convention, but because of the age and condition of the housing stock, the issue is particularly acute in the UK.

The policies required are therefore likely to have to be stronger than historically, and different from those for low-carbon energy supply, because households are less responsive to energy price incentives than energy businesses. DECC 2009 goes considerably further in seeking to address them than previous Government policy on household energy efficiency. Measures such as a new Supplier Obligation beyond 2012 and a careful look at the business models for delivering energy efficiency, particularly the role of the utilities vis-à-vis local authorities and others, are needed. It remains to be seen whether the concrete policies that emerge from the Consultation manage to achieve the very considerable and sustained increase in energy efficiency that is being sought.

Lifestyles

The Lifestyles scenarios in Chapter 6 have laid out clearly the kinds of energy lifestyle changes that would both enhance energy system resilience and reduce the costs of meeting the carbon reduction targets. More carbon-aware lifestyles can increase the propensity to invest in energy efficiency and microgeneration, but also reduce the demand for energy services in households and personal transport.

Historically there has been little emphasis in energy policy on how lifestyles might be induced to change in these directions, or even whether this is something that policy can have influence on, except through prices. Making high-energy lifestyles more expensive is likely to be strongly resisted unless such lifestyles are perceived to be less attractive. Addressing this issue effectively points to extending the conception of energy policy: to include the infrastructures and institutions within which such choices are made, notably in housing and transport; and to education, both to ensure citizens have a clear understanding of climate and energy challenges and to re-skill the huge numbers of professionals and trades-people who will be employed. This in turn points to a greater emphasis in energy policy on the role of local government, where many of the relevant decisions are made.

Policy makers could perhaps start by making high-energy lifestyles less necessary, for example by focusing more systematically, especially in towns and cities, on ensuring ready and safe access to basic services and amenities to everyone without the use of private vehicles, i.e. by walking, cycling or public transport. It is

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possible then that the social norms would develop that would increasingly allow private vehicle access to be restricted, so that the low-carbon modes could be expanded and used even more effectively. There is already evidence of this beginning to happen in some cities, notably London where car ownership is relatively low. However, the policy priority that has been so long given to car ownership and use is still prevalent. Its abandonment would make a low-carbon energy system much easier and less expensive to achieve.

Decarbonising Electricity

A major theme that emerges from nearly all the scenarios is the importance of decarbonising electricity. The three big centralised electricity options that are most important are large-scale renewables (mainly wind, but also biomass and marine renewables in the longer-term), new nuclear and fossil fuels with CCS. The modelling indicates that, provided good levels of technological development are achieved over time, the costs entailed in the large-scale deployment of these technologies, while still uncertain, are likely to be affordable.

Policy in this area must therefore focus on:

- Resolving outstanding technical uncertainties and developing the potential of those technologies which are close to deployment (large-scale wind, new nuclear and CCS) and those which are currently further away on technical or cost grounds (e.g. marine renewables, photovoltaics, hydrogen fuel cells) but which could have an important role to play in the longer-term. Substantially increasing UK commitment to RD&D for these technologies, as part of expanded wider international efforts, is of primary importance here
- Putting in place the necessary financial incentives to cause the private sector to start making the investments in deployment at the necessary scale, including ensuring that the banding of the ROCs really is going to bring forward important low-carbon technologies that the Renewables Obligation has so far marginalised. Longer-term investments to develop more emergent options will require a greater share of public investment, alongside some private investment
- Removing the non-financial barriers to large-scale deployment of the technologies. These seem particularly problematic in the UK context. In BERR 2008a some of the relevant issues are identified as the effectiveness of financial incentives, planning issues, grid issues, supply chain issues, information issues, network issues, and market structure (for example, the appropriateness of the wholesale electricity market for smaller generators). Having identified these issues, it is far from clear whether the proposals being made will in fact lead to the step change in the deployment of renewables of different kinds as required for them to achieve the 15% share in final energy demand by 2020 mandated by the EU Renewable Energy Directive

Renewables

Broadly, for renewables it is clear that time is running out if the 15% renewable energy share in final energy demand is to be achieved by 2020. For example, BERR (2008a, p.57) estimated that this could require around 3,000 extra offshore turbines of 5MW, a deployment rate of about five per week, from a base of 0.8GW at the end of 2008. The rate for extra onshore wind turbines is around seven 3MW machines per week, when at the end of 2008 the total operational capacity was only 1.7GW (BWEA 2008). The realisation of these numbers strains credibility in the absence of a completely transformed policy landscape that clearly addresses all the issues relating to both financial incentives and non-financial constraints. Much hangs on the Government's Renewable Energy Strategy due in summer 2009.

Nuclear

Looking further into the future, the Government is keen to ensure that there is a favourable policy framework for a new generation of nuclear power stations, with a view to new nuclear plant coming on stream by 2020 at the latest (DECC 2008, BERR 2008c). The issues set out in the White Paper (BERR 2008c) as needing to be addressed include planning, site assessment, assessment of potential health impacts, design assessment and licensing, and review of the regulatory regime in general.

On the economics of nuclear, and therefore the potential need for public subsidy of new nuclear build, the Government has had a remarkable change of mind over the past five years, from thinking in 2003 that it was "an unattractive option" (DTI 2003, p.61), to believing in 2007 "that nuclear power stations would yield economic benefits to the UK in terms of reduced carbon emissions and security of supply benefits" (DTI 2007a, p.191), although there is a presumption that new nuclear build would neither need nor get public subsidy (DTI 2007a, p.17). "The Treasury and HMRC are, however, exploring the possibility that the timing of nuclear decommissioning could create a potential tax disadvantage for nuclear operators and, if so, whether it may be appropriate to take action to ensure a level fiscal playing field between nuclear power and other forms of electricity generation." (BERR 2008c (p.154). This may open the door to some public subsidy of decommissioning costs at least.

The issue is important, because if nuclear power is an important contributor to UK energy system resilience and decarbonisation – as is suggested in some of the scenarios presented here – and if private companies decide that it is not in fact financially viable without public subsidy (as has been the case in the past), then without public subsidy new nuclear stations will not be built and energy system resilience and/or decarbonisation will not be delivered.

Conclusions on the supply side

On the supply side it is therefore clear that, despite abundant technical potential at seemingly affordable cost renewables are not being introduced at anything like the required rate to meet the EU's 2020 target; the economics of new nuclear are still uncertain; CCS is still commercially unproven at the requisite scale; the next generation of renewable technologies are, as far as the UK is concerned, being developed and deployed very slowly; and non-financial barriers of all kinds to new energy technologies of all kinds still seem to be pervasive and are difficult to remove. Despite the rather optimistic outcomes of the Energy 2050 modelling on the supply side, there are therefore serious causes for concern that neither carbon reduction targets nor the necessary diversity in the energy system for resilience will be achieved.

Microgeneration

Microgeneration is another set of possible options, but the way forward here is complicated. The Government adopted a Microgeneration Strategy in 2006 (DTI 2006) which identified 25 actions to remove barriers to microgeneration, and by June 2008 was claiming (BERR 2008b, p.1) that 21 of these had been successfully completed, and the only action that remained outstanding (3 having been overtaken by other events) would be completed by the end of the year. Yet it is still not at all clear that microgeneration is on track to become more than an absolutely marginal contributor to UK energy supply (in the three years from the end of 2004 the number of microgenerators increased from 82,000 to only around 100,000, BERR 2008b, p.2).

The Microgeneration Strategy has therefore so far failed to deliver the uptake of microgeneration technologies that was hoped for. There is still also little clarity about the changes to the electricity grid and network structure that will be required for it to accommodate a large-scale take-up of microgeneration technologies, or who will have the responsibility (and will therefore require the incentive and access to the finance) to deliver this. It may be that this issue will only become clear once much higher levels of microgeneration start to be deployed, but the danger then is that structural issues will impede the growth in and destroy the momentum of microgeneration that may have been created by the recently proposed feed-in tariff. Whether the feed-in tariff will in fact generate such growth and momentum will obviously depend on the level at which it is set, and level of public awareness about and commitment to the technological opportunities that are offered. There are very likely to be comparable non-economic barriers to household microgeneration technologies as those that hinder the uptake of household energy efficiency technologies and these will need to be addressed far more quickly than has been the case with energy efficiency if microgeneration is not to continue as a marginal contributor to energy supply for the foreseeable future.

The prospects for micro-generation/CHP in the medium-term depend on the speed with which centralised electricity generation is de-carbonised. The slower decarbonisation scenarios such as LCR and LS LC will leave the window for cost-effective deployment open for a much longer period.

Environmental Sensitivities

Somewhere between lifestyle change and non-financial barriers to energy system change lie people's environmental sensitivities. A somewhat paradoxical message to emerge from Chapters 6 and 7 is that people need to become more environmentally aware in terms of climate change and the need for the reduction in carbon emissions (Chapter 6), but heightened environmental awareness related to other issues (e.g. visual or ecological impacts) could make it more difficult and expensive, and at the limit impossible, to meet the carbon reduction targets that have been proposed (Chapter 7). This emphasises again the importance of the demand reduction message: the less energy of any kind that people use, the easier it will be to reach the carbon targets without having the other kinds of environmental impacts to which significant numbers of people are opposed.

Broadly speaking, policies to reduce CO_2 emissions will also help to reduce environmental impacts associated with other types of emissions and environmental pressures. However, there are one or two areas where, without compensating action, environmental consequences could be exacerbated. Specific examples include increases in PM_{10} emissions in the event of the high deployment of biomass and pressure on water resources. This is not an argument against a vigorous climate policy, but areas of tension that call for compensating regulatory action.

In Conclusion

The scenarios outlined here have allowed for a structured and system-wide exploration of the main opportunities and barriers involved in energy system transformation from now to 2050. The basic message from this study is positive, in that multiple possible pathways have been identified for an affordable transition to a resilient and low-carbon energy system. In practice, there are perhaps fewer grounds for optimism, and there is an increasingly urgent need for translating potential into real changes, and for policy and societal responses of a scale to instigate required change over short and long timescales.

The question posed at the beginning of this chapter was: how can the transition to a secure and low-carbon UK energy system be achieved over time, and how can opportunities over short and long timescales, and between different parts of the system (production and consumption, technology and behaviour) be best brought together and barriers overcome? The UKERC Energy 2050 project has confirmed the key messages from the Stern Review (Stern 2007, p.349): carbon pricing, technology policy, and removal of the barriers to behaviour change are needed. It has also identified the scope for action in each of these areas and indicated what needs to be done in the shorter-term to make progress. What is clear is that as yet in the UK (and much of the rest of the world) none of these three elements of the framework are being implemented with the rigour required to achieve the objectives and targets that the policy makers have set themselves. For both the UK's own targets, and the wider issue of large-scale reductions in carbon emissions to avert dangerous anthropogenic climate change, time is not on the policy makers' side.

While this project has been primarily concerned with energy systems and policies from a UK perspective, the challenges facing energy production and use are global. UK ambitions to deliver resilience and especially decarbonisation can best, and perhaps only, be realised as part of international commitments and agreements. Achieving an international consensus on energy and climate issues is a formidable challenge, but shared efforts on, for example, low-carbon technology development and deployment, promise rich dividends. Policy responses to these challenges are already significant. For example, the UK Climate Change Act would have been an unlikely prospect just a few years ago. Much more is needed, and needed now, both in the UK and internationally. Among the many opportunities, uncertainties and risks involved, this research is intended to help guide the way ahead.

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