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Pathways to a Low Carbon Economy: Energy Systems Modelling

UKERC Energy 2050 Research Report 1

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ENERGY SYSTEMS AND MODELLING (ESM) THEME OF UKERC

UKERC's ESM research activities are being undertaken within the Department of Geography at Kings College London (KCL), and the Cambridge Centre for Climate Change Mitigation Research (4CMR) at the University of Cambridge.

The Energy Systems Modelling (ESM) theme has built comprehensive UK capacity in E4 (energy-economic-engineering-environment) modelling. Full and updated working versions of major UK modelling tools are in place, notably the technology focused energy systems MARKAL and MARKAL-Macro models, and the macro-econometric MDM-E3 model. These models have been used to address a range of UK energy policy issues including long-term carbon reductions, the role of innovation in the future energy system, the development of hydrogen infrastructures, and the uptake of energy efficiency technologies and measures. International activities include the Intergovernmental Panel on Climate Change (IPCC) and the Japan-UK Low Carbon Societies research project.

ESM is focused on the following three principal activities:

- Modelling the UK energy-environment-economy-engineering (E4) system.
- UK energy scenarios and mapping of UK energy modelling expertise.
- Networking and co-ordination.

Executive Summary

This report is the first in the UKERC Energy 2050 project series. It focuses on a range of low carbon scenarios underpinned by energy systems analysis using the newly developed and updated UK MARKAL elastic demand (MED) model. Such modelling is designed to develop insights on a range of scenarios of future energy system evolution and the resultant technology pathways, sectoral trade-offs 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. Therefore, subsequent UKERC Energy 2050 reports focus on a broad scope of sensitivity analysis to investigate alternative scenarios of energy system evolution. In particularly, these alternative scenarios investigate different drivers of the UK's energy supply and demand, and combine the twin goals of decarbonisation and energy system resilience. Future analysis includes the use of complementary macro-econometric and detailed sectoral energy models.

Over the last decade a series of UK policy papers have been commissioned on long-term decarbonisation targets and strategies. This has been heavily influenced by the strengthening scientific consensus on the costs and benefits of mitigation actions to respond to global climate change. The UK's greenhouse gas (of which CO_2 is the UK's dominant source) reduction target has now been increased to 80% below 1990 levels by 2050, with interim (2020) targets, and this new target is incorporated in the Climate Change Bill following a recommendation by the new Committee on Climate Change (CCC). Energy system modelling (using variants of UK MARKAL) has played a key underpinning role in assessing the costs, trade-offs and pathways related to achieving such long-term targets.

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.

MARKAL is a widely applied technology-rich, multi-time period optimisation model. For the UKERC Energy 2050 project a major development was the implementation of an elastic demand version (MED) to account for the response of energy service demands to prices. The model's new objective function of the sum of consumer and producer surplus is considered a valid metric of social welfare, and hence gives insights into a key behavioural implication of energy system changes. Additional MED model development included updated fossil resource costs; expanded categorisation of UK 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 UKDCM model; 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 2007 (including the current EU-ETS price).

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 this report. An important point to re-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.

A first set of scenarios (CFH, CLC, CAM, CSAM), focus on carbon ambition levels of CO_2 reductions (in 2050) ranging from 40% to 90% reductions[1]. These runs also have intermediate (2020) targets of 15% to 32% reductions by 2020 (from the 1990 base year). These scenarios investigate increasingly stringent targets and the ordering of technologies, behavioural change and policy measures to meet these targets. A second set of scenarios (CEA, CCP, CCSP) undertake sensitivities around 80% CO_2 reductions with cumulative CO_2 emission targets, notably focusing on early action and different discount rates. These scenarios investigate dynamic tradeoffs and path dependency in decarbonisation pathways.

[1] The -80% case (CAM is the low carbon core run. It is noted that if international bunker fuels and non-CO_2 GHGs were to be included in the UK's budget the overall target may be closer to CSAM i.e., a -90% case (CCC, 2008)

Together with a base reference case, all seven decarbonisation scenarios are detailed below in Table 1.

Scenario	**Scenario name**	**Annual targets (reduction)**	**Cumulative targets**	**Cum. emissions $GTCO_2$ (2000-2050)**
B	Base reference	-	-	30.03
CFH	Faint-heart	15% by 2020 40% by 2050	-	25.67
CLC	Low carbon	26% by 2020 60% by 2050	-	22.46
CAM	Ambition (called "low carbon core")	26% by 2020 80% by 2050	-	20.39
CSAM	Super Ambition	32% by 2020 90% by 2050	-	17.98
CEA	Early action	32% by 2020 80% by 2050	-	19.24
CCP	Least cost path	80% post 2050	Budget (2010-2050) similar to CEA	19.24
CCSP	Socially optimal least cost path	80% post 2050	Budget (2010-2050) similar to CEA	19.24

Table 1: Carbon pathway scenarios

In the Base Reference Case (B), if new policies/measures are not taken, CO_2 emissions in 2050 would be 584 $MtCO_2$, only 1% lower than 1990 levels. Existing (as of 2007) policies and technologies would bring down emissions in 2020 to about 500 $MtCO_2$ - a 15% reduction. However this would be considerably higher than the government target of at least 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.

Under decarbonisation pathways, the power sector is a key sector, where decarbonisation begins with the deployment of carbon capture and storage (CCS) for coal plants in 2020-2025 in all mitigation scenarios. However it is stressed that in model experiments there is considerable uncertainty over the dominant player in any optimal technology portfolio of CCS vs. nuclear vs. wind, due to the close marginal costs and future uncertainties in these technology classes. Specifically, when examining the investment marginal costs when CCS technologies are the optimal value, across the scenarios from 2030-2050 further tranches of offshore wind would be competitive with a cost improvement of between \$56 - £260/kWe installed - this represents only 5-25% of capital costs. Nuclear's marginal investment costs are even closer to CCS, at between $2 and 218/kWe installed, depending on scenario and time period.

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 (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 base case. 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).

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 base level 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 the 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 different 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).

These least-cost optimal model scenarios do not produce decarbonisation scenarios that are compatible with the EU's draft renewables directive of at least 15% of UK final energy from renewables by 2020. Major contributions of bio-fuels in transport and offshore wind in electricity production only occur in later periods following tightening CO_2 targets and advanced technology learning.

Besides efficiency and fuel switching (and technology shifting), the elasticity (demand reduction) also plays a major role in reducing CO_2 emissions by reducing energy service demands (5% - 25% by scenario and by ESD). Agriculture, industry, residential and international shipping have higher demand reductions than aviation, cars and HGV (heavy goods vehicles) in transport sectors. This is driven both by the elasticities in these sectors but crucially by the existence of alternative (lower cost) technological substitution options. The interpretation of significant energy service reductions (up to 25%) in key industrial and buildings sectors implies employment and social policy consequences that need further consideration.

Higher target levels (CFH to CLC to CAM to CSAM), produce a deeper array of mitigation options (likely with more uncertainty). Hence the Carbon Ambition runs produce a very wide range of economic impacts, with CO_2 marginal costs in 2035 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.

Welfare costs (sum of producer and consumer surplus) in 2050 range from £5 - £52 billion. In particular moving from a 60% to an 80% reduction scenario almost doubles welfare costs (from £20 - £39 billion). Note that welfare cost is a marked improvement on energy systems cost as an economic impact measure as it captures the lost utility from the forgone consumption of energy. However it cannot be compared to a GDP cost as wider investment, trade and government spending impacts are not accounted for. It is also difficult to attribute the welfare loss components to either producers or consumers as this depends on the shape of the supply and demand curves, and crucially on the ability of producers to pass through costs onto consumers.

Overall, the Carbon Ambition runs follow similar routes, with additional technologies and measures being required and targets become more stringent and costs rapidly increase. For dynamic path dependence in decarbonisation pathways, we focus next on the range of sensitivity runs with the same cumulative CO_2 emissions.

Giving the model freedom to choose timing of reductions under a cumulative constraint illustrates inter-temporal trade-offs in decarbonisation pathways. Under a cumulative constraint (CCP) the model chooses to delay mitigation options, with this later action resulting in CO_2 reductions of 32% in 2020 and up to 89% in 2050. This results in very high marginal CO_2 costs in 2050, at £360/tCO_2 higher even than the constrained 90% reduction case.

Conversely, 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, effort is placed on different sectors (transport instead of power), different resources (wind as early nuclear technologies are less cost competitive), and increased near-term demand reductions.

Within the CCSP transport sector the broadest changes are seen with bio-fuel options not being commercialized in mid-periods. Instead the model relies on much increased diffusion of electric hybrid plug-in and hydrogen vehicles (with H_2 generated from electrolysis). 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 assumptions of lowered discount and technology specific hurdle rates.

The inter-temporal trade-off extends to demand reductions where 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 as the model place more weight on late-period demand welfare losses. In terms of early demand reductions for CCSP, this is seen in residential electricity where demands are sharply reduced as an alternative to (relatively expensive) power sector decarbonisation.

In terms of welfare costs, the flexibility in the CCP case gives lower cumulative costs than the equivalent CEA scenario with cumulative CO_2 reductions; the fact that the CCSP run produces the lowest costs is a reflection of the optimal solution under social levels of discounting (and correspondingly reduced technology-specific hurdle rates). The interpretation of this is that consumer preferences change and/or government works to remove uncertainty, information gaps and other non-price barriers.

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. Furthermore, policy makers need to be cognisant of the range of inherent uncertainties in long term energy scenarios, and future UKERC Energy 2050 reports will investigate a broad range of alternative drivers and developments.

Rising carbon reduction targets (from 40-90% in CFH through to CSAM) gives 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, the Climate Change Levy at current rates 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 is currently (i.e. in 2008) 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 tax on other fuels would need to have been imposed at about the current fuel duty rate at 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 the 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 Base 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 fuel 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, but 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.

These model runs reveal the single most important policy priority to be to incentivise the effective decarbonisation of the electricity system, because low-carbon electricity can then assist with the decarbonisation of other sectors, especially the transport and household sectors. In all the 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, nor has the source been identified of the very considerable funds that will be required, and possible technical issues remain unresolved. 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 be able to build new nuclear power stations with appropriate regulatory and planning risk streamlining. However, the underlying investment costs, and expectations of future electricity and carbon prices are all matters of considerable uncertainty. The scenarios envisage later deployment 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 crucially provided 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 in order 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 the levels envisaged in the Renewables Obligations are attained, with current uptake is much lower than envisaged. 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 seems to have been failed 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 the 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 takes up electric (hybrid and 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 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 ensure that the full range of technologies has the opportunity to develop.

Contents

List of Figures

List of Tables

1. Introduction

1.1. UKERC Energy 2050 overview

The core aims of the UKERC Energy 2050 project are to generate evidence relevant to meeting the UK's principal long-term energy goals (DTI, 2007):

1. achieving deep cuts in carbon dioxide (CO_2) emissions by 2050, taking the current 60% - 80% reduction goal as a starting point;
2. developing a "resilient" energy system that ensures consumers' energy service needs are met reliably.

The concept of carbon reduction is relatively simple while that of resilience is complex and multi-faceted. We have adopted the following working definition of energy system resilience: *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*.

A set of four "core" UKERC Energy 2050 scenarios are used to highlight key policy issues and provide a starting point for variant scenarios.

- The "Reference" (REF) scenario assumes that concrete 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.
- The "Ambition" (CAM) scenario (i.e., the low carbon core scenario) assumes the introduction of a range of policies leading to an 80% reduction in UK carbon emissions by 2050 relative to 1990, with an intermediate milestone of 26% in 2020.
- The "Resilience" (R) 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) scenario combines the carbon and resilience goals.

This first paper in the UKERC Energy 2050 project series focuses on the Reference and Low Carbon scenarios, and a set of variants on the level and pathways of carbon targets (see section 2.1.5). Future reports (Table 2) extend the analysis through variant scenarios to investigate key uncertainties in low carbon and resilient energy futures.

Five important factors are held constant across the four core scenarios. One of the functions of the modelling tools described below is to ensure coherence across these different dimensions:

- the international context;
- the trajectory of technological change;
- the way energy investment decisions are made;
- the evolution of people's lifestyles; and
- energy consumers' preferences.

A combination of modelling tools is used to develop high-level insights from a systematic comparison of scenarios (see Table 2). The system level models can capture inter-relationships and choices across the energy system. The models are used in a "what if" mode to generate insights and quantify discussions. This report focuses on the MED model and the second report (1b in Table 2) will focus on E3MG model together with a comparison with MED runs. The core energy systems modelling tools are:

1. UK MARKAL Elastic Demand (MED); a technology-rich, multi-time period optimisation model (previously used for underpinning analysis for the UK Energy White Paper and Climate Change Bill)
2. Global E3MG; a macro-econometric model with an underlying input-output structure (previous uses have included inputs into the Intergovernmental Panel on Climate Change (IPCC) and the Innovation Modelling Comparison Project (IMCP)

These high level insights are supported by a range of sectoral models, including:

- WASP – electricity generation planning model
- CGEN – combined gas and electricity networks model
- Demand-side "accounting" models
- UK Domestic Carbon Model (UKDCM)
- UK Non-Domestic Carbon Model (UKNDCM)
- UK Transport and Carbon Model (UKTCM)

Finally the UKERC Energy 2050 project has focused on cross-disciplinary interactions between the UKERC themes through an iterative methodology. Working groups - drawn from different UKERC themes - have responsibilities to produce various reports as noted in Table 2. The construction, testing and elucidation of scenarios have involved adapting existing research activity in the themes, via a process of "loose coupling". These detailed insights from the research themes supplement the broader systems approach of the two models being used.

	Report title	Lead working group	Lead model	Support model
1a	Pathways to a low carbon economy: Energy systems modelling	Policy	MED	
1b	Pathways to a low carbon economy: Macro-econometric modelling	Policy	E3MG	MED
2	Technology's contribution to a low carbon economy	Supply	MED	E3MG
3	The UK and long-term global energy markets	Markets and security	E3MG	MED
4	Building a resilient UK energy economy	Markets and security	CGEN, WASP	E3MG
5	Sustainable energy lifestyles and behaviour	Demand	MED	Demand
6	The environment and sustainable energy	Supply	MED	
7	A decentralized energy system			Demand, CGEN, WASP
8	Synthesis report			

Table 2: UKERC Energy 2050 Reports

1.2. UK energy policy context

The UK's core energy policy goals are the mitigation of climate change and energy security (DTI, 2007). The latest scientific consensus (IPCC, 2007), has further strengthened the evidence base that it is very likely that anthropogenic GHG emissions at or above current rates would cause further warming and induce many changes in the global climate system during the 21st century. A major recent report on the economics of global climate change (Stern, 2006) recommended strong early action to mitigate climate change, in preference to weaker or a delayed response. In addition, the decline in domestic reserves and production of UK oil and natural gas, combined with increasing geopolitical instabilities in key gas production and transmission countries have highlighted the need for a secure and resilient UK energy systems (DTI, 2007). Further UK energy policy goals are reductions in vulnerable consumers' exposure to high energy prices (i.e., fuel poverty) and a continued emphasis on open and competitive energy markets.

The UK set itself a groundbreaking climate change mitigation policy with the publication of a long-term national CO_2 reduction target of at least 60% below 1990's level by 2050 (DTI, 2003). This target was established in response to the climate challenge set out by the Royal Commission on Environmental Pollution (RCEP, 2000). Climate change mitigation targets were reaffirmed in the 2007 Energy White paper (DTI, 2007). Additionally, the UK has been a leading proponent of global long-term CO_2 target setting within the G8 Gleneagles dialogues which resulted in agreement at the 2008 G8 Japanese summit of a robust response to climate change including the goal of achieving at least 50% reduction in global emissions by 2050 in agreement with other countries in the developing world.

The UK CO_2 reduction target has now been extended to all greenhouse gases (GHGs) and increased to 80% below 1990's level by 2050, with an interim 2020 target (see section 2.1.5.), and the new target incorporated in the Climate Change Bill (DEFRA, 2007a), following a recommendation by the new Committee on Climate Change (CCC)[2]. Energy systems modelling has played a key underpinning role in assessing the costs, trade-offs and pathways related to achieving such long-term targets (Strachan et al., 2009a)

In terms of existing and future UK energy policy instruments to meet these targets and to address other key public issues such as energy security, one typology of instruments may be grouped under four generic headings (see Jordan et al (2003)):

1. Market/incentive-based (also called economic) instruments (see EEA (2006) for a recent review of European experience). These instruments include "emissions trading, environmental taxes and charges, deposit-refund systems, subsidies (including the removal of environmentally-harmful subsidies), green purchasing, and liability and compensation" (EEA, 2006, p.13). Except for green purchasing, these instruments change the investment/return equation directly, by changing the relative prices and costs of inputs or processes in favour of those with less environmental impact.
2. Classic regulation instruments, which seek to define legal standards in relation to technologies, environmental performance, pressures or outcomes. Kemp, (1997) has documented how such standards may bring about innovation. Regulation can also include the imposition of obligations on economic actors, such as the renewable and energy efficiency obligations that have been imposed on energy suppliers in the UK. These instruments change the investment/return ratio by imposing penalties on actors

[2] The CCC long term decarbonisation scenarios utilised the same MARKAL MED model as developed and used for UKERC Energy 2050, but run with alternate assumptions and a focus on alternate key drivers, including discounting, build rates, international credits, and path dependency (CCC, 2008).

who fail to meet the standards or obligation. Where the obligation is tradable, the instrument is a hybrid regulation/economic instrument and is listed separately.

3. Voluntary/self-regulation (also called negotiated) agreements between governments and producing organisations (see ten Brink, 2002, for a comprehensive discussion). These change the investment/return ratio either by forestalling the introduction of market-based instruments or regulation (i.e. they are more profitable than the counter-factual, which is perceived to involve more stringent government intervention, rather than necessarily the status quo). They can also lead to greater awareness of technological possibilities for eco-innovation that increase profitability as well as improving environmental performance (see Ekins & Etheridge, 2006 for a discussion of this in relation to the UK Climate Change Agreements).
4. Information/education-based instruments (the main example of which given by Jordan et al. (2003) is eco-labels, but there are others), which may be mandatory or voluntary. These change the investment/return ratio sometimes by promoting more eco-efficient products to consumers. They can also improve corporate image and reputation.

It has been increasingly common in more recent times to seek to deploy these instruments in so-called ‘policy packages’, which combine them in order to enhance their overall effectiveness across the three (economic, social and environmental) dimensions of sustainable development. Instrument packages have been implemented in the UK for both the demand-side in end-use sectors (industry, households, commerce, agriculture, government and transport) and the supply-side, including key energy supply chains (notably electricity, biomass, and hydrogen).

In the UK, the majority of the policies implemented in relation to the energy system over the last ten years relate to the desire to encourage energy efficiency and low-carbon energy supply. While these have exhibited much innovation, in the sense of introducing completely new policy instruments, the instruments have not been of the required stringency to meet the Government’s carbon reduction targets for 2010, which look set to be missed by quite a large margin (BERR, 2008a) - carbon emissions have actually risen since 1997, despite these instruments.

Two of the more significant policies are the Renewable Obligation (RO) and the Energy Efficiency Commitment (now the Carbon Emissions Reduction Target, CERT), both place obligations on energy suppliers, the former to buy renewably generated electricity, the latter to make energy-saving investments in their customers' homes. A characteristic of both these obligations is that they do not involve public expenditure (they are funded by energy consumers), and neither of them are particularly visible, so that they do not raise awareness of the objectives they are intended to achieve. The RO buy-out price was also set at a level insufficient to stimulate the required investment to reach its targets for 2010. The desire to limit the cost of carbon reduction has meant that, in addition to the RO, the various capital grants schemes (buildings, energy crop planting grants, bio-energy plant grants) have been so limited that they have not succeeded in widespread implementation and deployment of the technologies that they have sought to encourage.

Section 4.3 discusses the necessary policy measures to meet the range of low carbon pathways modelled in the report.

1.3. Overview and use of energy-economic models

In the extensive literature on energy-economic modelling of energy and climate policies, there are two widespread modelling approaches, known as 'bottom-up' and 'top-down' modelling. The two model classes differ mainly with respect to the emphasis placed on technological details of the energy system vis-à-vis the comprehensiveness of endogenous market adjustments (Bohringer and Rutherford 2007). However recent evaluations of the literature (IPCC, 2007) have shown the increasing convergence of these model categories as each group of modellers adopts the strengths of the other approach.

In terms of top-down modelling, a number of major international collaborations (Weyant 2004; van Vuuren et al. 2006) have assessed global scenarios of carbon dioxide (CO_2) and greenhouse gas (GHG) stabilization (and hence emission targets). Other modelling comparison exercises have focused on key model drivers, notably innovation and technological change (Edenhofer et al., 2006). One innovative top down model is E3MG, a dynamic macro-econometric model based on a detailed input-output structure of regions and industries. This model, discussed in a later UKERC Energy 2050 report, allows implementation of internationally differentiated policy, sectoral representation of energy-economic interactions including innovation, and non-equilibrium behavioural change by industries and consumers (Barker et al, 2006). A further extension has been the implementation of a detailed energy technology sub-model (Anderson and Winne, 2007).

In terms of bottom-up modelling, a wide range of studies have been carried out on global, national and sectoral models. A major tool in this energy systems approach is the MARKAL model, used by over 100 institutions and supported under the Energy Technology and Systems Analysis Program (ETSAP) of the International Energy Agency. In a wide range of studies on CO_2 mitigation, papers have focused on global scenarios (IEA, 2008a), technology pathways (Smekens, 2004), developing countries (Mathur, 2007), individual sectors (Endo, 2007), and individual polices (Unger and Ahlgren, 2005). Furthermore, a range of MARKAL model variants have been developed to investigate key modelling parameters, for example induced technological change (Barreto and Kypreos, 2002). The UK MARKAL model, discussed in section 2, has been substantially enhanced through a multi-year project within the UK Energy Research Centre (UKERC) (as discussed in Strachan et al., 2008a), and has provided a major analytical underpinning to UK energy policy developments. A range of modelling variants to address specific issues has been developed including MARKAL elastic demand (MED) which includes the response of consumers' demands for energy services to changes in energy prices (Loulou et al., 2004).

There is a long track record of energy models underpinning major energy policy initiatives, producing a large and vibrant research community and a broad range of energy modelling approaches (Jebaraj and Iniyan, 2006). Particularly in recent years, energy models have been directly applied by policy makers for long-term decarbonisation scenarios (IEA, 2008a; Das et al., 2007; European Commission, 2006), with further academic modelling collaborations directly feeding into the global policy debate on climate change mitigation (Weyant, 2004; Strachan et al., 2008a).

1.4. Report structure

This report is the first in the UKERC Energy 2050 project series. As such it focuses on a range of low carbon scenarios, both in terms of final level (in 2050) of CO_2 reductions as well as cumulative CO_2 emissions under different approaches to discounting.

Section 2 details the UK MARKAL MED modelling methodology, key 2008 updates and scenarios. Section 3 details results, focussing on decarbonisation pathways, energy-economic system implications, and key technology and behavioural trade-offs. Section 4 presents insights and conclusions, including policy implications to attain these low carbon economy pathways. The full set of modelling results output is given in the appendices for the interested reader.

2. The UK MARKAL (MED) 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).

This energy model framework has long been used in the UK for exploring longer term costs and technological impacts of climate policy through a scenario-based approach (Strachan et al., 2009a). In recent years, the extended UK model has been used to assess the implications of longer term policy targets as supporting analysis for the Energy White Paper 2007 and the Climate Change Bill (see Strachan et al., 2007a and DEFRA, 2007b respectively).

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 focused on specific variants and/or applications of the UK MARKAL model include Strachan and Kannan (2008), Strachan et al. (2009a), Kannan et al. (2008), Strachan et al. (2008c) and Strachan et al. (2009b).

2.1. Modelling methodology

2.1.1. UK MARKAL model development and validation

MARKAL portrays the entire energy system from imports and domestic production of fuel resources, through 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 optimization model, MARKAL minimizes discounted total 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.

The UK MARKAL model hence provides a systematic exploration of least-cost configurations to meet exogenous demands for energy services. These may be derived from standard UK forecasts for residential buildings (Shorrock and Uttley, 2003), transport (DfT, 2005), the service sector (Pout and Mackenzie, 2006), and industrial sub-sectors (Fletcher and Marshall, 1995). Generally these sources entail a projection of low energy growth, with saturation effects in key sectors.

One key set of input parameters is resource supply curves (BERR, 2008a). From these baseline costs multipliers are used to translate these into both higher cost supply steps as well as imported refined fuel costs. A second key input is dynamically evolving technology costs. Future costs are based on expert assessment of technology vintages, or for less mature electricity and H2 technologies via exogenous learning curves derived from an assessment of learning rates (McDonald and Schrattenholzer, 2002) combined with global forecasts of technology uptake (European Commission, 2006). Endogenous cost reductions from learning for less mature technologies are not employed as the relatively small UK market is assumed to be a price taker for globally developed technologies.

UK MARKAL is calibrated in its base year (2000) to data within 1% of actual resource supplies, energy consumption, electricity output, installed technology capacity and CO_2 emissions (all from DUKES, 2006). In addition, considerable attention is given to near-term (2005-2020) convergence of sectoral energy demands and carbon emissions with the econometric outputs of the government energy model (BERR, 2008a). The model then solves from year 2000-2070 in 5-year increments. All prices are in £(2000). Substantial efforts have been made in respect of the transparency and completeness of the model structure and assumptions, including through a range of stakeholder events (for example Strachan et al., 2007b), expert peer review, and publication of the model documentation (Kannan et al., 2007)

MARKAL optimises (minimises) the total energy system cost by choosing the investment and operation levels of all the interconnected system elements. The participants of this system are assumed to have perfect inter-temporal knowledge of future policy and economic developments. Hence, under a range of input assumptions, which are key to the model outputs, MARKAL delivers an economy-wide solution of cost-optimal energy market development.

An important point to stress is that MARKAL is not a forecasting model. It is not used to try and predict the future energy system of the UK in 50 years time. 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. The results detailed and discussed in sections 3 and 4 illustrate the complexity of insights that are generated from a large energy system model. They should be viewed and interpreted as different plausible outcomes from a range of input parameters and modelling assumptions. There is no attempt to assign probabilities to the most likely outcome or “best” model run. Equally there is no attempt to assign probabilities to individual model parameters.

The strengths of the UK MARKAL energy system model include:

- A well understood least-cost modelling paradigm (efficient markets);
- A framework to evaluate technologies on the basis of different cost assumptions, to check the consistency of results and explore sensitivities to key data and assumptions;
- Transparency, with open assumptions on data, technology pathways, constraints etc;
- Depiction of interactions within the entire energy system (e.g. resource supply curves, competing use for infrastructures and fuels, sectoral technology diffusion);
- Incorporation of possibilities for technical energy conservation and efficiency improvements;
- The ability to track emissions and energy consumption across the energy system, and model the impact of constraints on both
- The ability to investigate long timeframes (in this case to 2050) and novel system configurations, without being constrained by past experiences or currently available technologies, thus providing information on the phasing of technology deployment.
- And through MARKAL MED (section 2.1.2), demand-side responses to price changes.

The principal disadvantages or limitations of the MARKAL energy system model include:

- The model is highly data intensive (characterization of technologies and RES);
- By cost optimizing it effectively represents a perfect energy market, and neglects barriers and other non-economic criteria that affect decisions. One consequence of this is that, without additional constraints, it tends to over-estimate the deployment of nominally cost-effective energy efficiency technologies;
- Being deterministic the model cannot directly asses data uncertainties, which have to be investigated through separate sensitivity analyses;

- Limited ability to model behaviour (partially addressed by MED in respect of price changes);
- There is no spatial disaggregation and hence no representation of the sitting of infrastructures and capital equipment;
- There is limited temporal disaggregation, so that the model cannot be used to explore such issues as the daily supply-demand balancing of electricity, heat and other energy carriers.

2.1.2. UK MARKAL elastic demand (MED) model

A major development of the UK MARKAL model for the UKERC Energy 2050 project was the implementation of an elastic demand version (MED) to account for the response of energy service demands to prices. This is implemented at the level of individual energy service demands using linear programming (LP)[3]. The UK model does not represent trade and competitiveness effects, and as a partial equilibrium energy-economic model does not include government revenue impacts, and hence does not provide an assessment of macro-economic implications (e.g. GDP).[4]

A simplified representation of energy supply and elastic demands is given in Figure 1. The standard MARKAL model optimization, when energy service demands are unchanging - i.e. are a straight vertical line on the horizontal axis, is on (discounted) energy systems cost - i.e. the minimum cost of meeting all energy services. With non changing demands, this is equivalent to the area between the supply curve and the horizontal line from the equilibrium price. In MED, these exogenously defined energy service demands have been replaced with demand curves (actually implemented in a series of small steps). Following calibration to a reference case that exactly matches the standard MARKAL reference case, MED now has the option of increasing or decreasing demands as final energy costs fall and rise respectively. Thus demand responses combine with supply responses in an alternate scenario (e.g. one with a CO_2 constraint).

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[3] As demand and supply responses are in fact represented using step functions, these can approximate non-linear aggregated curves but still solved via an LP for computational considerations.
[4] The UK MARKAL-Macro model (Strachan and Kannan, 2008) incorporates a simple general equilibrium model but with the loss of sub-sectoral demand responses and the relative simplicity of LP calibration.

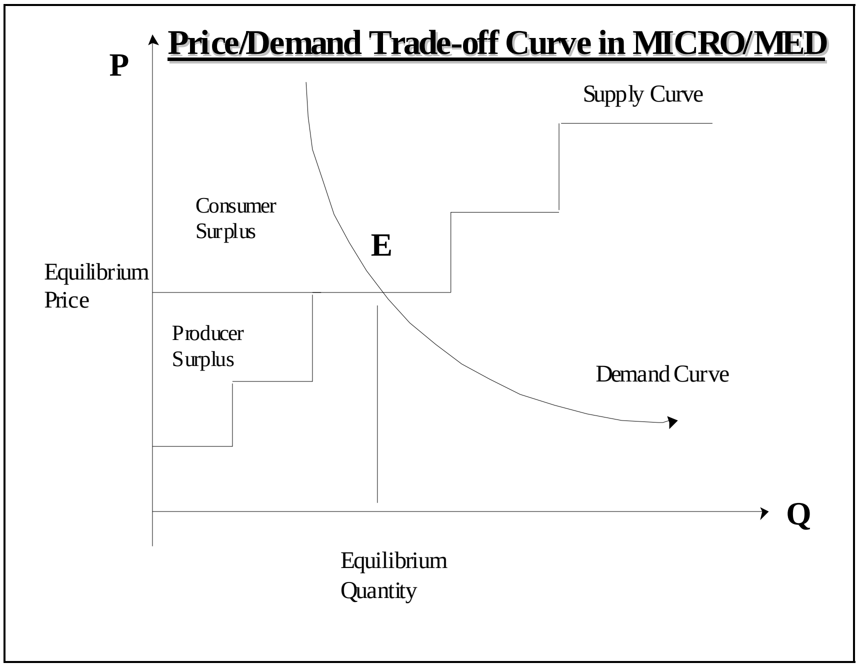

Figure 1: Representation of MED supply-demand equilibrium

In MED[5], demand functions are defined which determine how each energy service demand varies as a function of the market price of that energy service. Hence, each demand has a constant own-price elasticity (E) in a given period. The demand function is assumed to have the following functional form:

$$ES/ES_0 = (p/p_0)^{E}$$

Where: *ES* is a demand for some energy service;
ES_0 is the demand in the reference case;
p is the marginal price of each energy service demand;
p_0 is the marginal price of each energy service demand in the reference case;
E is the (negative) own-price elasticity of the demand.

In this characterization, ES_0 and p_0 are obtained by running standard MARKAL. ES_0 is the energy service demand projection as defined by the user exogenously (as a function of social, economic and technological drivers). p_0 is the marginal price of that energy service demand determined endogenously by running the reference case. As noted above, a simple

[5] And also in the MARKAL Micro formulation which includes non-zero cross price elasticities

calibration process ensures that the MED reference case is consistent with the reference case run in the standard model (based on use of the standard case total system cost (MED-BASEOBJ) and undiscounted annual system cost (MED-BASEANNC)).

Three additional MED parameters are required when undertaking an MED run:
MED-ELAST: Elasticity of demand. This indicates how much energy service demands rise/fall in response to a unit change in the marginal cost of meeting the demands.
MED-VAR: Variation of demand. This limits the upward / downward movement of demand response. In the UK model, this is set to a limit of 50% reduction in demand / 25% increase in demand.[6]
MED-STEP: Defines the steps on the demand curve; for demand decreases, this has been set at 20 (2.5% reductions) and 10 for demand increases (for consistency with MED-VAR parameter).

A combination of the proportional change in prices (p/p_0) and the elasticity parameter (E) determines when the energy service demand changes by the step amount. Note that changes in energy service demand also depend on the availability and costs of technological conservation, efficiency and fuel switching options. The variation parameter sets the ultimate limit to the demand change and the step parameter determines the size of the increment the model can select for that variation. This formulation means that each demand response is log-linear but the overall demand function is NOT log-linear as different demand steps are triggered by different price changes, depending on the elasticities.

ESD code	**Sector and Description**		**Price Elasticity**
ICH	Industry and agriculture	Chemicals	-0.49
IIS		Iron & steel	-0.44
INF		Non ferrous metals	-0.44
IOI		Other industry	-0.32
IPP		Pulp and paper	-0.37
AGRI		Combined agriculture	-0.32
R-ELEC	Residential	Electrical appliances	-0.31
R-GAS		Gas appliances	-0.33
RH-S-E		Space heat (existing)	-0.34
RH-S-N		Space heat (new homes)	-0.34
RH-W-E		Water heat (existing)	-0.34

[6] i.e., demand increases are considered to be less sensitive to price changes.

RH-W-N		Water heat (new homes)	-0.34
SCK	Services	Cooking	-0.23
SCL		Cooling	-0.32
SETC		Electrical appliances	-0.32
SH-S		Space heating	-0.26
SH-W		Water heating	-0.26
SLIT		Lighting	-0.32
SREF		Refrigeration	-0.25
TA	Transport	Air (domestic)	-0.38
TB		Bus	-0.38
TC		Car	-0.54
TF		Rail (freight)	-0.24
TH		HGV	-0.61
TI		Air (international)	-0.38
TL		LGV	-0.61
TR		Rail (passenger)	-0.24
TS		Shipping (domestic)	-0.18
TW		2 wheelers	-0.41

Table 3: Price elasticities of energy service demands

The elasticities used in this analysis (Table 3) are long-run elasticities (due to the MED model's 5 year time periods and perfect foresight assumptions), and are derived from three key sources: 1) Other MARKAL modelling teams outside the UK (Loulou and van Regemorter, 2008); 2) MDM-E3 macro-econometric model (Dagoumas, 2008), and 3) the BERR energy model (BERR, 2006). It is important to note the aggregate nature and sparse empirical basis for the price elasticities of energy service demands[7], so that sensitivity analysis around the elasticities becomes important.

Now the MED objective function maximises both producer surplus (PS) and consumer surplus (CS) - this is the combined area between the demand function and the supply cost curve in Figure 1. This is affected by annualized investment costs; resource import, export and domestic production costs; taxes, subsidies, emissions costs; and fuel and infrastructure costs as before in the standard model. However in addition the MED model accounts for welfare losses from reduced demands - i.e. if consumers give up some energy services that they would otherwise have used if prices were lower, there is a loss in utility to them which needs to be accounted for. Note that the MED model actually calculates the change in are under the shifted demand curve.

[7] Elasticities for energy demand and fuel demands are somewhat more readily available.

In the MED policy scenarios, transfers between producer surplus (PS) and consumer surplus (CS) are possible. In general if the policy case has higher prices (e.g., from a CO_2 constraint) it is likely that the PS may take some of the CS; with the opposite occurring if the policy case prices fall – i.e. then CS takes some of the PS (this may be seen in Figure 1 by shifting the Equilibrium Price line up or down). The exact mechanisms of this will depend on the shape of the two curves, and of course on how prices are being passed through (or not). However in a higher price policy case, the combined surplus (PS + CS) will *always be lower*. In a lower price policy case, the combined surplus (PS + CS) will *always be higher***.**

The sum of consumer and producer surplus (economic surplus) is considered a valid metric of social welfare in microeconomic literature, giving a strong theoretical basis to the equilibrium computed by MARKAL.

2.1.3. Key updates for UKERC Energy 2050

In addition to the welfare optimization approach via price responses in the MED model formulation, a range of additional model updates have been implemented. This has developed the 2007 MARKAL mode to its current 2008 vintage. Key updates are discussed below. In addition, a wide range of data updates and minor technical adjustments have been made (see the continuously updated documentation - Kannan et al., 2007).

Fossil resource costs

In line with a consolidated analysis of the most recent projections of global fossil fuel prices (IEA, 2007; BERR, 2008a), MED resource supply curves for coal, oil and natural gas have been shifted upward. These reflect long-term drivers of rising energy demands and constrained supplies. Base prices are shown in Table 3, and are converted into energy units (PJ) in gross calorific terms (GCV) and deflated into £2000[8]. Historically estimated multipliers (see Kannan et al., 2007) are then used to construct full resource supply curves as well as costs of refined fuels.

Original units		2000	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
Crude Oil	2005$ /bbl	31.38	50.62	57.50	55.00	55.00	57.50	60.00	65.00	70.00	70.00	70.00
Gas	2005$ /MMBTU	4.77	7.46	6.75	6.75	7.00	7.32	7.64	8.27	8.91	8.91	8.91

[8] Currency conversion factors used are £1 = \$1.8 = €1.4

Coal	2005$ /tonne	35.89	60.48	55.00	55.00	57.04	59.63	62.22	67.41	72.59	72.59	72.59
PJ (GCV)		2000	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
Crude Oil	2000£/GJ	2.53	4.08	4.64	4.44	4.44	4.64	4.84	5.24	5.65	5.65	5.65
Gas	2000£/GJ	2.35	3.67	3.32	3.32	3.44	3.60	3.75	4.07	4.38	4.38	4.38
Coal	2000£/GJ	0.66	1.11	1.01	1.01	1.05	1.09	1.14	1.24	1.33	1.33	1.33

Table 4: Updated fossil resource costs

CCS and wind resources

Other resource updates include revised cost curves (steps) for carbon capture and storage (CCS). Combined with a more detailed CCS reservoir description (aquifers, enhanced oil recovery (EOR), depleted oil/gas fields storage) this has led to an overall doubling of cumulative UK CCS capacity (DEFRA, 2007b), to a theoretical potential of 21 $GtCO_2$. A further resource update has been to disaggregate UK on- and off-shore wind resources for diurnal and seasonal availability (Sinden, 2007).

International emissions purchases

Inclusion of global emission trading via global marginal abatement cost curves (MACs) based on combined models (van Vuuren et al., 2006). Depending on the international policy regime, these are implemented (see Strachan et al., 2008c) via Annex 1 mitigation only, global mitigation (all regions buying and selling), or Annex 1 mitigation with global permit sales only (this last case gives a very large availability of low-cost emissions permits).

Biomass chains

Extensive updates to biomass energy chains and technologies have been implemented, taking key changes from a comprehensive review of the UK MARKAL model’s biomass treatment (Jablonski et al., 2008). The main biomass chains have been broken out into wood, ligno-cellulosic crops, bio pellets (high and low quality), first and second generation bio-oils, bio-diesel, ethanol, methanol, bio-gases, bio-methane and wastes. The range of bio delivery options (oils, pellets etc) are disaggregated to the industrial, residential and service sectors. Biomass boilers, utilising both solid and liquid fuels, are included for all buildings sectors. In terms of electricity generation, biomass-based CHP and electricity-only plants are updated based on the DEFRA (2007c) biomass strategy report, and further detail is added on enhanced co-firing to use different biomass fuels. Finally in the transport sector the extensive bio-energy chains have been added to with the option of bio-kerosene fuel chains and technologies for aviation (domestic and international).

Hydrogen infrastructures

Hydrogen (H_2) distribution infrastructures have been updated based on work in the SuperGen UKSHEC H2 infrastructure project (Strachan et al., 2007d). This has focused on a scale and distance approach to the costs and efficiencies of gaseous and liquid H_2 options for the full range of transport demands. In addition H_2 chains for storage and transportation have been included for stationary electricity generation and CHP applications. Liquid H_2 distribution is now available for both liquid internal combustion engine (ICE) and gaseous fuel cell technologies. Finally all transport fuel duties are updated, with a common approach to the taxation of fuels, which also maintains government revenue streams.

Intermittency

New data and a new modelling approach for intermittent technologies has been added from the WASP/CGEN model run. This has focused on the contribution to peak constraints (capacity credits), and to remote generation transmission costs. As the penetration of intermittent electricity technologies rises, their impacts on the overall system also change. Utilising WASP's calculation of the capacity credit (the extent to which intermittent sources can replace continuous sources without reducing the system's ability to meet peak demands), successive incremental capacity credits for different levels of intermittent capacity are calculated as in Table 4. Note that availability factors are unchanged.

Intermittent capacity[9]	Incremental capacity credit	Applied to
0-5 GW	28%	Onshore wind (tranches T1-T7), Offshore wind tranche 1
5-15 GW	18%	Onshore wind (tranches T8-T9), Tidal, Wave (tranches T1-T2), Offshore wind tranches T2 (adjusted for 15GW limit)
15-50 GW and above	8.6%	Offshore wind (tranches T3-T4), Severn Barrage

Table 5: Intermittent generation capacity credit

Off-shore wind transmission costs are now calculated from the WASP model using a £4000/MW/km estimate – it is assumed that offshore wind is at 0km, 60km, 120km and

[9] Calculated as the effective capacity generating on the system (i.e., taking availability into account)

180km from the shore for successive tranches. Subtracting the original £55/kW remote connection charge, this gives additional connection charges for offshore wind at £0/kW, £185/kW, £370/kW and £555/kW which are added to tranches T1-T4 respectively. No remote connection charges are applied to onshore wind or tidal or wave.

Electricity technologies

In addition to the revised intermittency treatment, a comprehensive revision of cost and efficiency data on key nuclear, CCS, wind, marine and biomass technologies has been undertaken (Winskel et al., 2008). Renewable and base-load plant availability and peak contributions have also been updated as have electricity inter-connectors for balanced utilization. In terms of near-term technologies, commissioned wind investments are included, restrictions on CCS & nuclear investment prior to 2020 are put in place to reflect lead time to operation, and the option of the Severn barrage is included.

Integration with the UKDCM model

To reflect the non-energy cost drivers of many residential demands, the MED model's residential sector has been integrated with exogenous energy service demand assumptions for electricity and gas appliances from the UKDCM model (Layberry, 2007). As a result the efficiency and fuel switching options for these ESDs has been removed, although the model can still reduce demands through price-elastic behavioural changes in response to price changes. The space and water heating energy chains are unchanged in their original technological detail reflecting the role of energy costs in decision making in these demands. Finally conservation cost curves are retained in the service sector, adjusted in the industrial sector and replaced by UKDCM estimates in the residential sector.

Buildings technologies

For space and water heating application in the residential and service sectors, learning rates are now included for micro generation (capital cost is reduced at 2-3% and 2% per year till 2020 which represents a 45% cost reduction by 2020). In addition, in the residential sector, heat pumps are activated. Similarly night storage electric heating is included and is limited to a max of 30% of total residential heating.

Transport technologies

Plug-in hybrid vehicles with both night and daytime charging options are now included in the MED model, reflecting the potentially important aggregate and temporal interactions between the transport and electricity sectors. In addition flex-fuel E85 hybrid cars have been added, and battery costs for electric vehicles have been reviewed to make later year vintages more directly comparable to conventional/other technologies.

Hurdle rates

Hurdle rates are applied to transport technologies and to conservation technologies in buildings to reflect market (non-cost) barriers, consumer preferences and risk factors that limit the purchase of new energy technologies (Train, 1985). The hurdle rate is applied only to annualized capital investment, effectively increasing the capital cost of the affected technologies. All other costs associated with that technology, e.g. fuel cost or O&M cost, is still discounted using the global discount factor (10%).

Hurdle rates of 25%, 20% and 15% are applied, graded on dates of commercial availability, the severity of perceived market barriers and the uncertain requirements of new infrastructures. All building conservation technologies, and all personal electric and hydrogen transport vehicles have a 25% hurdle rate. Public transport modes using hydrogen see a 20% discount rate. Other advanced personal road transport options have a hurdle rate of 25% except for hybrid technologies which are closer to market and are implemented with a 15% hurdle rate.[10]

Energy service demands

As a critical driver of energy system costs, which incorporates a range of demographic, economic and social aspects, the energy service demands (ESDs) have been reviewed. Industrial energy service demands have been updated to reflect international trends (McKenna, 2008). Transport energy service demands have been adjusted to reflect revised growth rates (DfT, 2005) and saturation effects, notably in the domestic aviation sector (IPPR / WWF, 2007). International aviation is included and uses the same saturation constraint.[11] Finally the seasonality of ESDs have been updated (Stokes et al, 2004; Abu-Sharkh et al, 2006).

[10] It is noted that hurdle rates are not employed in the parallel government analysis (CCC, 2008), which is intended to give a normative finding of which sectors and technologies decarbonisation measures should be focused.

[11] Final energy use through 2050 is held at 2010 levels, which equates to a 30% increase in passenger numbers and a balancing efficiency improvement.

EU-ETS

The EU Emissions trading scheme is imposed with a EU-ETS price of €20/tCO_2 from 2010 onwards in the electricity and industrial sectors - broadly on EU-ETS Phase 2 coverage (46% of total CO_2). This price level and coverage is maintained through 2050. CCS technologies (electricity and hydrogen) are credited with negative EU-ETS emission coefficients, but corrected to account for capture efficiency (90%). Note that this price applies only to UK emissions and no international trading is permitted to occur.

Non-implemented policy variables

All Energy White Paper (DTI, 2007) policy measures are implemented (e.g., renewable obligation at 15%, energy efficiency commitment). The proposed EU renewable energy target of 15% of UK final energy demand and the zero carbon homes requirements are not implemented.

Calibration

The base year for the CO_2 reduction scenarios is adjusted from 2000 to 1990 to be consistent with the Climate Change Bill (DEFRA, 2007a). Base year 2000 CO_2, final energy, and primary energy have been fine-tuned to exactly match with calibration sources (DUKES, 2006; BERR, 2008c). Discrepancies in sectoral emissions tracking have been fixed. This included hydrogen production, imported and exported refined oils, and coking coal emissions.

2.1.4. Core model drivers

One core set of drivers in the UK MED model stem from the structure of the model itself. As an integrated energy systems model, the model elucidates trade-offs between sectors, technology changes and supply vs. demand interactions. This is done at a high level of technological detail on the full UK energy system, based on different technology chains. In addition the MED model incorporates demand side responses to price changes for a calculation of social welfare impacts.

MED assumes perfect foresight of decision makers, with clear and consistently sustained policy signals[12]. Furthermore the optimal solution assumes competitive and rational markets

[12] Investigation of the relaxation of this perfect foresight assumption - including fixed levels of investment and the options of retrofitting CCS - is a major focus of the CCC (2008) report.

with removal of regulatory barriers (unless explicitly added via hurdle rates, technology growth rates etc). International drivers are exogenous to the model and trade, competitiveness and broader macro impacts are not considered. Policy drivers are implemented as appropriate in both the reference case and other scenarios.

The variant scenarios incorporate different assumptions about technology and behaviour, and different policy measures. In particular the key variables for the different scenarios are:

- Resource supply curves (updated as of 2008)
- Other international drivers (e.g. emission credit purchases)
- Technology costs (vintages and learning)
- Option of new energy technology chains
- System implementation (e.g., treatment of intermittency)
- Energy service demands (all sectors)
- ESD price responses via demand elasticities
- Policy variables (e.g., renewables obligation)
- Imposition of taxes and subsidies (e.g. fuel duties on all road transport options, EU-ETS)
- System and technology-specific discount rates (market vs. social)
- Different emissions constraints (the focus of this report – see section 2.1.5)

As has long been stressed by energy modellers (e.g. Huntington et al., 1982), the objective of a model such as MARKAL is to generate broad insights, and these should be the focus of the interpretation of model results, rather than the absolute numbers. Model data and assumptions described in this paper are for only for the core runs of this UKERC Energy 2050 exercise.

2.1.5. Carbon pathway scenarios

The MED model has been run for a Base reference case and a total of seven low carbon pathways. These are listed in Table 5 and their associated emission pathway shown in Figure 2. These runs are designed for relevance to the UK policy process for the near- and long-term targets of the Climate Change Committee.

A first set of Carbon Ambition runs (CFH, CLC, CAM, CSAM) focus on ever more stringent 2050 CO_2 reduction targets ranging from 40% to 90% reductions.[13] These runs also have intermediate (2020) targets of 15% to 32% reductions by 2020 (from a 1990 base year). The set of increasing stringency runs (CFH, CLC, CAM) are also being run using the E3MG model and will be compared to these MED runs in a later UKERC Energy 2050 report.

A second set of 80% reduction sensitivity runs (CEA, CCP, CCSP) focus on differences in the constraint around an 80% CO_2 reduction target. These involve early action and two runs with the same cumulative emissions but different discount rates (see below).

The majority of the runs - B, CFH, CLC, CAM, CSAM, CEA, CCP - employ a market discount rate of 10% to trade-off action in different time periods as well as annualise technology capital costs. This 10% market discount rate is higher than a risk-free portfolio investment return (which could be around 5%) and accounts for the higher return that investors require to account for risk. In addition the model uses technology specific 'hurdle' rates on future transport technology and on building conservation and efficiency options. These hurdle rates apply only to, and effectively increase, the capital costs of these efficiency technologies, in order to simulate the barriers to investment in them. Set at 15%, 20% and 25% these hurdle rates represent information unavailability, non price determinants for purchases and market imperfections (e.g., principal agent issues between landlords and tenants).

Scenario	**Scenario name**	**Annual targets (reduction)**	**Cumulative targets**	**Cum. emissions $GTCO_2$**
B	Base reference	-	-	30.03
CFH	Faint-heart	15% by 2020 40% by 2050	-	25.67
CLC	Low carbon reference	26% by 2020 60% by 2050	-	22.46
CAM	Ambition (low carbon core)	26% by 2020 80% by 2050	-	20.39
CSAM	Super Ambition	32% by 2020 90% by 2050	-	17.98
CEA	Early action	32% by 2020 80% by 2050	-	19.24

[13] The -80% case (CAM is the low carbon core run. It is noted that if international bunker fuels and non-CO_2 GHGs were to be included in the UK's budget the overall target may be closer to CSAM i.e., a -90% case (CCC, 2008)

CCP	Least cost path	80% post 2050	Budget (2010-2050) similar to CEA	19.24
CCSP	Socially optimal least cost path	80% post 2050	Budget (2010-2050) similar to CEA	19.24

Table 6: Carbon pathway scenarios

A further run (CCSP) employs a social discount rate of 3.5% (HMT, 2006). The social discount rate covers the social rate of time preference, which is society's pure time preference for consumption, plus the diminishing marginal utility of consumption as wealth increases. In this CCSP run technology hurdle rates are reduced proportionally - i.e. a previously doubled hurdle rate of 20% is now still doubled but only to 7%.

The intuition behind these different discount and hurdle rates is as follows. The market discount rate describes situations in which markets work perfectly and it is considered appropriate that market criteria should govern all (including social and government) decision-making. Hurdle (higher than market) rates are introduced to take account of market imperfections which impede investments. Social (lower than market) rates are appropriate where there are public or social reasons for undertaking investments, or assessing costs, that supplement purely market considerations.

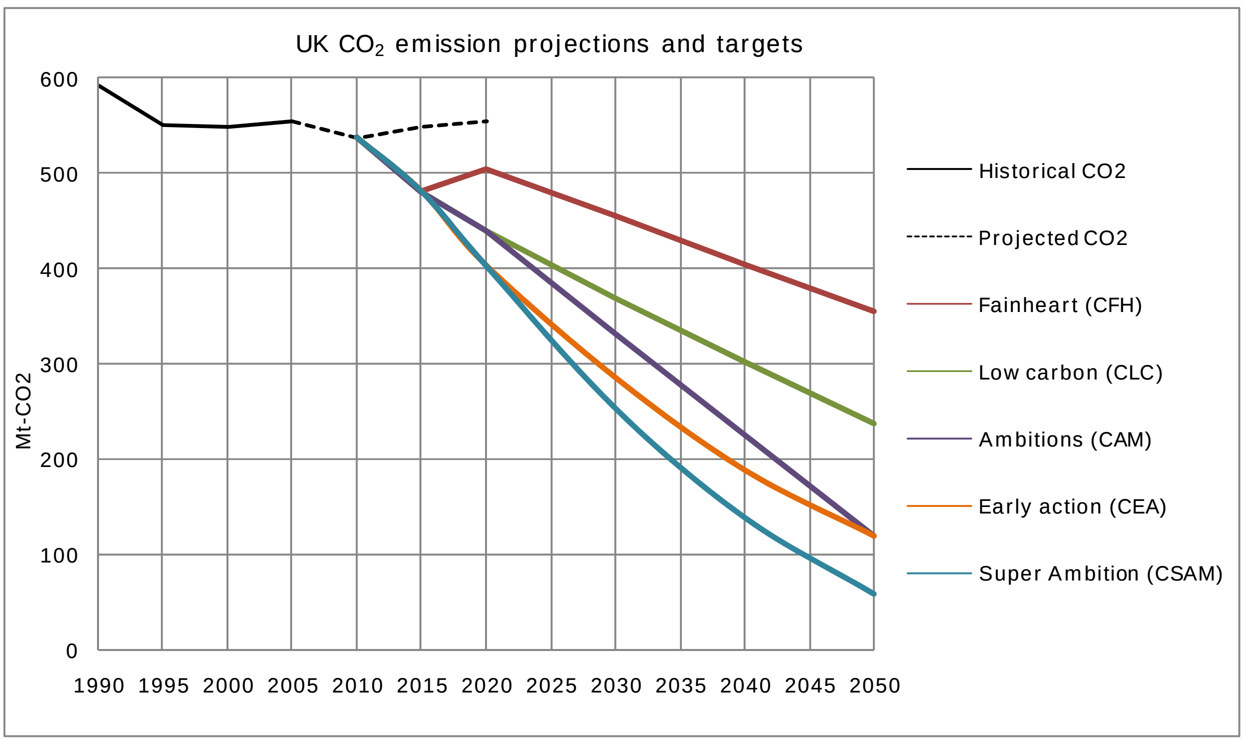

Figure 2: Annual CO_2 emissions trajectories for different scenarios

The scenario pathways in Figure 2 are derived by imposing an annual carbon emission constraint from 2015 to reach the 2050 emissions target. The 2020-2050 period trajectories for the CFH, CLC and CAM scenarios follow a straight line trajectory (SLT). In the CEA and CSAM runs carbon emissions decline exponentially to ensure that the annual percentage reduction in late-periods is not excessive. The cumulative constraint runs (CCP, CCSP, not shown in Figure 2, see Figure 4) have the same cumulative emissions as the CEA 80% reduction case.

3. Scenarios and Results

The full result outputs for the set of carbon ambition runs (CFH, CLC, CAM, CSAM) and the set of 80% reduction sensitivity runs (CEA, CCP, CCSP), are given in Appendices A1 and A2 respectively.

3.1. Decarbonisation Pathways

CO_2 Emissions

If no new policies/measures are enacted, energy related CO_2 emissions (in the Base Reference Scenario, B) in 2050 would be 584 $MtCO_2$, which is 6% higher than the 2000 emission level and only 1% lower than the 1990 emission level. Existing policies and technologies would bring down the emissions in 2020 to about 500 $MtCO_2$ achieving over 15% reductions, which falls well short of the minimum government target of a 26% reduction. From 2020-2050, economic and energy service demand growth overwhelms near term efficiency and fuel switching measures (which are partially driven by the effects of the EU-ETS price, and the electricity and transport renewables obligations), and CO_2 emissions rise. Figure 3 provides annual CO_2 emission levels under different scenarios over the projection period.

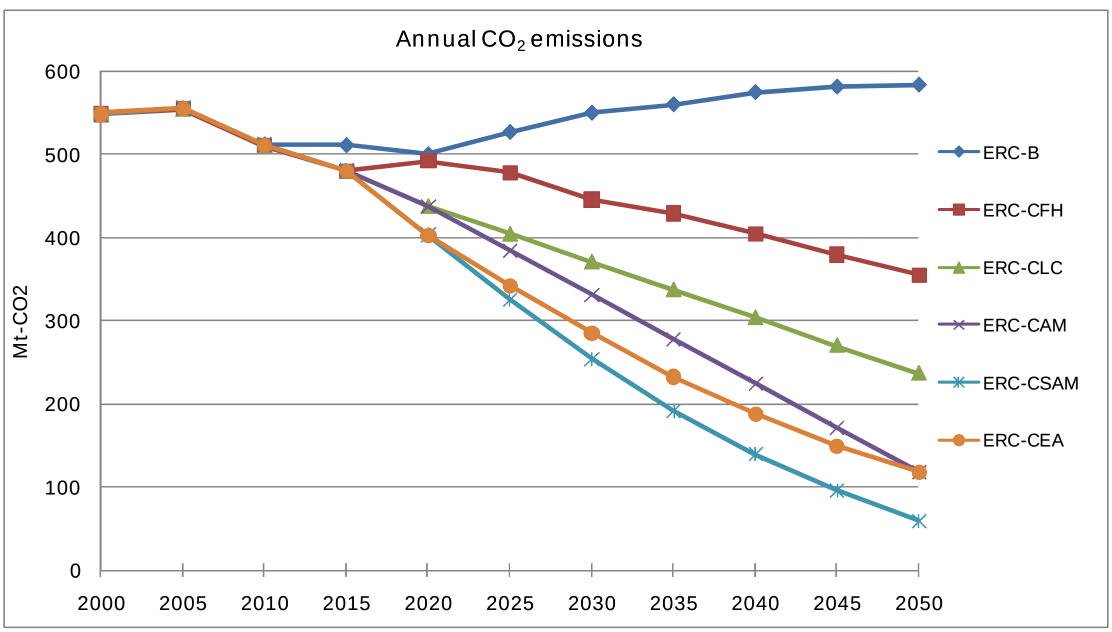

Figure 3: CO_2 emissions under scenarios with different annual carbon constraints

For the CO_2 mitigation scenarios where annual emissions constraints are not imposed (CCP and CCSP), these two scenarios choose the optimal emissions path with the cumulative emissions level as CEA (Figure 4). As expected, UK MARKAL MED results shows *later* action for the CCP run as the model tries to delay reductions as far as possible (owing to the 10% discount rate and hence lower costs assigned to reductions in later periods). For the CCSP run (at 3.5% discounting), the model undertakes *earlier* decarbonisation as the overall objective function now gives more weight to costs imposed later in the time horizon. As CCSP focuses on earlier emission reductions it requires a reduction of only 70% in 2050. On the other hand, the CCP run suggests that the UK can go beyond an 80% target in 2050 as its later action cuts UK emissions by 89% in 2050. The flexibility offered by the cumulative constraint rather than imposed annual reductions is reflected by a slightly lower discounted system cost in CCP, about £700 million lower than in CEA (with the same cumulative emissions).

For nearer-term emissions reductions (2020), the CO_2 emissions constraint in 2020 is imposed in CLC (26%) and CAM and CEA (32%). Among the cumulative scenarios, the CCSP scenario has the lowest emission level in 2020, emitting 39% lower CO_2 emissions than in 1990 while the CCP cuts only 32%.

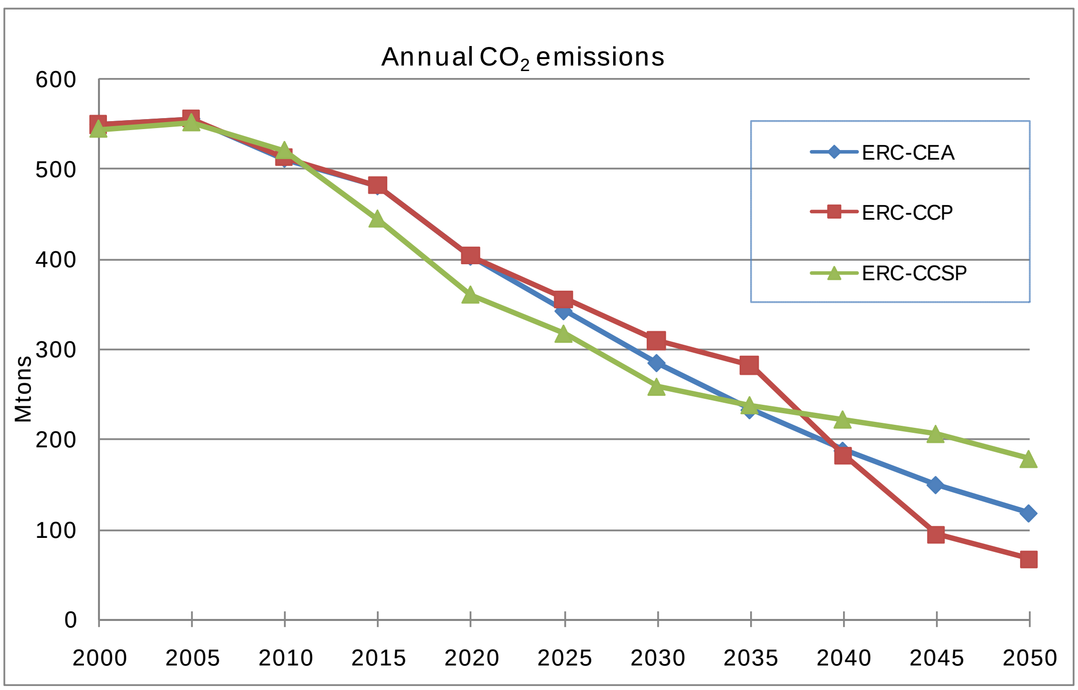

Figure 4: CO_2 emissions under cumulative constraint scenarios

<u>Sectoral CO_2 Emissions</u>

The power sector has a relatively high share of total CO_2 emissions in the Base Reference Case followed by transport, residential and industrial sectors (Figure 5). The contribution of the power sector to total CO_2 emissions increases from 35% in 2020 to 45% in 2050 while the transport and residential sectors show slight reductions. The increased level of renewable electricity (especially wind) due to the 15% Renewables Obligation brings down the power sector emissions during 2005-2020 while replacement of retiring existing nuclear and gas power plants by high CO_2 emitting coal plants during 2025-2030 radically increase the power sector CO_2 emissions between 2020 and 2030.

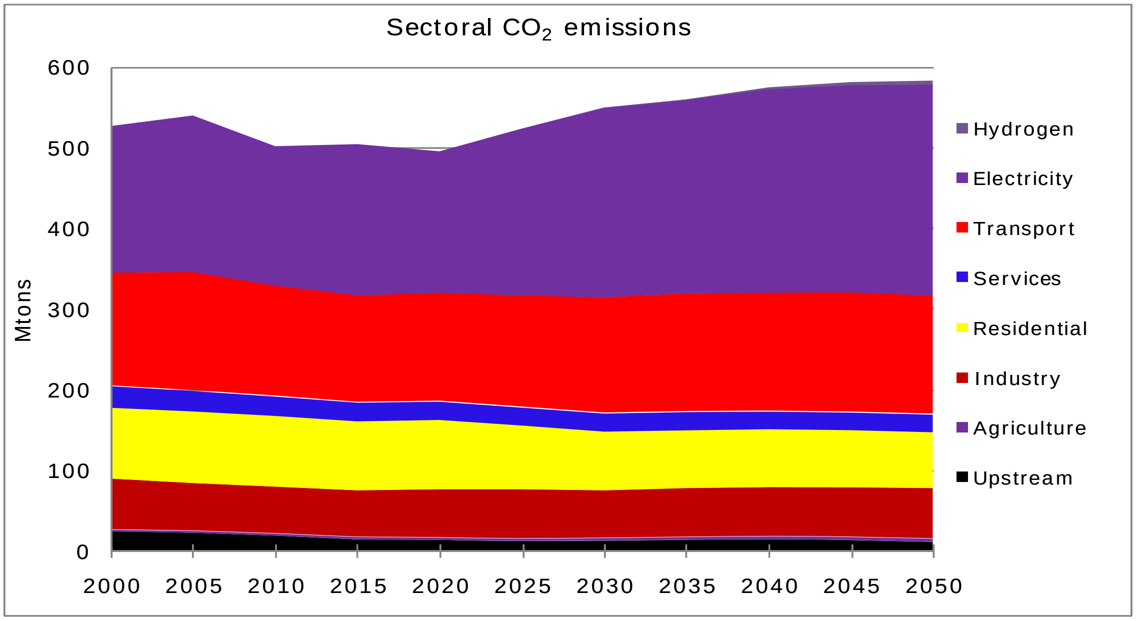

Figure 5: Sectoral CO_2 emissions during 2000-2050 in the Base reference case

Figure 6 presents the sectoral CO_2 emissions in B, CFH, CLC, CAM and CSAM for the selected years 2035 and 2050. Decarbonisation is foremost in the power sector till the middle or end of the projection period. Then major efforts switch to the residential and/or transport sector. Service sector and upstream emissions are also heavily decarbonised in the CAM and CSAM cases in 2050 as the residual emissions budget shrinks. Residential and transport sectors work harder to meet relatively higher early mitigation target in CSAM, reducing their emissions respectively by 67% and 47% in 2035 as compared to B.

To meet the 80% target in CAM, the power sector CO_2 emission is reduced by 93% compared to B in 2050. The respective figures for the residential, transport, services and industrial sector are 92%, 78%, 47% and 26% respectively. Since the industrial sector is only moderately decarbonised[14], in 2050 it is the prime contributor to the remaining CO_2 emissions in CAM and CSAM, followed by transport sector.

End-use sectors have their lowest CO_2 emissions in CSAM, which has the highest mitigation target of 90% in 2050. Conversely, the model meets the modest 40% CO_2 reduction target in CFH by decarbonising the power sector (and limited reductions in industry and service sectors) in 2035 and then further decarbonising the power sector in 2050.

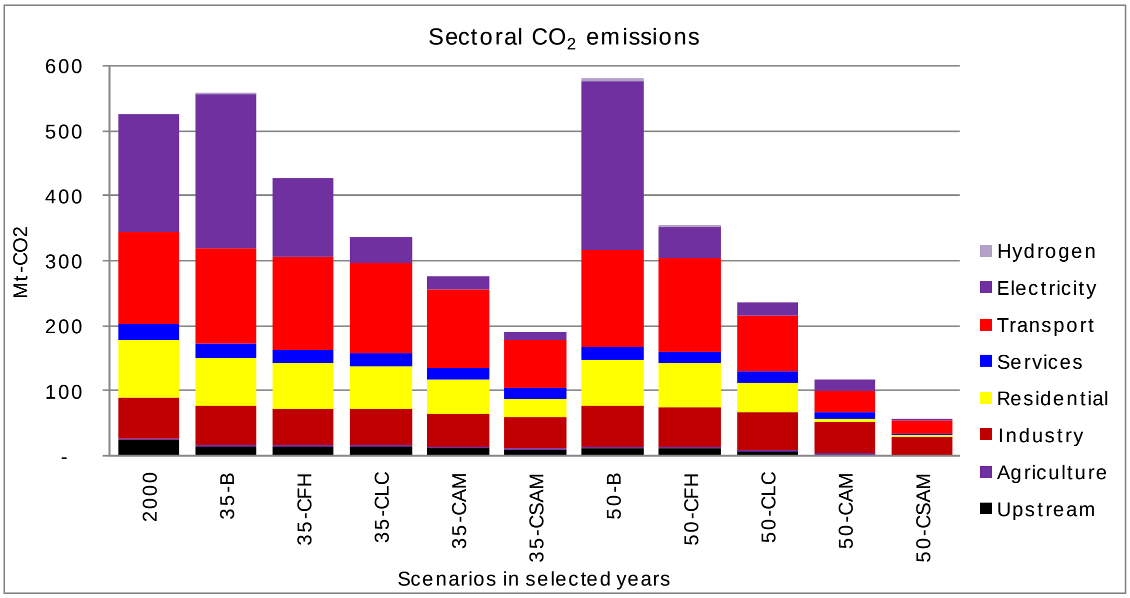

Figure 6: Sectoral CO_2 emissions in years 2000, 2035, 2050: Carbon ambition scenarios

Sectoral CO_2 emissions under the 80% constraint cases (CAM, CEA, CCP and CCSP) are presented in Figure 7. In these cases, there are exceptions to the general pattern of early decarbonisation focused on the power sector. Exceptions to the general pattern include the CEA and especially the CCSP runs where a focus on earlier action means the transport sector works harder, as the lowest cost power sector zero-CO_2 technologies are not ready till 2030+. Although all the end-use sectors contribute to meet the CO_2 targets beside the power sector, in 2035 the residential sector plays a major role in CEA and CCP and transport sector plays major role in CEA and CCSP.

[14] Note that some potential industrial emission reductions measures, notably enhanced energy conservation and CCS from industrial facilities are not included in the MED model.

In 2050, power sector CO_2 emissions are almost the same low level in all CO_2 mitigation scenarios, and the decarbonisation is shifted from power sector to end-use sectors especially residential and transport sectors. In the CCP scenario, industry and services sectors are also heavily decarbonised in 2050 as the total CO_2 emission reduction is 89%. A point here to be noted is that decarbonisation of end-use sectors results in shifting to greater levels of low carbon electricity from the power sector.

All the end-use sectors have their lowest CO_2 emission level under the tightly decarbonised CCP scenario in 2050. Residential, upstream and services sectors combined emit only 5 $MtCO_2$ while power, transport and industry sectors emit 13 $MtCO_2$, 26 $MtCO_2$ and 20 $MtCO_2$ respectively in 2050 under the CCP scenario.

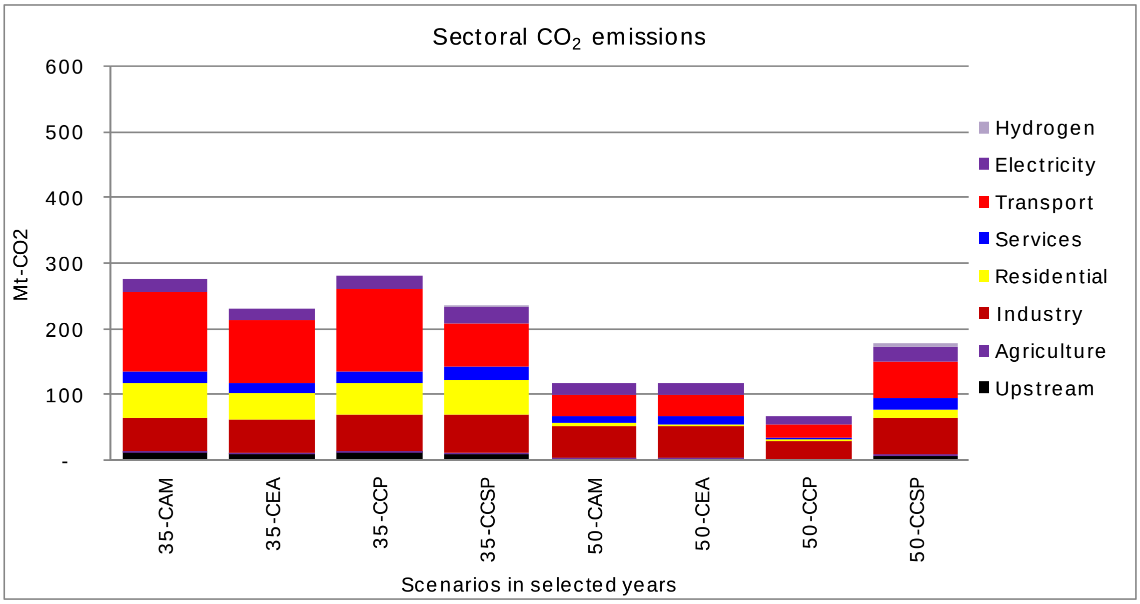

Figure 7: Sectoral CO_2 emissions in years 2035, 2050: 80% constraint cases

If electricity sector emissions are distributed to the end-use sectors, then residential, industry and transport sectors will have relatively higher shares as compared to the residential and service sectors in CCP, CCSP and CEA. This indicates that electric heating and transport technologies are playing a major role. In the CCP case, a larger portion of the electricity sector emissions go to the industry and residential sectors instead of the transport sector, i.e., the transport sector here is decarbonised mainly by bio-fuel (bio-diesel and ethanol)[15].

3.2. Energy-economic system implications

<u>Primary Energy Demand</u>

Despite the fact that final energy demands increase slightly during 2000-2050 to meet the UK's growing energy services demand (see Figure 12), the primary energy demands are well below the 2000 level during 2000-2050 in the Base Reference Case (Figure 8). This is due to the improvement in efficiency of energy process and conversion technologies (power plants) and the increased share of renewables (notably wind). Primary energy demand decreases till 2020. The increased level of renewable electricity replacing oil and its product, due to the Renewable Obligation, reduces the primary energy demand until 2020. Thereafter, selection of coal especially for power generation replacing nuclear and gas slightly increase the primary energy demand in B.

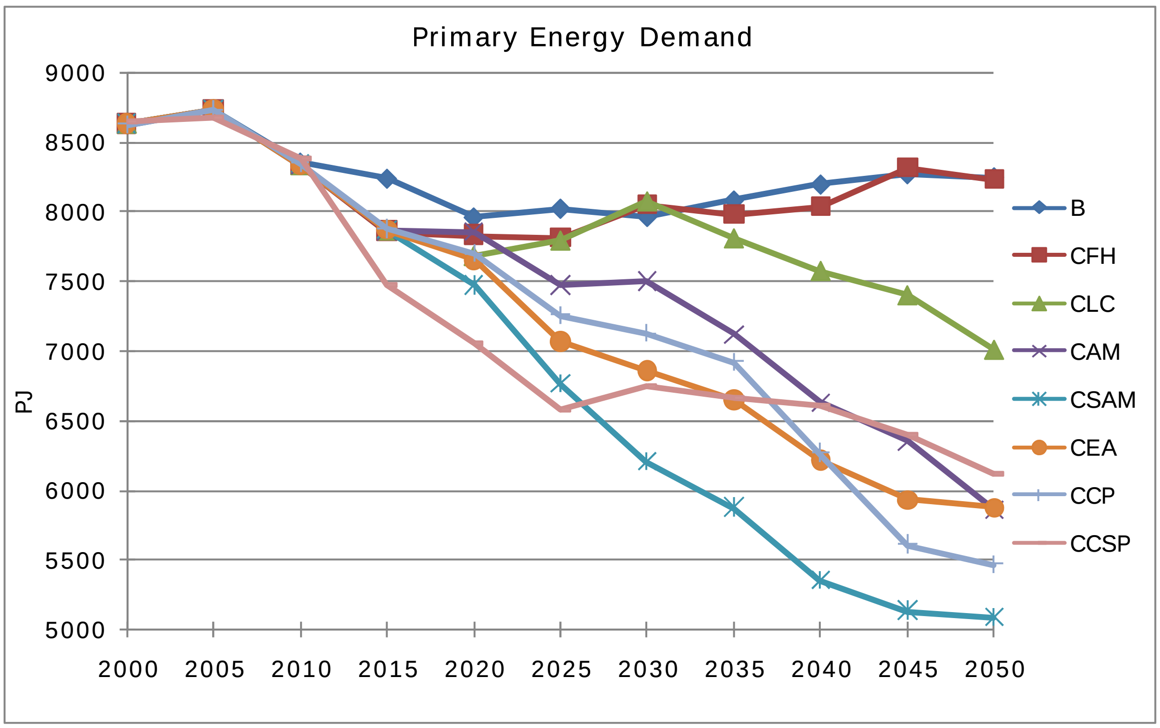

Figure 8: Primary energy demand under different scenarios

[15] A major assumption is that bio-fuels are produced in a sustainable way leading to zero CO_2 emissions.

In the Base (B) case, fossil fuels (coal, oil and gas) dominate the primary energy supply in the early years (Figure 9). The UK's primary energy demand in 2000 was met by fossil fuels with 81% from natural gas and oil. But the trend changes as the share of coal increases in the medium and long-term (especially). This is largely due to replacement of retiring gas power plants by coal plants. Further, there is no nuclear electricity in the primary energy demand after 2035 as they are retired and replaced by coal plants in B. Demand reduction and efficiency improvements reduce the carbon emissions and primary energy demand in the early years in B.

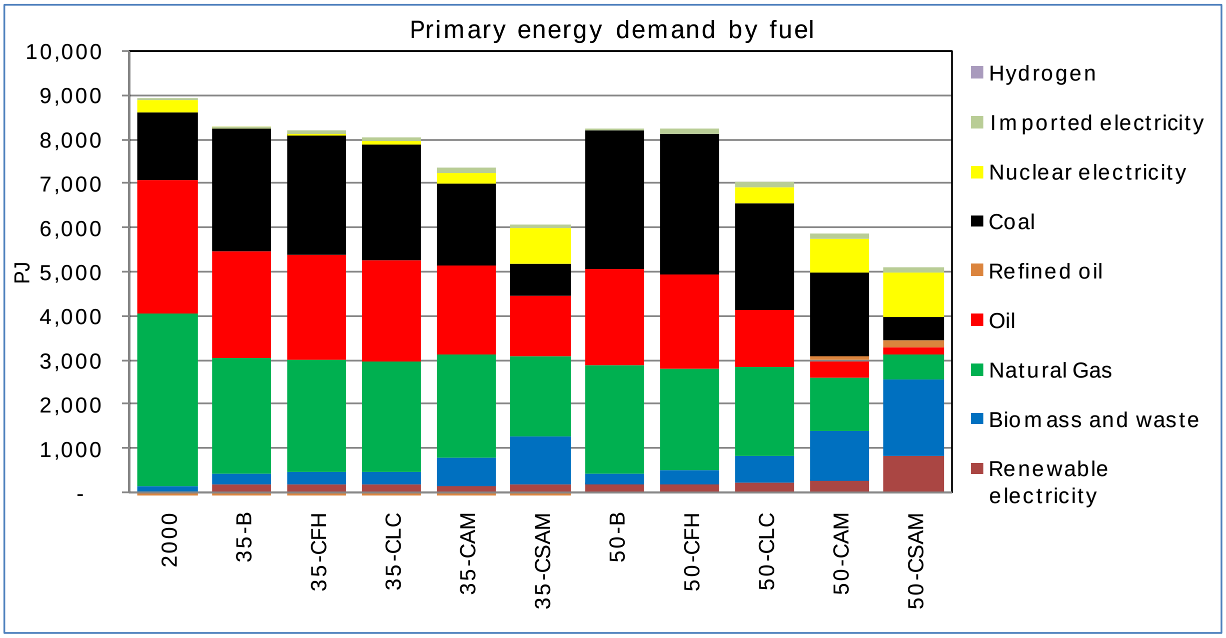

Figure 9: Primary energy demand in selected years under different scenarios

Total primary energy demand during 2000-2050 under all the carbon mitigation scenarios is presented in Figure 8, and by fuel/resource types under B, CFH, CLC, CAM and CSAM in Figure 9. Decarbonisation essentially defines the future of energy supply. When the carbon target is increased, fossil fuels are replaced by nuclear and renewable electricity[16] and by biomass. Biomass is mainly imported (Figure 11) and heavily used in the transport sector, along-with the residential and service sector at a smaller scale. Very large amount of biomass is selected at higher mitigation targets especially in CAM and CSAM, where biomass

[16] Note that in these runs, only the nuclear, imported and renewable electricity is counted as primary energy, not the equivalent heat content.

is the dominant resource supplying one third of the total primary energy demand in 2050 (Figure 9).

When the carbon target gets more stringent (40%, 60%, 80% and 90%), very large reductions in primary energy demand are possible by 2050 as nuclear and renewable (especially wind) plays a major role in the power sector besides the efficiency improvement and demand reduction in the end-use sectors. These primary energy reductions would be moderated if the primary energy in nuclear (and geothermal) resources was calculated on a heat content basis (as in some energy statistics publications (e.g., DUKES, 2006)).

In 2020, there is no significant change in total primary energy demand in CFH, CLC, CAM and CSAM as compared to that in B. This is mainly due to the decarbonisation of the power sector by coal-CCS plants to meet the mitigation target in 2020. Further, as coal-CCS plays a major role in meeting the 40% mitigation target in CFH, there is no big change in the primary energy demand mix as compared to B except the early years when the CCS technology was not available. In 2050, in B and CFH over 93% of the primary energy demand is supplied by fossil fuel, with coal accounting for over 38%. In 2050, natural gas is mainly used in the residential sector and is the sole contributor to the residential sector CO_2 emissions.

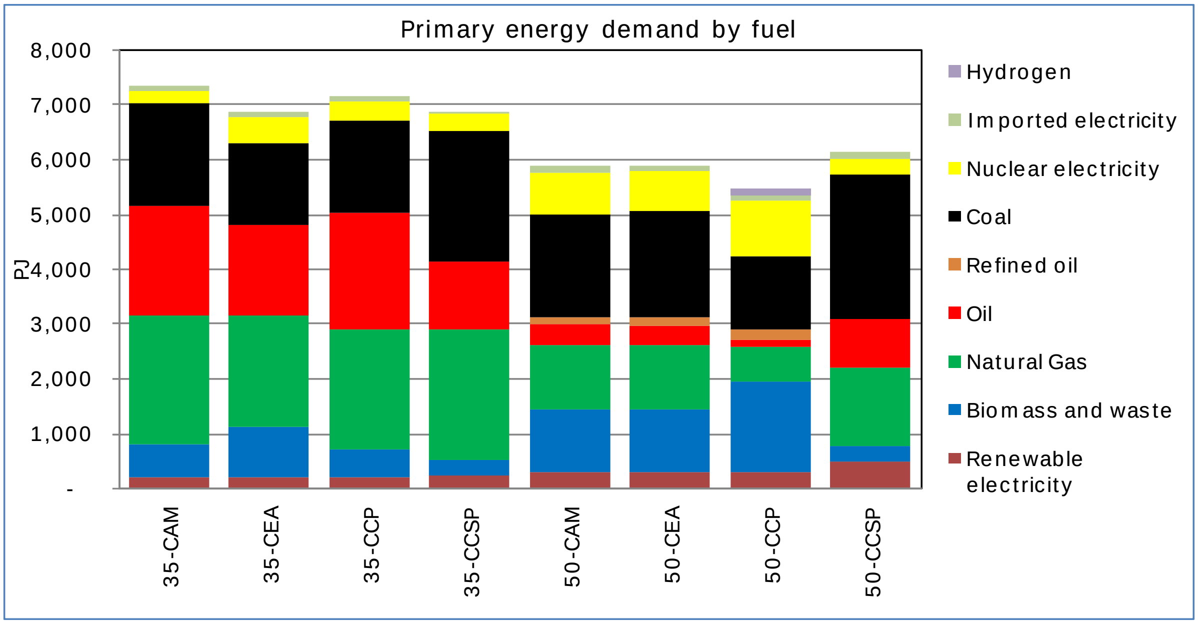

Figure 10: Primary energy demand in selected years in CAM, CEA, CCP and CCSP scenarios

Figure 10 shows primary energy demand under 80% reduction scenarios including early action (CEA) and cumulative emissions (CCP and CCSP) scenarios. Primary energy demand in CCP and CCSP is similar to the CO_2 emissions pattern. The early action under CEA and CCSP demands lower primary energy than that in CAM in 2035 while later acting CCP demands lower primary energy than that in CAM in 2050. Note that CCSP demands a very low level of primary energy in the early years till 2025. This is because of the decarbonisation of transport sector by hybrid and plug-in vehicles, which reduces oil demand, in addition to accelerated demand reductions. In CCSP, the share of nuclear and biomass is relatively low in 2035 and large amounts of oil are replaced by coal with CCS (through electricity and hydrogen production). Among the scenarios, primary energy demand has its lowest value in 2050 under CCP, where nuclear plays a major role in meeting the CO_2 target.

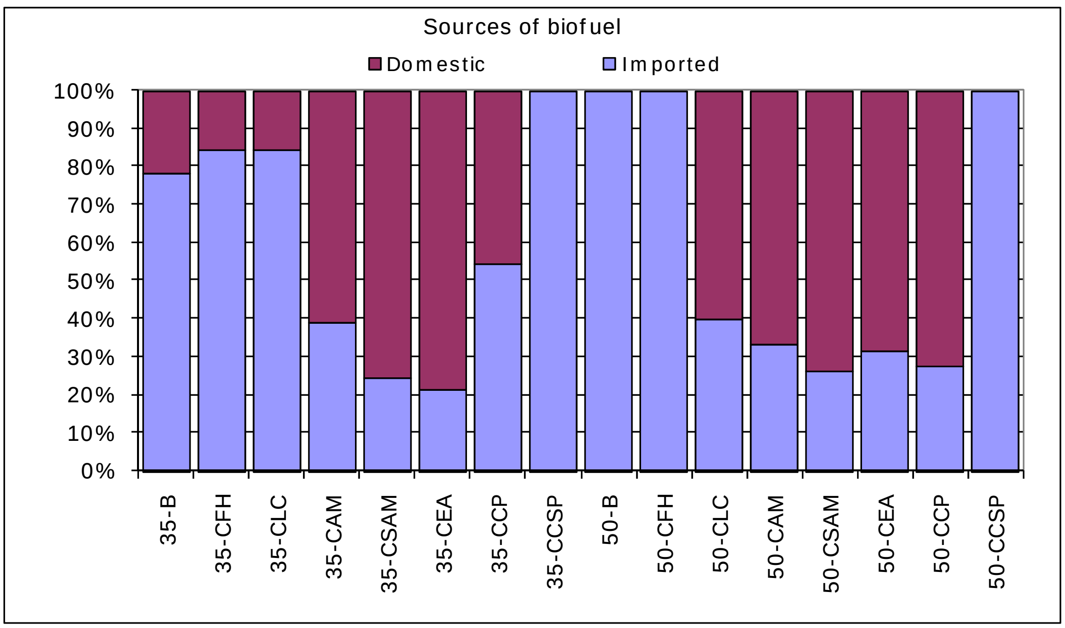

Figure 11: Share of import/export of biomass

Coal is largely used in the power sector and with CCS in all CO_2 mitigation scenarios. When the carbon target is increased, the fossil fuels are replaced by biomass and nuclear. By 2050 CCP requires a large amount of biomass, accounting for 30% of the total primary energy, to meet its stringent CO_2 target. In CCP, half of the primary energy is supplied by biomass and nuclear in 2050. When the demand for biomass is increased, the supply is shifted from import to domestic, owning to conservative assumptions on the imports of sustainable biomass the UK has access to[17]. Hence a large proportion of biomass is coming from expensive domestic resources in CAM, CEA and CCP (Figure 11). Interestingly, a considerable amount of hydrogen (139 PJ) is supplied in CCSP for transport sector.

Final Energy Demand

Though primary energy demand was lower during 2000-2050 than that in 2000 in the base case B, final energy demand slightly increases during the period (Figure 12). However its growth rate is much lower when compared to the growth in energy service demands. This is due to the increased efficiency of the end-use devices, and energy conservation measures especially in buildings.

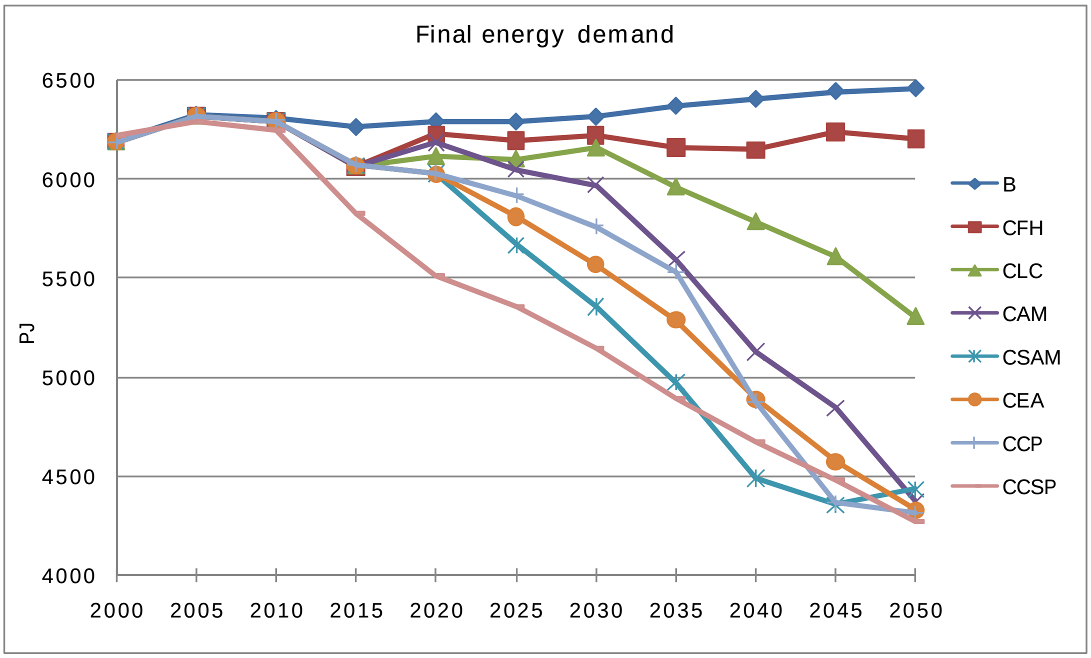

Figure 12: Final energy demand under different scenarios

The UK economy is decarbonised partly by end-use efficiency improvements (and fuel switching), energy conservation measures and demand reduction. This leads to reductions in the final energy demand in each successive CO_2 reduction target in CFH, CLC, CAM and CSAM throughout the period except meeting the target of 90% (CSAM) in 2050 (Figure 12). Even though the CSAM meets the 90% in 2050, it demands slightly more final energy than that in CAM, which meets only 80% CO_2 reduction target in 2050. This reflects the fact that mitigating CO_2 emissions by fuel switching does not always mean reducing final energy

[17] See IPPR/WWF (2007) for a discussion on sustainable global biomass trade

demand. Mitigation is also possible and cost effective with a less carbon intensive fuel with lower energy efficiency.

Figure 13 provide the final energy demand by fuel types for selected years in B, CFH, CLC, CAM and CSAM. Gas is the dominant fuel in the base year as well as in 2035 accounting more than one third of the final energy demand in all scenarios. Overall, although the share of gas is decreasing over time in the low carbon scenarios, still gas and electricity dominate the final energy demand in all scenarios except CSAM in 2050. The share of electricity in total final energy demand is only 19% in 2000, but its share increases continuously throughout the period, reaching 23% in 2050. Petrol and diesel together meet about one third of the final energy demand with diesel having a slightly higher share in the early and middle period. Bio-energy (bio-diesel and ethanol) plays a considerable role in CSAM in 2050. The transport sector consumes large amount of bio-energy (ethanol and bio-diesel) leading to greater final energy demand in CSAM as compared to CAM as the efficiency of bio-diesel based vehicles is relatively low compared to the hybrid plug-in vehicles. Further, large amount of biomass is used in the service sector for heating. Note that the remaining (high efficiency) gas will be a major contributor to residential and service sector CO_2 emissions, along-with transport (including aviation) and industrial liquid fuels.

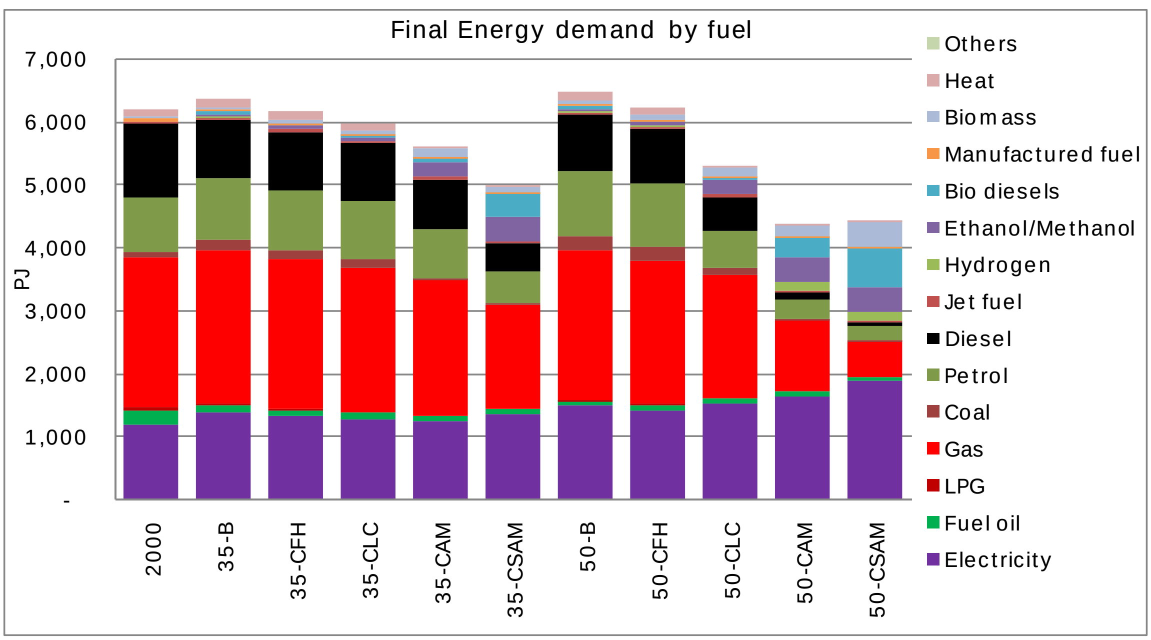

Figure 13: Final energy demand by fuel under different scenarios

Final energy demand by fuel type under CAM, CEA, CCP and CCSP is shown in Figure 14. The two mitigation scenarios (CCP and CCSP) which are run with the cumulative CO_2 constraints show a completely different final energy demand pattern. CCP demands more final energy than CEA, 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. 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. High-capital cost hydrogen vehicles become relatively cheaper in CCSP as the annualised cost is lower due to the technology specific social hurdle rates. This early decarbonisation means 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.

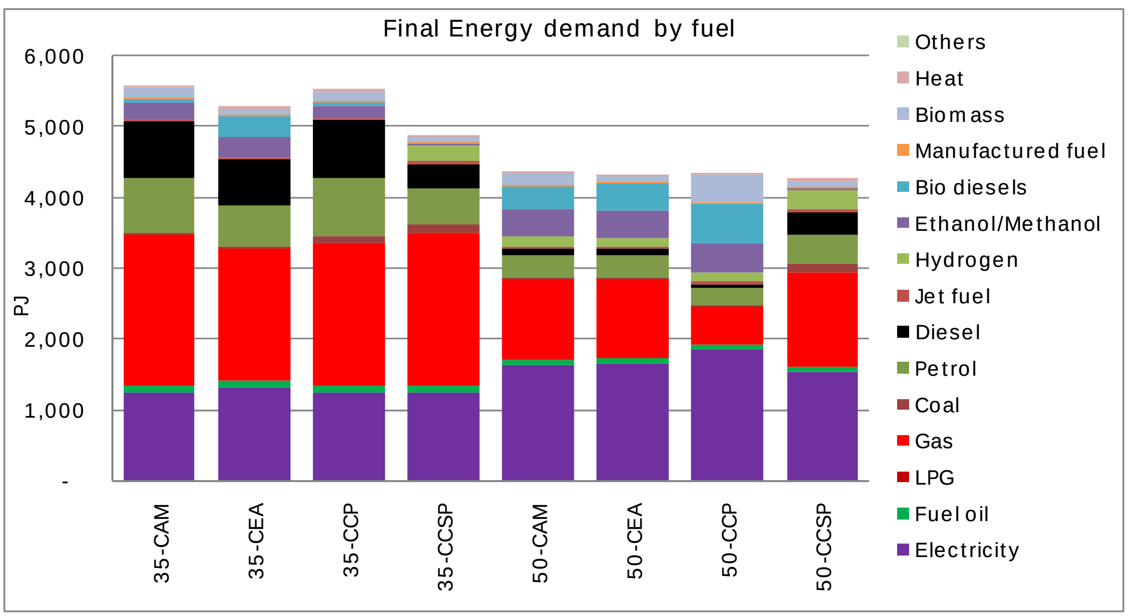

Figure 14: Final energy demand by fuel in CAM, CEA, CCP and CCSP

Calculations show that none of the scenarios would meet the EU's draft renewable directive of at least 15% of UK final energy from renewable by 2020. Analysis shows that share of renewable on final energy would be at least 5% in 2020 under any CA scenario. Further, by 2050, share of renewable on final energy demand can go up to 49% in the CSAM case. The respective figures for other scenarios are 6% in B, 7% in CFH, 13% in CLC, 27% in CAM, 27% in CEA, 39% in CCP and 12% in CCSP in 2050.

Electricity Generation

In the Base B, electricity generation increases by 24% during 2000-2050 to meet continuously increasing electricity demand in the end-use sectors. Over two thirds of total electricity generation comes from fossil fuels (coal and gas) in the base reference case in 2020 (Figure 15). In the absence of significant CO_2 pricing, high carbon content coal becomes the dominant fuel for electricity generation gradually replacing gas and nuclear over the years, generating more than 80% of the total electricity supplied in 2050 (Figure 16). Since coal is responsible for almost all CO_2 emissions from the power sector in 2050, decarbonisation of the power sector in the long-term involves decarbonising coal generation by coal-CCS and/or replacing coal generation with nuclear and renewable generation such as wind, biomass, marine and solar. In 2020, the early decarbonisation requirements of the electricity sector are achieved by replacing coal plants with coal-CCS plants in all mitigation scenarios.

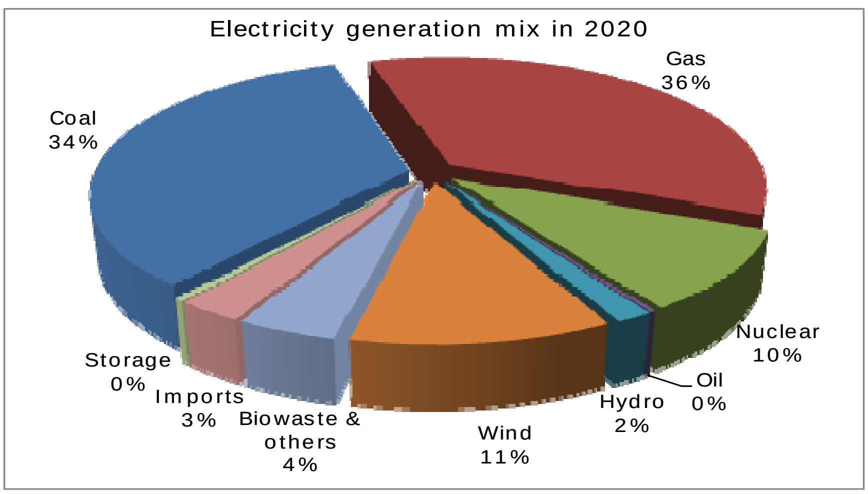

Figure 15: Electricity generation fuel mix in 2020 in the Base reference case

To meet CO_2 reduction levels in 2020, end-use sectors also contribute to meet the carbon target by means of efficiency improvements and demand reductions beside the decarbonisation of the power sector. As the power sector is decarbonised by capturing the carbon from coal plants, there is no big change in the fuel mix of power generation in 2020 in all carbon mitigation scenarios.

Electricity generation mixes under B, CFH, CLC, CAM and CSAM are shown in Figure 16 for selected years 2035 and 2050. Total electricity generation would increase or decrease in the mitigation scenarios as compared to that in the Base reference case 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 mitigation target. As decarbonisation efforts tighten through 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.

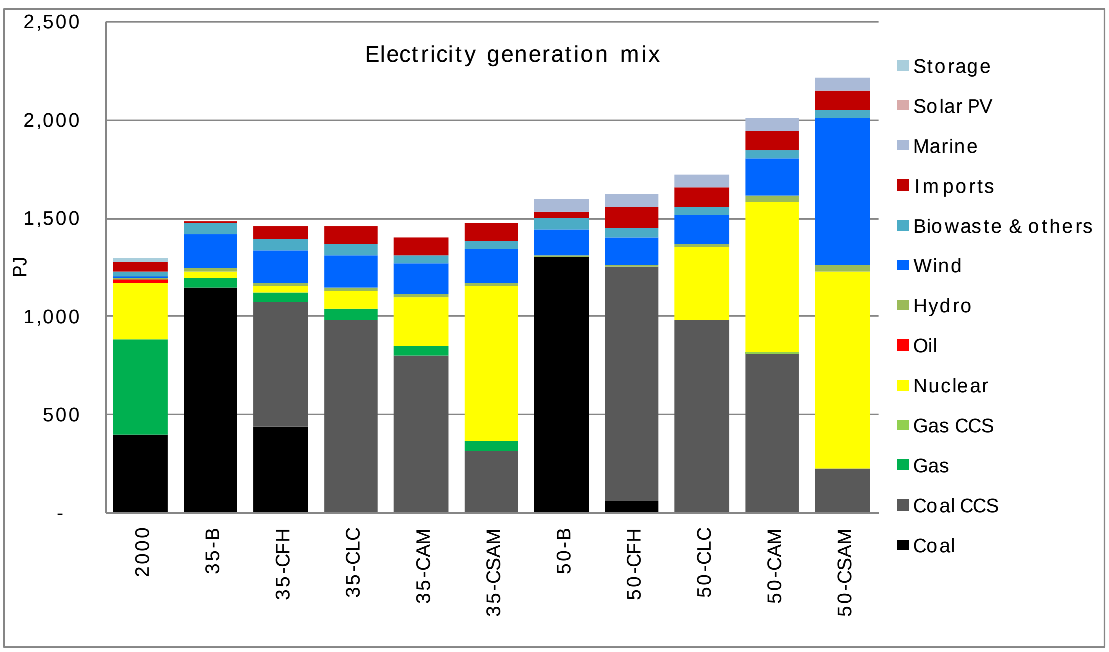

Figure 16: Electricity generation mix under different scenarios

As carbon reduction requirements increase down to very low levels 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.

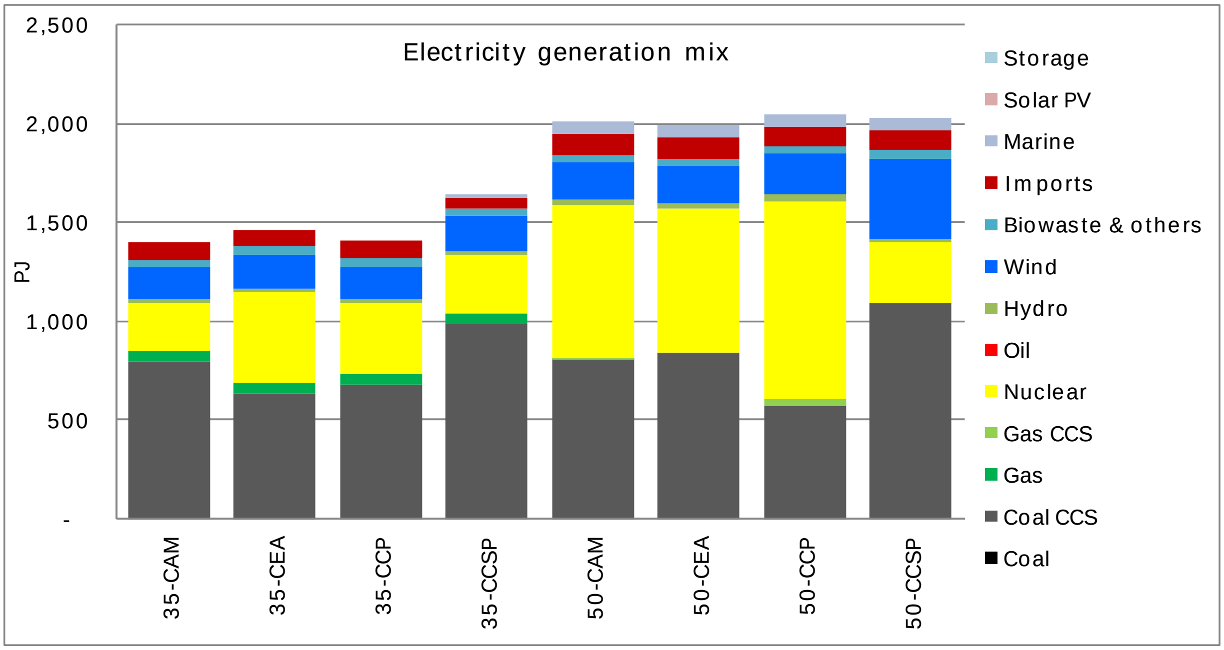

Figure 17: Electricity generation mix in CAM, CEA, CCP and CCSP

Figure 17 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 commercialized zero carbon technology) that necessitates a very large expansion in overall electricity capacity for peak constraints. Wind expansion is mainly from offshore wind as all cost effective onshore wind is already selected in B 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 (see Figure 30).

Marginal Cost of CO_2

MARKAL is a least-cost optimisation model, and the model produces marginal emissions prices to meet the CO_2 constraints based on a range of input assumptions, including competitive markets, rational decision-making and perfect foresight. Note that emission trading could be a cheaper option (buying carbon credits), if the international carbon price is less than the UK MARKAL marginal cost of CO_2, but these runs focus only on national CO_2

reductions. The marginal prices shown in Figure 18, 19 and 20 illustrate that marginal emission prices rise as the annual CO_2 constraint tightens across scenarios and through time. In 2035 marginal CO_2 prices rise from £13/tCO_2 in CFH to £133/tCO_2 in CSAM, and by 2050 this range is £20/tCO_2 to £300/tCO_2. This convexity illustrates the difficulty of achieving very deep CO_2 reductions.

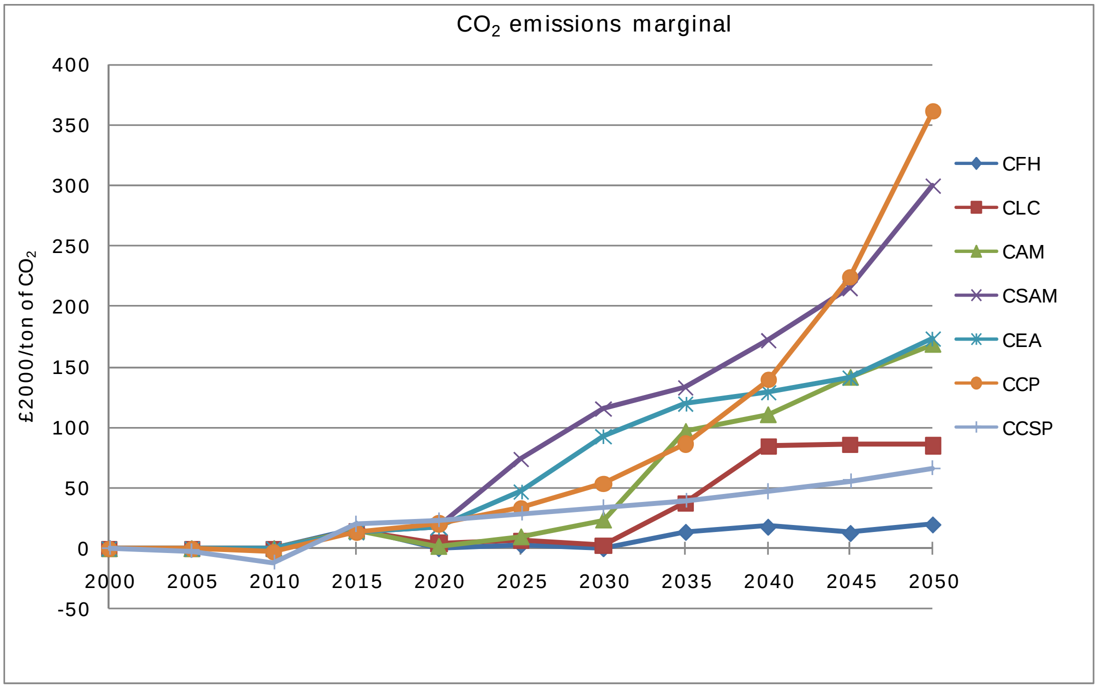

Figure 18: Marginal price of CO_2 emissions under different scenarios

The cumulative emissions constraint cases (CCP and CCSP), which chose the least cost path from 2010 through 2050, again follow the logic of later and earlier action depending on the weight given by the discounting process. The CCSP (early action) costs £24/tCO_2 and £66/tCO_2 in 2020 and in 2050 respectively, while the CCP costs respectively £21/tCO_2 and £360/tCO_2. The implied methodology of this is that in a CCSP future, consumer preferences change and/or government works to remove uncertainty, information gaps and other non-price barriers. Hence the cost comparison between our reference and policy cases is biased downwards through such "better" decision making.[18]

[18] Alternatively, generating a base case with a 3.5% discount rate would give a similar CO_2 cost results as the "distance to target" is reduced, albeit with a different interpretation of consumer preference change with and without decarbonisation policies.

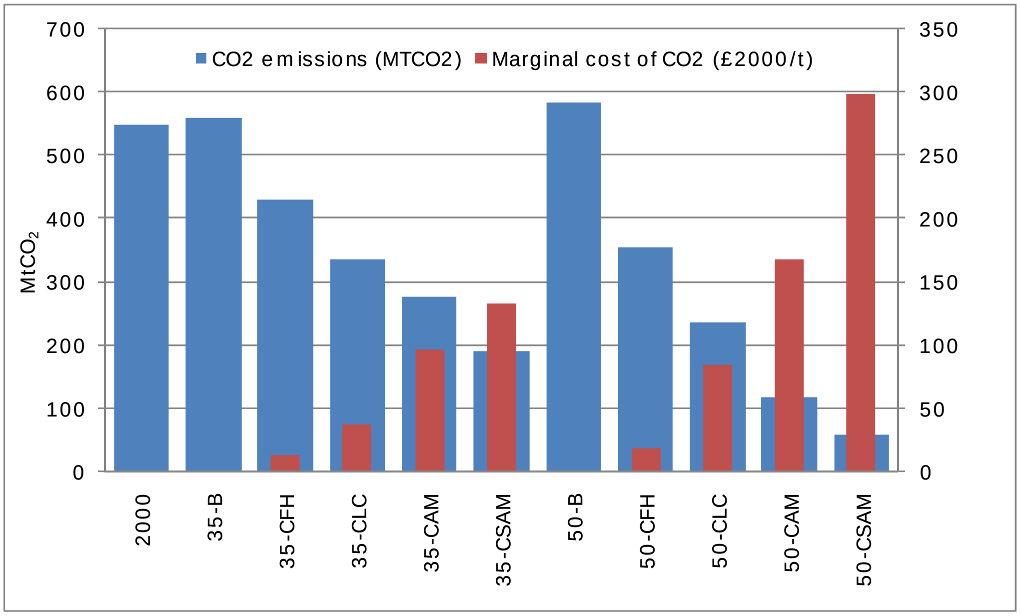

Figure 19: Carbon ambition runs: marginal price of CO_2 and CO_2 emissions

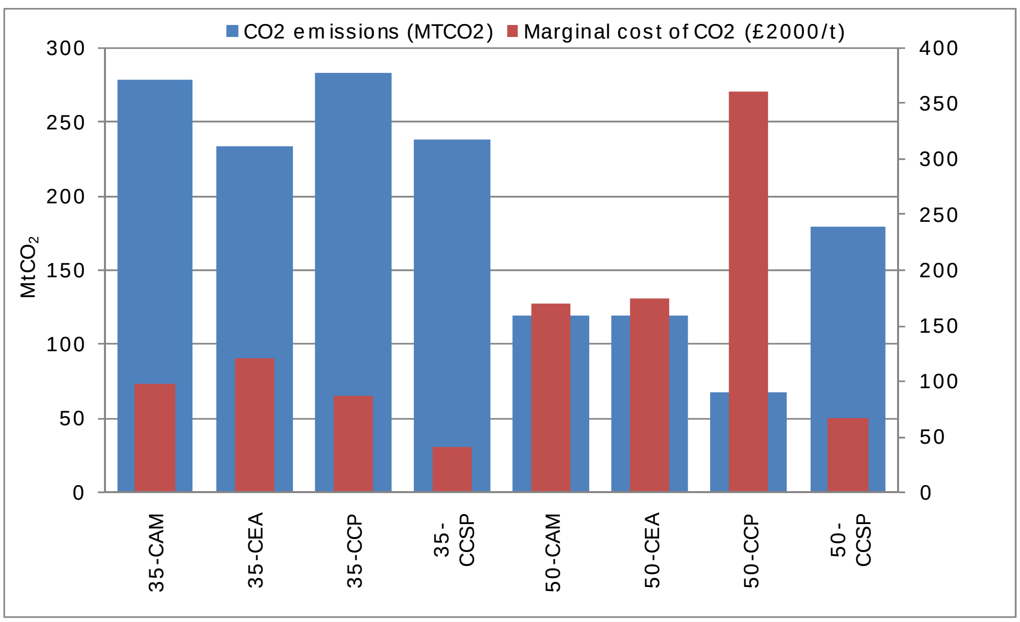

Figure 20: 80% reduction sensitivity runs: marginal price of CO_2 and CO_2 emissions

<u>Demand Reduction</u>

Demand reduction is one of the preferred options to reduce CO_2 emissions, notwithstanding the societal loss in utility due to the demand reduction. The MARKAL MED version's objective function maximises the combined producer and consumer surplus, which included demand reductions when finding the optimal solution. Demand reduction levels for selected sectors and transport energy service demands under different scenarios in 2050 are shown in Figure 21 (full demand reduction tables are in Appendices A1 and A2). Demand reduction levels are relatively higher in 2050 than in 2035 as the CO_2 reduction constraint is tighter. Agriculture, industry, residential and international shipping have higher demand reductions than the air, car and HGV (heavy good vehicles) transport sectors.

The demand reduction level is influenced by the demand function that is constructed based on the price elasticity and reference prices of the Base case. The level of demand reduction then depends on both the price elasticity of demand and the prices of alternative technologies and fuels available to meet the particular energy service demand. For a particular energy service demand, if the alternatives are available with a relatively high incremental cost, then the demand reduction level would be high (or vice versa). For example, the price elasticity of demand is very low for transport shipping (-0.17) and very high for transport HGV (-0.61). However, demand reduction is relatively higher for transport shipping than transport HGV as the transport shipping has no alternative technologies in the UK MARKAL model other than diesel, which is a high carbon content fuel, while the transport HGV has many alternative technologies such as diesel ICE, diesel hybrid, hydrogen ICE and hydrogen fuels. Similarly, car demand also has a relatively high price elasticity (-0.45), but because of the availability of the alternative technology with relatively cheaper cost, the demand reduction level is low.

Demand reductions in the agriculture, industry, services and residential sectors are combinations of reduced individual energy service demands for the sub-sectors of the respective sectors. In particular, relatively high elasticities and restricted technology options for the residential demand (notably direct electricity and gas use) and industrial sectors (notably chemicals) results in substantial reductions in energy service demands. Reaching 20-25% reductions in service demands implies both a significant behavioural change and an industrial reorientation process concerning energy usage.

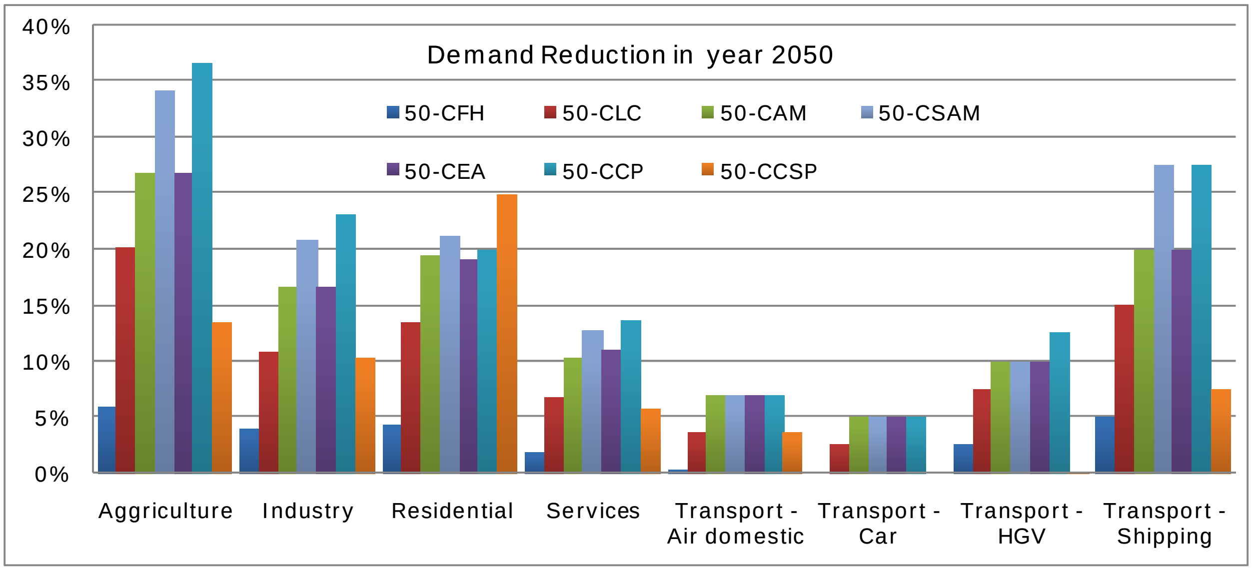

Figure 21: Selected demand reduction level in 2050 under different scenarios

As expected demand reduction levels are lowest in CFH for all sectors. The level of demand reduction increases with the successive mitigation targets in CFH, CLC, CAM and CSAM in 2035 and 2050. But demand reduction under CCP and CCSP in 2050 are not similar as the mitigation pattern is different for these runs. As before the relatively lower weight on near term costs in CCP, results in the model not taking up the immediately available options for demand reductions, although this is reversed by 2050 when the CCP runs is decarbonising to a very great extent. Demands reductions in 2050 under CCSP are generally lower as the model place more weight on late-period demand welfare losses except residential sector (electricity and gas energy service demands). In terms of early demand reductions for CCSP, this is seen in residential electricity and gas energy service demands where demands are sharply reduced as an alternative to (relatively expensive) power sector decarbonisation. Interestingly, no demand reductions are envisaged in personal transport where the CCSP run undertakes very significant technological substitution.

<u>Welfare</u>

Though demand reduction is an immediately available option to reduce demand for energy and consequently CO_2 emissions, it has a negative impact in loss utility from not having the benefit of this additional energy use. When combined with reductions in producer surplus, the resulting metric is social welfare losses (loss of consumer + producer surpluses). This is a far superior metric than changes in energy system costs as the size of the overall energy system is itself changing.

As shown in Figure 22, by 2050, overall welfare losses[19] in the carbon ambition runs range from £5 billion for 40% reductions to £52 billion for 90% CO_2 reductions (all costs are in £2000). The significant increases in welfare loss - including a near doubling of costs for a 60% vs. an 80% reduction – represent a key decision variable when deciding on more stringent UK emission reduction targets. Note that the low welfare losses in the CCSP run are again a reflection of optimal decision making under a social discount rate where consumer preferences change and/or government works to remove uncertainty, information gaps and other non-price barriers. Note that the precise split between producer and consumer surplus is dependent on the ability of producers to pass through additional CO_2 emission costs.

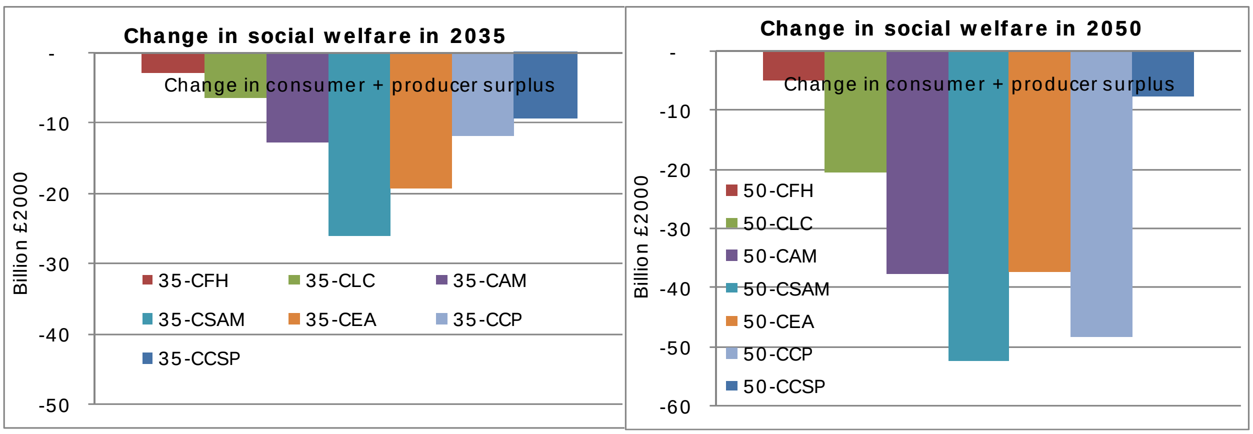

Figure 22: Change in social welfare under different scenarios

3.3. Key Sectoral and Energy Technology Trade-offs

<u>Sectoral Energy Demand and Technologies</u>

Final energy demand by end-use sector is presented in Figure 23 for selected years under B, CFH, CLC, CAM and CSAM scenarios. In absolute terms, the transport, residential and industry sectors have relatively high energy demands while the agriculture sector has the lowest energy demand (50-70 PJ/annum during 2000-2050) among the sectors. Overall in B, sectoral energy demands in transport, industry and agriculture seem to be increasing during the projection period while the residential and services sectors' energy demand would be lower in 2050 than that in 2000.

Decarbonisation essentially defines the sectoral energy demand and technology mix. End-use sectors' decarbonisations are achieved by means of efficiency improvements, demand

[19] Note that welfare is not comparable to % losses in GDP

reductions and low-carbon fuels with efficient technologies. This leads to the reduction in end-use sector final energy demand under the low carbon scenarios as compared to the reference (B) case.

When looking at the decarbonisation of end-use technologies, in general, the residential sector is decarbonised by shifting to electricity (from gas) as well as technology switching from boilers to heat pumps for space heating and hot water heating. The transport sector is decarbonised by shifting to hybrid plug-in, ethanol, hydrogen and battery operated vehicles. The service sector is decarbonised by shifting to biomass (in the CCP case) and electricity. Besides efficiency and fuel switching (and technology shifting), the elasticity (demand reduction) also plays a major role in reducing CO_2 emissions by reducing energy service demand. ESD reductions contribute to the low level of final energy demand and consequently the reduced level of CO_2 emissions.

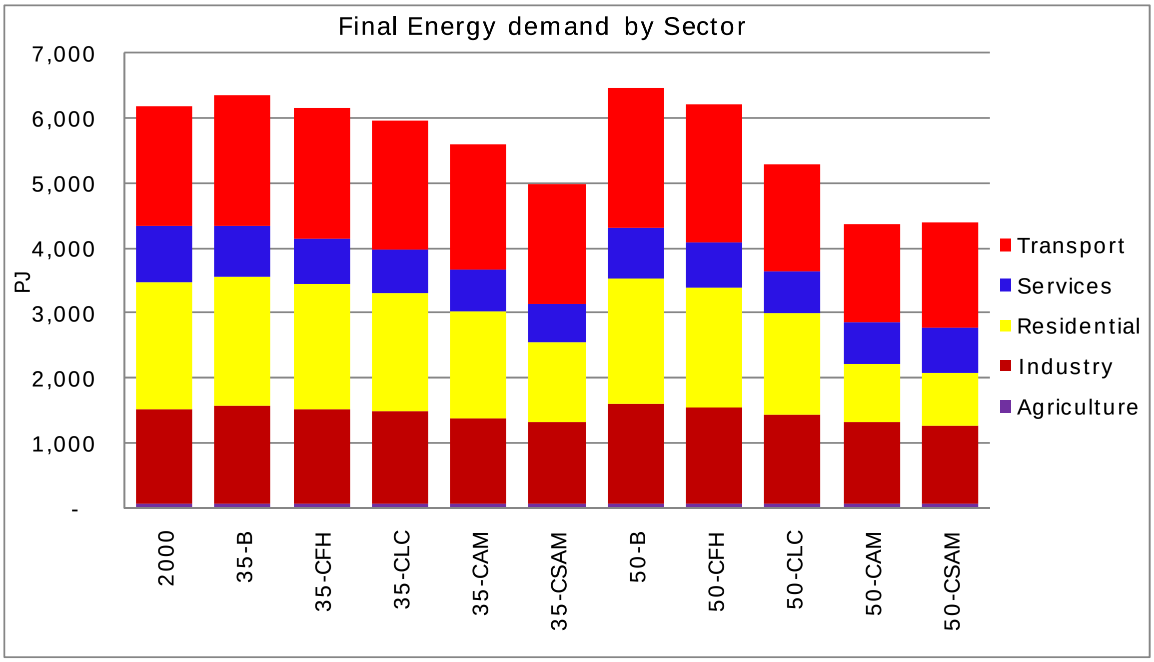

Figure 23: Sectoral energy demand under different scenarios

Despite the fact that the residential, services and transport sectors have been heavily decarbonised to meet the carbon targets the residential sector shows relatively large reductions for final energy demand (Figure 23) in the successive targets as compared to transport sector and other end-use sectors. The reasons for the low energy demand in the residential sector is that here decarbonisation is mainly by shifting from gas to electricity, the end-use devices of which have relatively high efficiency, especially heat pumps (Figure

26) for space and water heating, and relatively high demand reductions (Figure 21). In the case of the transport sector, bio-fuels also play a role for decarbonisation in addition to the switch to electricity (Figure 25). Further, demand reductions in the transport sector are relatively low especially for cars, which consume two thirds of the transport sector energy demand in B, as compared for example to the residential sector.

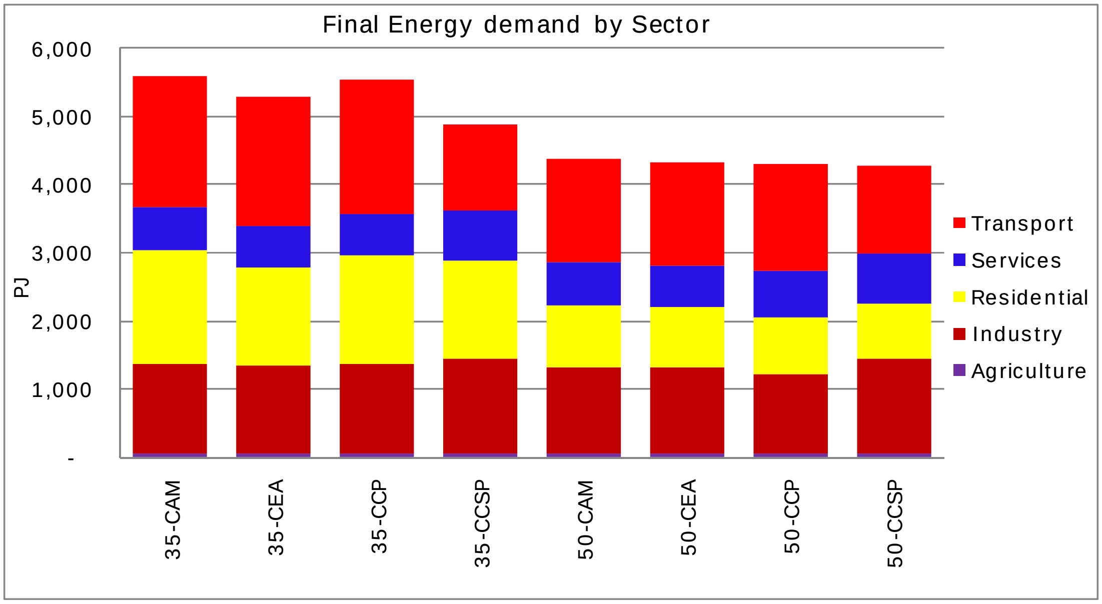

Figure 24: Sectoral energy demand under CAM, CEA, CCP and CCSP scenarios

Sectoral final energy demand in CAM, CEA, CCP and CCSP is presented in Figure 24. Early decarbonising end-use sectors in CCSP and CEA (Figure 7) are the residential and transport sectors. Demand reduction plays a considerable role in early decarbonisation of the residential sector. The demand reduction is mainly in residential space heating, water heating and electricity (there is less demand in CEA than in CAM). Decarbonisation technologies in the residential sector are electric boiler night storage, and more heat pumps (Figure 26) for water heating in 2035. In the transport sector, early decarbonisation is by early shifting to car hybrids and hybrid plug-ins from 2020 in CCSP and early shifting (from 2030) to E85 cars and battery buses, and a very low amount of shifting to Rail-Electric in the CEA. Later acting CCP meets the constraint by a large amount of nuclear replacing coal-CCS, which has residual emissions of 10%, and also by means of transport demand reduction (HGV and shipping) and by shifting to bio-energy (service and transport sectors, Figure 25).

Though the service sector is heavily decarbonised (by 94%) in CSAM in 2050 (Figure 6), the change in the service sector's energy demand is not visible as the decarbonisation is mainly through the replacement of gas boilers with biomass boilers and also partly by demand reductions (Figure 21). The service sector consumes 373 PJ of biomass mainly in biomass boilers in 2050 (Figure 25). A similar finding for enhanced biomass use in the transport sector under the most stringent scenarios (especially CEA, CCP and CSAM) illustrates how the model can increase final energy use while still decarbonising. This is also the case in CCSP although here the low carbon technologies are hydrogen and electric vehicles rather than biomass.

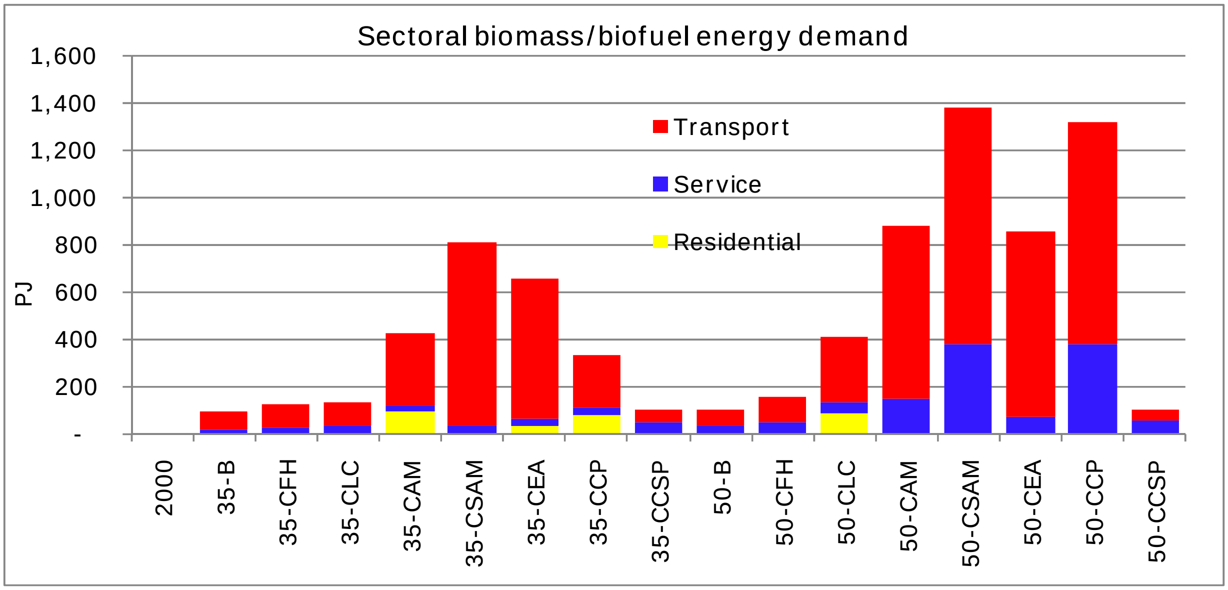

Figure 25: Sectoral bio-fuel energy demand under different scenarios.

Though heat pumps are capital intensive, large numbers of them have been selected for space heating and water heating replacing gas boilers, due to their low energy consumption, as they can deliver more output energy (heat) than the input to them (electricity). In the residential sector, heat pumps become cost effective from 2030 in CEA, from 2035 in CAM, CCP, and CCSP and from 2045 in CLC (Figure 26). Heat pumps consume large amounts of electricity, equivalent to about 350 PJ in 2050 in CLC, CAM, CSAM, CEA and CCP. Though the heat pumps are used for space and water heating more than three quarters (in some cases all) are selected to serve residential space heating.

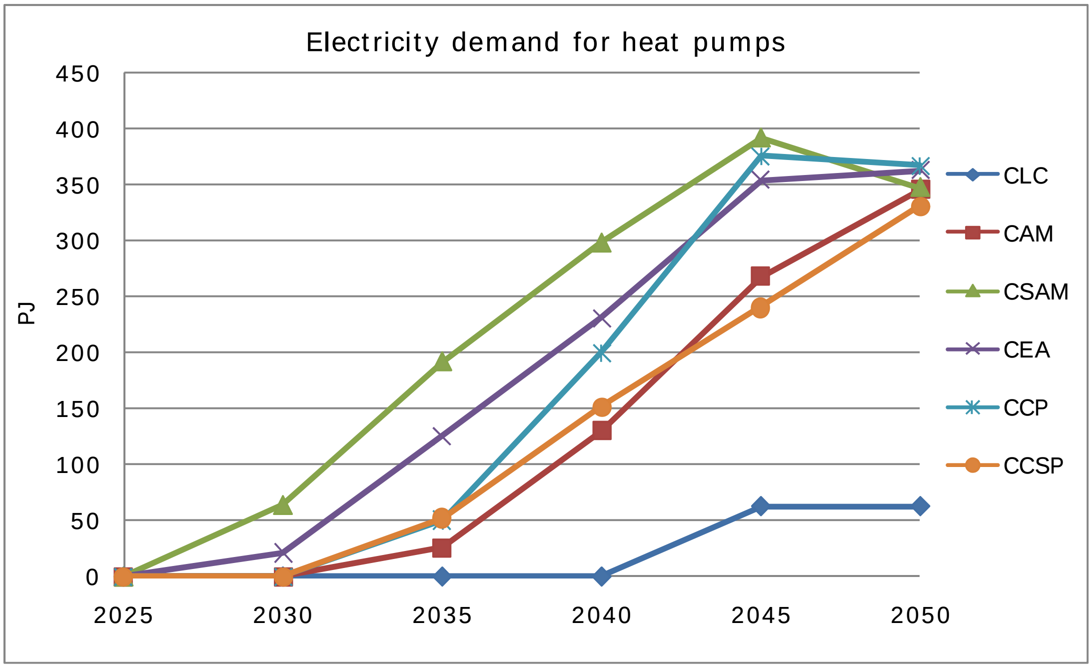

Figure 26: Electricity demand for heat pumps under different scenarios

Transport Fuel Demand

Cars are the biggest energy consumers in the UK transport sector, accounting for over half of the transport sector energy demand in B (Figure 27). This is mainly due to the high demand for transport services in terms of passenger-km in the base years as well as the expected high growth rate during the period. Further, cars tend to have a low occupancy, leading to high-energy consumption/passenger-km. Goods transport vehicles (HGV and LGV) are responsible for at least 27% of transport energy demand. In the Base reference case, petrol and diesel IC engines cars are selected to meet the demand for cars while in 2-wheelers only petrol engines are selected. In the bus mode, there are complete transitions from diesel to diesel hybrid during 2010-2015 and then from hybrid to battery operated electric buses during 2040-2045 in B itself. Hybrid (diesel) vehicles replaces diesel based HGV and HGV during 2010-2015 and thereafter no technological change or fuel switch for the goods vehicles in the Base reference case.

In the carbon ambition mitigation scenarios (CFH, CLC, CAM and CSAM) (Figure 27), as the transport sector is not heavily decarbonised in 2035, there are only small reductions in the energy demand between the CO_2 mitigation scenarios, In 2035 under the largest change in CSAM, where the transport sector has to work harder, decarbonisation is mainly by shifting to Car-ethanol (E85) (55%) and, to a smaller extent, to petrol plug-in cars (11%). In 2050, a significant difference in energy demand can be observed in the higher target scenarios (i.e. not CFH) as the transport sector is decarbonised in the latter part of the period. Though transport sector CO_2 emissions are the lowest in CSAM, its energy demand is higher than in CAM. This is due to the larger consumption of bio-diesel and ethanol in CSAM and greater penetration of plug-in cars in CAM and CLC.

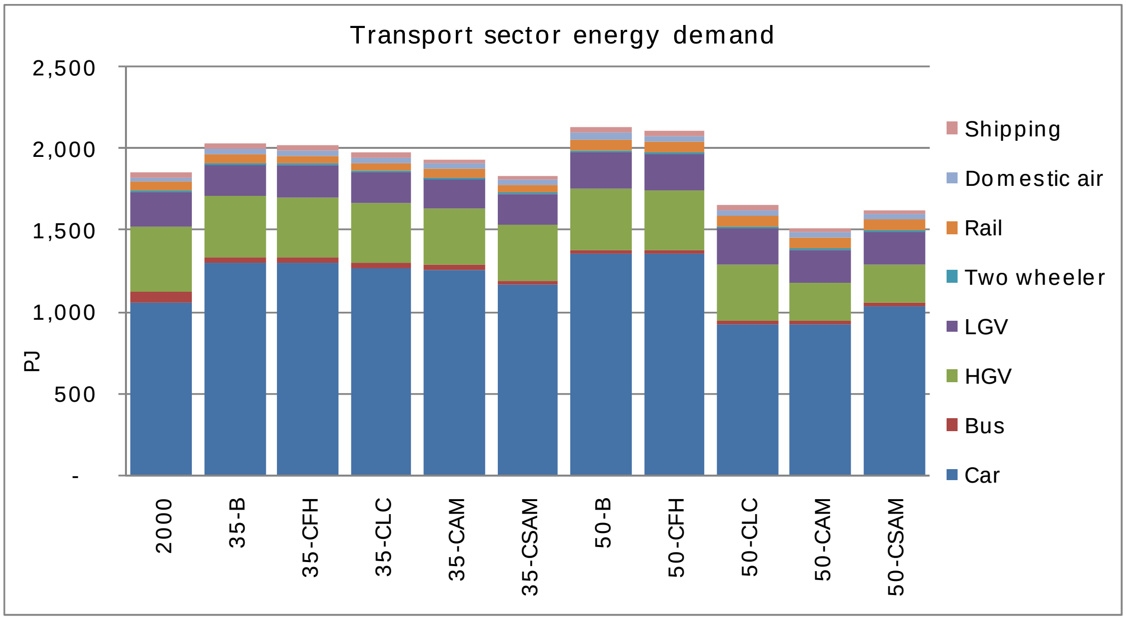

Figure 27: Transport sector energy demand by modes under different scenarios

With regard to the cumulative constraint scenarios, as expected early CO_2 reductions in CCSP mean relatively low transport energy in 2035 when compared to other scenarios (CAM, CEA, CCP) as shown in Figure 28. As in CAM, bio-diesel and/or ethanol decarbonises the transport sector in CEA and CCP, in addition to electric (hybrid) cars (petrol and diesel) and goods vehicles (HGV and LGV). Demands for bio-diesel and/or ethanol fuels are more or less proportional to the transport sector decarbonisation level (Figure 25 and Figure 6) while the demand for electricity stays more or less the same in CEA and CCP, in the range of 200-250 PJ in 2050. The transport sector also consumes a small amount of hydrogen in CAM (138 PJ), CEA (114 PJ) and CCP (136 PJ), mainly for HGV.

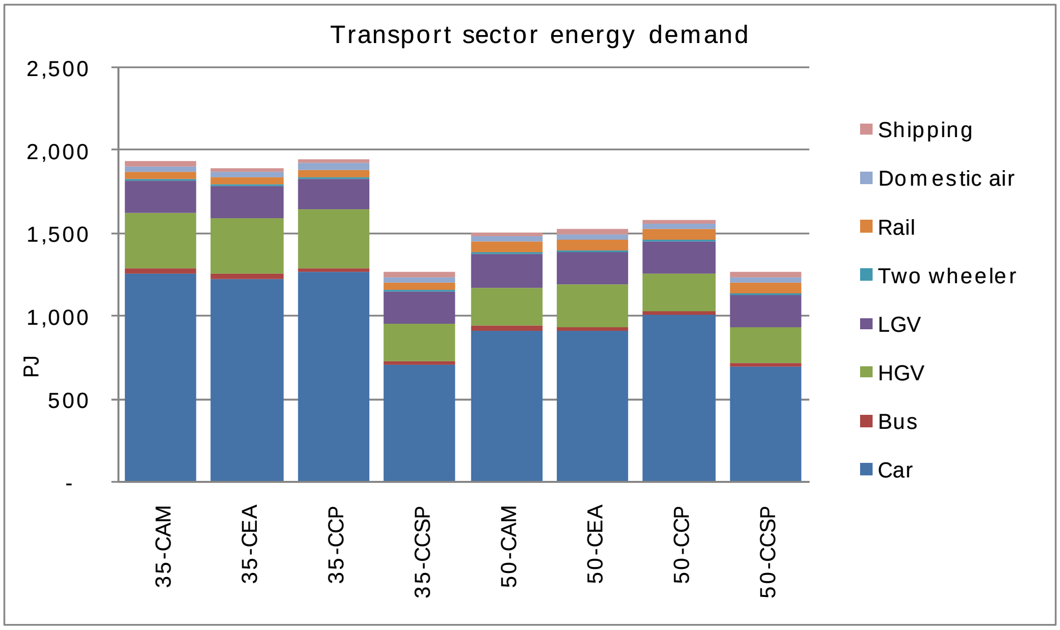

Figure 28: Transport sector energy demand by modes in CAM, CEA, CCP and CCSP

A large reduction in transport final energy occurs in CCSP, with a shift to hydrogen fuel cell vehicles replacing petrol and diesel vehicles especially in 2035. The CCSP scenario demands 218 PJ and 279 PJ of hydrogen in 2035 and 2050 respectively for goods vehicles, especially HGV. In addition to hydrogen, CCSP demands considerable electricity for the decarbonisation of the transport sector, amounting to 140 PJ in 2035 and 220 PJ in 2050. Interestingly, the level of energy service demand reduction level (Figure 21) is also relatively low for CCSP, especially in 2035 as compared to CEA, CAM and CCP, despite a greater CO2 mitigation, illustrating a key trade-off between energy service demand reductions, final energy reductions from higher efficiency vehicles and zero carbon transport fuels.

Battery buses have been picked up from 2030 in CEA, and in CCP - plug-ins from 2040, ethanol (E85) from 2035 and H_2 (HGV) from 2045. In CCSP, H2 and battery cars have been selected in 2050 and no ethanol cars have been selected. Battery buses and H_2 HGVs have been picked up from 2030. Battery and H_2 LGVs are selected in 2050 under CCSP. The diversity of different technologies in different runs indicates both the range of broadly competitive options in the transport sector, and the effect of the change in the discount rate, which also has a significant impact on economic costs (welfare and CO_2 marginal costs).

<u>Electricity Generation Technologies</u>

Electricity generation in B is mainly from coal, gas, nuclear and wind technologies. Small amounts of oil, hydro and bio-waste generations are also selected. Marine becomes cost effective from 2045. In terms of installed capacity, Figure 29 shows the Base reference (B) case by fuel type. Coal, nuclear and some of the gas power plants are defined as the base load plants, for the operation of which the model prescribes a fixed capacity utilisation for a particular season. The rest of the gas-based plants, wind, marine, bio-waste, storage and electricity imports are not base load technologies.

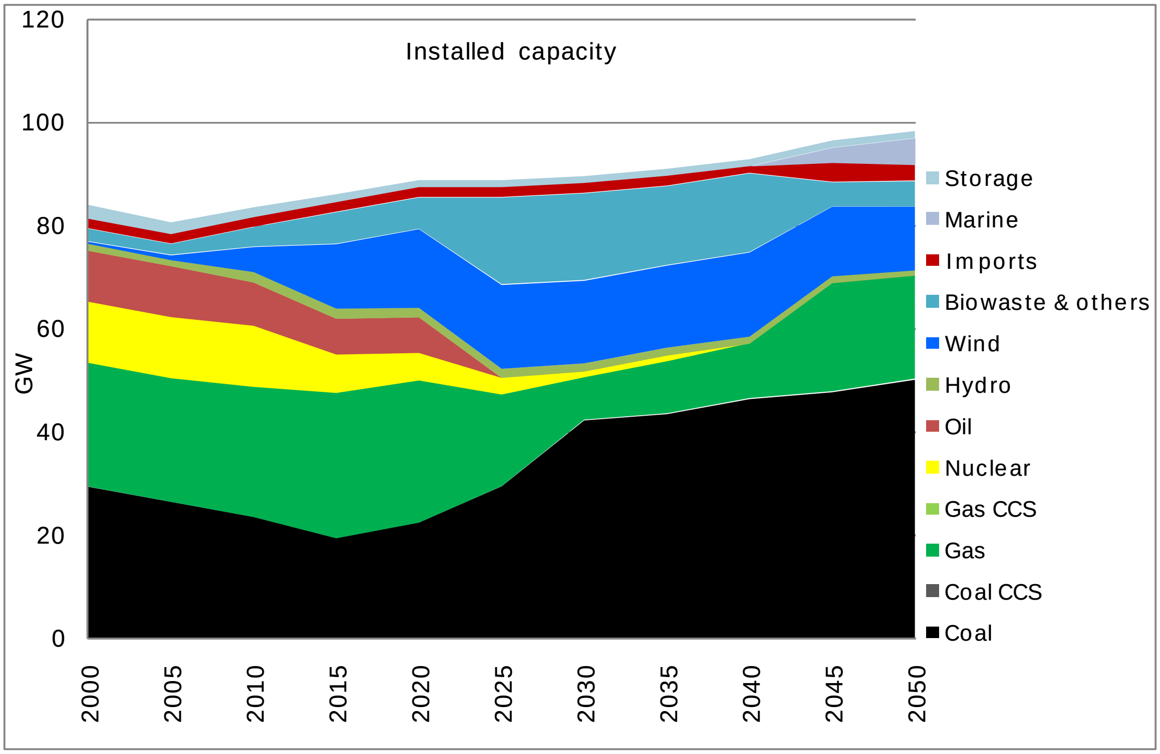

Figure 29: Installed capacity in the Base reference case during 2000-2050

Coal, nuclear and a small amount of gas-based power plants are selected for the base load generation in the Base reference case. Existing coal plants dominate in the early part of the projection period, accounting for 67% of installed base load capacity in 2020. Existing nuclear technologies (advanced gas cooled reactor, magnox reactor and PWR) are selected in the early years till they are retired. The share of nuclear plants in base load capacity decreases from 33% in 2010 to 2% in 2035 due to the retirement of the plants. Coal plants (pulverised fluidization technology) gradually replace the existing coal and nuclear power plants from 2020. Their capacity gradually increases from 17GW in 2020 to 50 GW in 2050. A growing capacity of gas turbine combine cycle (GTCC) plant is also selected to serve as base load installed capacity from about 1 GW in 2010 to 13GW in 2050. Existing GTCC (20.5 GW installed capacity in 2000), coal plants, and gas and oil fired steam turbines are utilized till they are retired as non-base load plants in the Base reference case. Gas turbine and gas engines are selected from 2010 and 2015 respectively for the non-base load gas plants. Wind, particularly on-shore wind, plays a major role for non-base load, with over 12 GW during 2015-2050. In the middle part of the period, a large quantity of sewage and landfill gas IC engines are also selected, their capacity increasing from 2.5 GW in 2015 to 13 GW in 2025. As the share of base load plants on total installed capacity is relatively high at the end of the projection period, the capacity of the sewage gas plants declines to 1 GW in 2050. Further, 3 GW and 5 GW of tidal stream are selected in 2045 and 2050 respectively. There is also a slight decrease in the wind capacity during the latter part of the projection period. A small amount of energy crops gasification and generation from municipal solid waste based steam turbines, agro-waste steam turbines and landfill gas IC engines are also selected in the Base reference case.

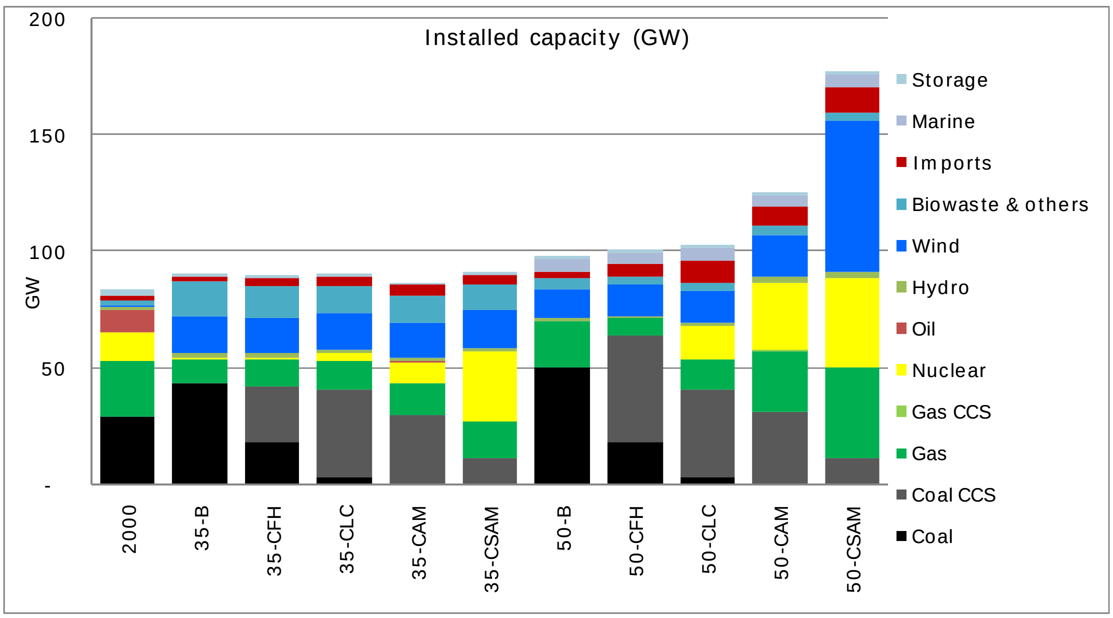

Figure 30: Installed capacity under different scenarios

When CO_2 emissions are increasingly constrained (CFH, CLC, CAM, CSAM), the UK MARKAL model strongly decarbonises the electricity sector, and there is a huge change in the capacity mix in the power sector (Figure 30). The decarbonisation of end-use sectors by means of shifting to electricity as well as selection of non-peak contributing plants, which needs reserve capacity, increases the installed capacity level in the mitigation scenarios particularly during the latter part of the projection period.

Though there are several available broadly competitive options including renewables, nuclear power and carbon capture and storage (CCS) associated with coal and gas-based fossil fuel power stations, decarbonisation of the power sector begins with the deployment of CCS for coal plants in 2020 in all mitigation scenarios (Figure 30), with non-CCS coal in 2035 only remaining in any quantity in CFH, with its relatively low mitigation target. Coal-CCS is the main technology to meet the mitigation target in CFH and CLC in the later period. Coal-CCS decreases with the increased CO_2 reduction target level in CAM and CSAM, as the carbon capture rate is only 90% (i.e., there are 10% residual emissions). Nuclear is selected at the cost of CCS to meet the carbon target in CAM. A large amount of wind is selected with the 90% target in 2050 of CSAM, together with a large capacity of back-up gas plants. The technology learning rate, which reduces the capital costs of technologies over the period, also affects the results, with as marine for example becoming cheaper and being selected in 2045 because of its relatively high learning rate.

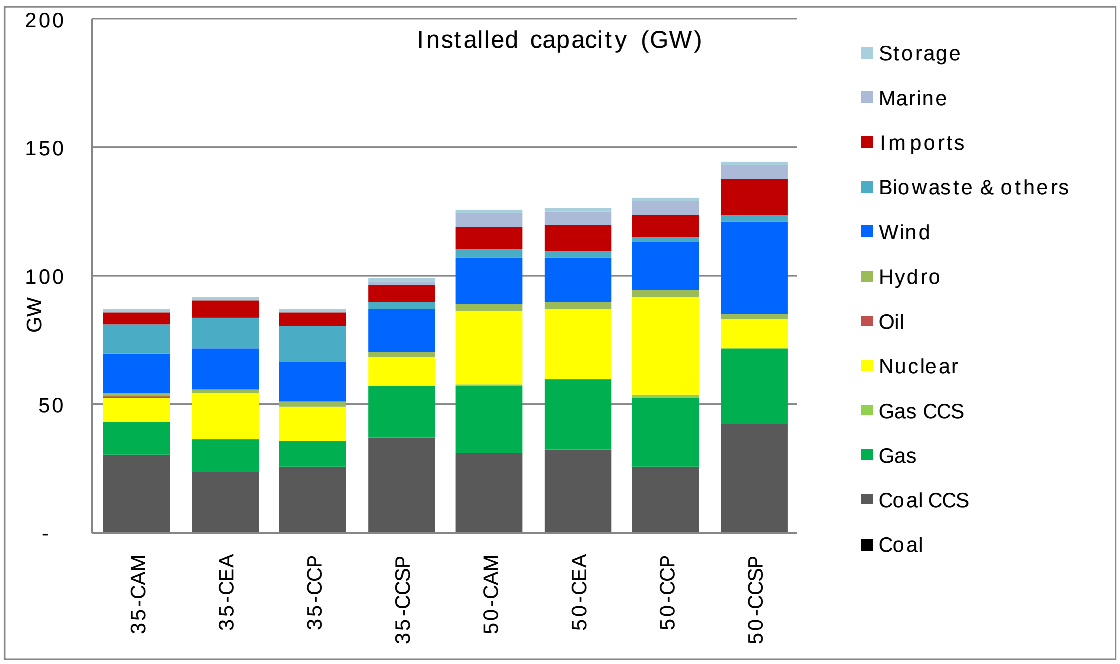

Figure 31: Installed capacity under CAM, CEA, CCP and CCSP scenarios

For the cumulative constraint runs (CCP and CCSP) the required capacities in 2050 show a similar pattern. The cumulative constraint run (CCP) with a very high 2050 decarbonisation (89%), shows lower electricity generation and capacity than CSAM owing to dynamic flexibility in selecting an electricity portfolio.

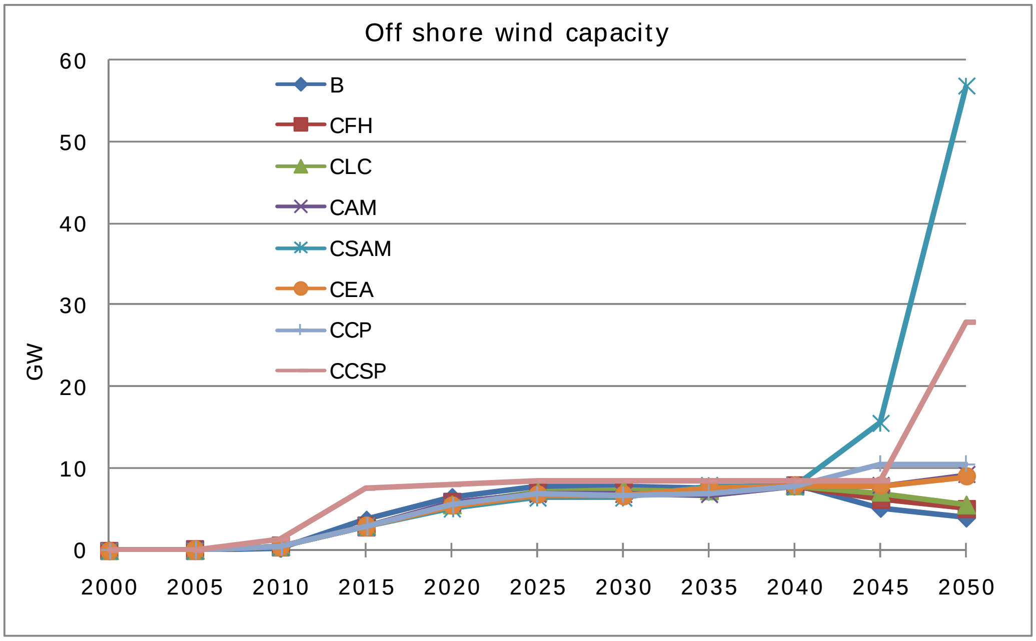

Figure 32: Off shore wind installed capacity under different scenarios

Onshore wind is selected to its full capacity in the Base reference case itself, while the deployment of off shore wind increases the wind capacity in the mitigation scenarios. Figure 32 presents the deployment of off-shore wind under different scenarios. As early action requires near competitive technologies (and also as the social discount rate prefers capital-intensive technology), a large amount of off-shore wind is selected particularly in 2050 reaching 28GW in CCSP, and 57GW in the 90% CSAM scenario case. When UK MARKAL selects more and more wind it has to increase the capacity of back up plants for peak generation as the capacity utilisation for the peak load is reduced. The back-up plants are mainly gas based GTCC.

4. Insights and Conclusions

Before seeking to derive insights and conclusions from the scenarios, or considering what policies might be required to produce or approximate their outcomes, to avoid misunderstanding it is worth summarising again how the scenarios themselves have been generated. Each scenario is the result of a whole range of assumptions about the costs of the different energy technologies and infrastructures, and when they might be available, plus a number of constraints to reflect the current configuration of the UK energy system and the policies relating to it that have already been implemented. For the scenarios in this report the only variables that have been changed are the carbon reduction targets (for the CFH, CLC, CAM and CSAM scenarios these are 40, 60, 80 and 90% from 1990's level by 2050 respectively), and the emission reduction pathway for a certain cumulative carbon emissions total to 2050 (for the CEA, CCP and CCSP scenarios), by either specifying some early emission reduction (CEA) or changing the discount rate (CCSP). Given these assumptions and constraints the model then derives the energy system that has the lowest energy system cost.

There are two major sets of issues which mean that the scenario runs are unlikely to represent the real evolution of the UK energy system to 2050. The first is to do with the inherent uncertainty around the costs and other parameters relating to the technologies in the model. We simply do not know and cannot know how these will develop over the next four decades. The numbers in the model are expert estimates, validated by peer review, but they are still very uncertain. One of the major uses of the model is to do sensitivity analyses around these numbers (i.e. change the numbers relating to one or more technology in a plausible way, and see how this affects the scenario outcomes). Such sensitivity analyses are undertaken and reported in other reports from the Energy 2050 project.

The second set of issues derives from the fact that the model's optimisation procedure implies that, given the assumptions and constraints, decision makers in the energy system have perfect foresight of events and developments through to 2050, they take decisions based only on market criteria, and markets work perfectly. Of course this is not the case in the real world.

It should therefore be clear that in no sense are any of the scenarios, even the Base reference case, predictions of what will happen if carbon constraints are applied with different levels of stringency. Instead they are quantitative aids to thought and analysis of different possible developments in the energy system given concerns to reduce carbon emissions from it. Generating such insights is the reason for undertaking energy systems modelling as in this report.

4.1. Insights from Carbon Ambition pathways

The set of Carbon Ambition scenarios (40%, 60%, 80% and 90% reductions from 1990 levels by 2050) offer insights on decarbonisation pathways, sectoral-technology-behavioural trade-offs, and resultant cost implications.

In the base reference case (B), if new policies/measures are not taken, base case CO_2 emissions in 2050 would be 584 MtCO2: 6% higher than 2000 levels and 1% lower than 1990 levels. Existing (as of 2007) policies and technologies would bring down emissions in 2020 to about 500 $MtCO_2$ - a 15% reduction. However this would be considerably higher than the government target range of 26-32% reductions 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.

Under decarbonisation pathways, the power sector is a key sector, where decarbonisation occurs early. This early electricity decarbonisation (combined with end-use conservation measures) reflects low cost opportunities led in these scenarios by coal-CCS technologies, However it is stressed that in model experiments there is considerable uncertainty over the dominant player in any optimal technology portfolio of CCS vs. nuclear vs. wind, due to the close marginal costs and future uncertainties in these technology classes. Specifically, when examining the investment marginal costs when CCS technologies are the optimal value, across the scenarios from 2030-2050 further tranches of offshore wind would be competitive with a cost improvement of between $56 - £260/kWe installed - this represents only 5-25% of capital costs. Nuclear's marginal investment costs are even closer to CCS, at between $2 and 218/kWe installed, depending on scenario and time period. Note that electricity system operation and wider energy system tradeoffs will also influence the optimal uptake of these technologies.

Decarbonisation of the power sector begins with the deployment of CCS for coal plants in 2020-2025 in all mitigation scenarios. 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 (CCGT) as reserve capacity. Import electricity is also selected for reserve margins, with waste generation (landfill and sewage gas plants) contributing to the generation portfolio. Under stringent CO_2 reduction scenarios, zero carbon electricity is rounded out by 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. Note that as emissions targets tighten, final energy use falls in 2050 from around 6,500 PJ in the base case to around 4,500 PJ, Upon reaching this level decarbonisation measures that do not reduces energy use continue to be implemented.

Decarbonisation remains foremost in the power sector till middle or end of the planning horizon depending on the stringency of the target, then major efforts switch to the residential and transport sector. The exception to this is in the 90% CSAM case where transport and residential sectors must be heavily decarbonised by 2035. By 2050, to meet the 80% target in CAM, the power sector emissions are reduced by 93% compared to the base case. The reduction figures for the residential, transport, services and industrial sectors are 92%, 78%, 47% and 26% respectively. Hence residual CO_2 emissions are concentrated in selected industrial sectors, and in transport modes (especially aviation).

In 2035, overall electricity generation declines (while decarbonising) with target stringency owning to the role of early end-use efficiency and demand changes. 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 base level 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 major 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 transport) utilize plug-in vehicles and then ethanol (E85). Buses switch to electric battery options. Goods vehicles (HGV and LGV) switch to bio-diesel then hydrogen (only for HGV).

These least cost optimal model scenarios does not produce decarbonisation scenarios that are compatible with the EU's draft renewables directive of at least 15% of UK final energy from renewables by 2020. Major contributions of bio-fuels in transport and offshore wind increases in electricity production only occur in later periods following tightening CO_2 targets and advanced technology learning.

Besides efficiency and fuel switching (and technology shifting), the elasticity (demand reduction) is 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 that of air, car and HGV (heavy good vehicles) in transport sectors. This is driven both by the elasticities in these sectors but crucially by the existence of alternate (lower cost) technological options. The interpretation of significant energy service reductions (up to 25%) in key industrial and buildings sectors implies employment and social policy consequences that need further consideration.

Higher target levels (CFH to CLC to CAM to CSAM), produce a deeper array of mitigation options (likely with more uncertainty). Hence the Carbon Ambition runs produce a very wide range of economic impacts, with CO_2 marginal costs in 2035 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.

Welfare costs (sum of producer and consumer surplus) in 2050 range from £5 - £52 billion. In particular moving from a 60% to an 80% reduction scenario almost doubles welfare costs (from £20 - £39 billion. Note that welfare cost is a marked improvement on energy systems cost as an economic impact measure as it captures the lost utility from the consumption of energy. However it cannot be compared to a GDP cost as wider investment, trade and government spending impacts are not accounted for.

Overall however, the Carbon Ambition runs follow similar routes, with additional technologies and measures being required and targets become more stringent and costs rapidly increase. For dynamic path dependence in decarbonisation pathways, we focus next on the range of sensitivity runs under 80% CO_2 reduction constraints.

4.2. Insights from 80% reduction sensitivity runs

Giving the model freedom to choose timing of reductions under a cumulative constraint illustrates inter-temporal trade-offs in decarbonisation pathways. Under a cumulative constraint (CCP) the model chooses to delay mitigation options, with this later action resulting in CO_2 reductions of 32% in 2020 and up to 89% in 2050. This results in very high marginal CO_2 costs in 2050, at £360/tCO_2 higher even that the conventional 90% reduction case.

Conversely, 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, effort is placed on alternate sectors (transport instead of power), alternate resources (wind as early nuclear technologies are less cost competitive), and increased near-term demand reductions.

Within the CCSP transport sector the broadest changes are seen with bio-fuel options not being commercialized in mid-periods. Instead the model relies on much increased diffusion of electric hybrid plug-in and hydrogen vehicles (with hydrogen generated from electrolysis). As hydrogen and electric vehicles dominate the transport mix by 2050, this has resultant impacts of the power sector with vehicles being recharged during low demand (night time). Note that the selection of these highly efficient by high capital cost vehicles is strongly dependant on assumptions on lowered discount and technology specific hurdle rates.

The inter-temporal trade-off extends to demand reductions where 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 as the model place more weight on late-period demand welfare losses except residential sector (electricity and gas energy services demand). In terms of early demand reductions for CCSP, this is seen in residential electricity and gas energy services demands where demands are sharply reduced as an alternative to (relatively expensive) power sector decarbonisation.

In terms of welfare costs, the flexibility in the CCP case gives lower cumulative costs than the equivalent CEA scenario with cumulative CO_2 reductions. The fact that the CCSP run produces the lowest costs is a reflection of the optimal solution under social levels of discounting (and correspondingly reduced technology-specific hurdle rates). The implied methodology of this is that consumer preferences change and/or government works to remove uncertainty, information gaps and other non-price barriers.

4.3. Policy discussion of the scenarios

In the model the carbon constraint is simply imposed and the model computes the least-cost energy system configuration. In real life the carbon constraint has to be imposed through public policy at different levels, from global through national to different local levels, the outcomes from which are as uncertain as the assumptions in the models. The policy discussion that follows is intended just to give an idea of the sorts of policies that might cause the energy system to develop in the directions illustrated by the various scenarios. Because of the uncertainties of outcome, policy implementation should be an iterative process characterised by learning at every stage. Over the kinds of periods of these scenarios, policy makers do not know the outcomes of their policies. They can only monitor them over time, and adjust the policies if they do not appear to be delivering the intended results, or are not delivering them at the pace intended.

4.3.1. UK energy and carbon policy instruments

In the UK over the past ten years there has been enormous policy innovation and experimentation in relation to the energy system and, especially, the carbon emissions produced by it. The most recent expression of this innovation was the setting up in 2008 of the independent Committee on Climate Change (CCC), and the passing of the Climate Change Bill, which imposed on the UK Government the statutory obligation to achieve the emission reduction target in the Bill (an 80% reduction of GHG emissions from 1990's level by 2050) and the five-year carbon budgets leading up to 2050, which would be set by the CCC. The challenge facing the Government is now to use the experience of carbon reduction policies it has acquired over the past decade to put in place the policies that will achieve the carbon reduction targets.

The Stern Review (Stern 2006, p.349) considered that a policy framework for carbon reduction should have three elements: carbon pricing (for example, through carbon taxes or emission trading); technology policy (to promote the development and dissemination of both low-carbon energy sources and high-efficiency end-use appliances/buildings); and the removal of barriers to behaviour change (to promote the take-up of new technologies and high-efficiency end-use options, and low-energy/low-carbon behaviours).

A major policy uncertainty is the extent to which behaviour in different sectors responds to changes in price, in the short and long term, and therefore the extent to which carbon pricing needs to be supplemented by the second and third policy elements. As noted above, the MED model simply assumes different elasticities (derived from the literature) for these responses to price, but in reality the size of these is uncertain, nor is it clear that they will not change over time. In this connection, it will be interesting to see to what extent especially motoring behaviour changed in response to the oil price increases of the past two years.

As discussed in Section 1.2, environmental policies may be categorised as economic instruments (including those which price carbon), regulation, voluntary agreements and information. In relation to climate change mitigation, one major objective of these policies is the decarbonisation of energy supply, including electricity (through the use of renewables, nuclear power and carbon capture and storage [CCS]), heat (through the use of low-carbon biomass or low-carbon electricity), transport fuels (through the use of low-carbon bio-fuels, low-carbon electricity, and low-carbon hydrogen), and the increased efficiency of energy generation for power, heat, and mobility (through CHP, heat pumps, power generation, road fuels). A key requirement of policies in this area is their ability to mobilise very large investment from the private sector, given that the investments required are well outside the level which can be financed by governments alone. For example, IEA (2008a, pp.41-43) estimates that, in its low-carbon scenario, the extra (global) investment requirements (i.e. over and above the investment in the global energy system that would be necessary if carbon were of no concern) are USD 7.4 trillion in buildings and appliances, USD 3.6 trillion for the power sector, USD 33 trillion in the transport sector and USD 2.5 trillion in industry. These are enormous numbers, which make climate change mitigation easily the largest public policy thrust ever attempted, in terms of its direct economic impacts.

The policy instruments that are available to government to achieve the objective of decarbonising energy supply are carbon pricing (e.g. carbon tax, emissions trading); price support for low-carbon technologies (for example, feed-in tariff/premium, obligation/quota with tradable certificate); investment support, such as through capital grants, Enhanced Capital Allowances or tax credits); the removal of barriers to the deployment of low-carbon technologies, such as ensuring access to infrastructure (e.g. transmission, grid connection); timely planning, regulation and licensing procedures; availability of skills; simple administrative requirements; and public funding or co-funding of research, development and demonstration of the whole range of low-carbon technologies.

In its analysis of policies for deploying renewable, IEA (2008b, p.23) identified a number of principles for successful policies for renewable support, namely: removal of non-economic barriers (relating to administrative hurdles, planning, grid access, skills, social acceptance); predictable, transparent policy framework to support investment; technology-specific incentives based on technological maturity; transition incentives to foster innovation and move technologies towards competitiveness; due consideration of system considerations (e.g. penetration of intermittent renewables). In addition, for effective deployment each technology that was not yet competitive on the energy market needed to receive a minimum level of remuneration, which varied with the technology, through the policy framework (for onshore wind and biomass electricity, which are among the renewable closest to market, this was USD 0.07-08/kWh [IEA 2008b, pp.100, 109]).

In addition to decarbonising energy supply, policy may seek to manage energy demand, using instruments such as carbon rationing (Personal Carbon Allowances, emission trading), carbon pricing (for example carbon taxation or environmental tax reform), subsidies or tax reductions for low-carbon behaviours, or a wide range of regulations, voluntary agreements, or information instruments, of which some examples for the UK are given below.

The UK has deployed a very wide range of policy instruments of different kinds over the last ten years, developed through and discussed in two Climate Change Programme (DETR 1990, HMG 2006), two Energy White Papers (DTI 2003, 2007), two Energy Reviews (PIU 2002, DTI 2006) and the many consultation papers that preceded them.

There have been a number of economic instruments, illustrating the importance of resource and emission prices as drivers of efficient resource use, and emission and waste reduction. These have included;

- The climate change levy (an energy tax on business, which in 2005 was forecast to reduce carbon emissions by 3.5 $MtCO_2$ by 2010 [HMT 2005, p.171]),
- Fuel taxes (Sterner [2007, p.3201] estimates that the difference in fuel taxes between Europe and the USA, which results in European consumer prices of road fuels being about three times higher than those in the US, has resulted in European CO_2 emissions from road fuels being about half what they would be at the US price. The average new car fuel efficiency in Europe is also about 25-50% better than the US [EEA, 2005]).
- Emissions trading, including the UK Emissions Trading Scheme (ETS), which operated from 2002-2006[20], the EU ETS for energy-intensive industry, Phase 2 of which began in 2007, and the Carbon Reduction Commitment (CRC)[21] for large business and public sector organisations, which will begin operation in 2009.

Regulatory climate policy instruments have included:

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[20] See http://www.defra.gov.uk/Environment/climatechange/trading/uk/index.htm
[21] See http://www.defra.gov.uk/environment/climatechange/uk/business/crc/index.htm

- The Renewable Obligation (RO), the target for which is 15% of UK electricity generation by 2015. However, it is behind its current target, so there must be some doubt as to whether it will achieve this. IEA (2008b, p.17) found that for onshore wind, the RO had proved substantially more expensive per unit of generation deployed, and been significantly less successful in deploying capacity, than the feed-in tariffs in a number of other countries, indicating the importance in the UK of non-economic barriers to deployment.
- The Energy Efficiency Commitment (EEC), now called the Carbon Emissions Reduction Target, which is an obligation on suppliers to reduce carbon emissions (or energy use in EEC) from their customers' homes
- Warm Front and Warm Zones, two schemes for installing subsidised energy efficiency measures, especially in the homes of relatively poor people.
- Building Regulations for new buildings, which are intended to reduce carbon emissions from new homes, such that by 2016 new homes will be 'zero carbon'.

Voluntary agreements have included:

- Climate change agreements, which were estimated to have reduced carbon emissions by 4.5 million tonnes of carbon in their first target period of 2001-03 (HMT 2005, p.171)
- EU fuel efficiency agreements for new vehicles. Because the target fuel efficiency improvements have not been met, the new targets currently under negotiation will be mandatory

The principal information policy in the UK is related to labelling, which is now required for a wide variety of white goods and, most recently, vehicles and buildings. Figure 33 (Source: Lees, 2006) shows how this has worked for fridge freezers, with the most efficient A-rated fridge freezers increasing to around 80% of the market over a period of about five years.

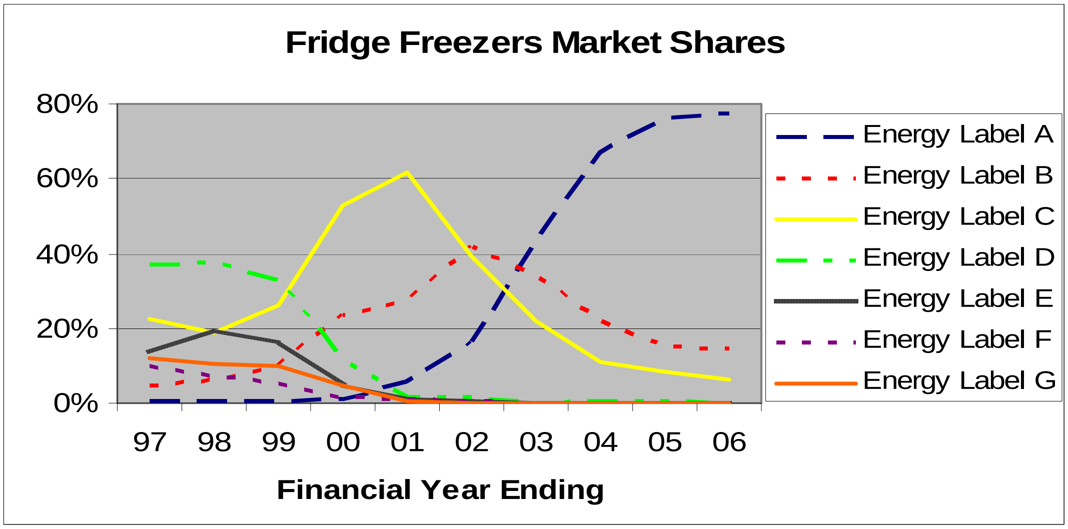

Figure 33: Development of the fridge freezer market by energy rating to September 2005

Labels (Energy Performance Certificates) have recently been introduced for homes, and there are ongoing trials of so-called 'smart meters' which give consumers real-time information about their energy consumption.

Finally, many climate policies are implemented in 'policy packages' of policy measures affecting different actors, with such names as Market Transformation[22], which includes EU energy labelling; marketing campaigns (e.g. Energy Efficiency Recommended branding and advertising) by the Government and its agencies (e.g. Energy Saving Trust [EST]); consumer advice from Energy Efficiency Advice Centres; media coverage on climate change; retail staff training and point of sale material from the EST; EU Minimum Performance Standards; EEC funding for incentives for consumers to purchase the energy-efficient models; or EU Integrated Product Policy, which includes Sustainable Consumption and Production (itself a package of different policy approaches, state aid, voluntary agreements, standardisation, environmental management systems, eco-design, labelling and product declarations, greening public procurement, encouragement of green technology, and legislation in areas including waste and chemicals.[23]

There has therefore been huge innovation in climate policy over the last ten years. These are the kinds of policies which will have to be applied to achieve the targets underlying the

[22] See http://www.mtprog.com/
[23] See http://ec.europa.eu/environment/ipp/

various scenarios described in the previous section. However, these policies have so far yielded limited results. As noted above, it is estimated that the Government will miss its 2010 target of a 20% reduction in carbon emissions from 1990's level by quite a large margin. It seems likely that while the policies have been innovative, they have not been applied stringently enough and, no doubt, some barriers to policy effectiveness have still not been identified and tackled. Moreover, many climate policies (for example, Building Regulations) need local implementation/enforcement, which may not always be effective (see EST 2004 for Building Regulations).

4.3.2. Application of energy demand policies to MED model scenarios

Reductions in energy service demands in MARKAL-MED result from the rising price of carbon as carbon emissions are reduced towards the targets in 2050. Appendix A1 shows that this price in 2050 ranges from £19.5-299/tCO_2 as the target reductions increase from 40-90% in CFH through to CSAM. 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 (and therefore having to cut 2050 emissions by 89%), although in terms of total discounted energy system cost this is the lower-cost scenario than CEA, the early action scenario. Not surprisingly the final energy demands decrease with the reduced energy service demands associated with rising carbon target reductions (i.e. through CFH, CLC and CAM), but are very similar for the scenarios with an 80% reduction target and the same discount rate (CAM, CEA, CCP)

In policy terms the implication of these scenarios is that these energy service demand reductions have been incentivised through a carbon tax or carbon rationing (and trading) scheme (other routes to behaviour change are being considered in another Energy 2050 report), the tax being applied at a rate, or the trading scheme delivering a carbon price, at the level of the marginal cost of CO_2 abatement in the model. For comparison, it may be noted that at current rates of the Climate Change Levy (0.46p/kWh for electricity, 0.16p/kWh for gas and 1.24p/kWh for coal), this 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 is currently (i.e. in 2008) about 50p/l. If this is all considered as an implicit carbon tax (i.e. ignoring any other environmental consequences of road travel which the duty may be considered to seek to account for), this amounts to about £208/tCO_2[24]. 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 other fuels would need taxes to have been imposed taxes at about the current fuel duty rate at 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 former result in energy savings without using energy themselves, e.g. building insulation, while the latter cause appliances, for example, to use energy more efficiently). Except in the service sector, the increased uptake of conservation measures in these runs are taken from the UKDCM model, rather than computed directly by MARKAL. In the service sector, conservation measures save 151 and 172 PJ in the CAM and CSAM runs respectively, compared to 64 and 135 PJ in the Base and CFH respectively. The relatively high uptake of the measures in CFH 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 the conservation measures.

The uptake of efficiency technologies in buildings is again taken from UKDCM, with the major exception of space and water heating applications. One MED model example here is heat pumps, which play a major role in all the 80% and 90% carbon reduction scenarios, as seen in Figure 27. 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, where there is significant deployment of heat pumps from 2025, 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 (although MARKAL only

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[24] The CO_2 emission factors used for these calculations may be found at http://www.carbontrust.co.uk/resource/conversion_factors/default.htm. See the Appendix B.

distinguishes between differently fuelled vehicles, rather than vehicles of the same type [e.g. petrol ICEs] with different energy efficiency – improved vehicle efficiency within types has to be imposed exogenously as part of the technology characterisation). Energy service demands in the transport sector in 2050 are not greatly reduced as the carbon targets become more stringent (falling from about 890 bv-km in the Base to about 842 bv-km in CAM and 840 bv-km in CSAM), but the energy demand required to meet those energy service demands falls by considerably more, from 2130 PJ in the Base to 1511 in CAM (but 1656 PJ in CSAM, due to its larger consumption of bio-diesel and ethanol, as explained above). This means that the efficiency of fuel use has improved from 0.42 v-km/MJ in the Base to 0.56 v-km/MJ in CAM. Even more dramatic, however, is the improvement in the Base over the year 2000 efficiency, which was only 0.26 v-km/MJ. This was due to the large take-up in the Base of HGV diesel/biodiesel hybrids (this switch from HGV diesel/biodiesel to HGV diesel/biodiesel hybrids results in an efficiency improvement in 2050 from 0.08 to 0.14 v-km/MJ), and LGV battery-electric vehicles (BVs) and petrol plug-ins, as well as improving energy efficiency across the vehicle fleet (for example, the efficiency of diesel/biodiesel ICE cars, which are taken up in all the scenarios, improves from 0.37 v-km/MJ in the year 2000 to 0.51 v-km/MJ in the Base in 2050). The development of these new vehicle types, and of more efficient existing vehicle types, will be partly incentivised by the carbon price, but 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. Such policies will be even more required to incentivise the development and take-up of the petrol plug-in and E85 cars, and the hydrogen HGVs (which have an efficiency of 0.25 v-km/MJ, nearly twice as efficient as the HGV diesel/biodiesel hybrids they largely replace), that make an appearance in 2050 in the most stringent carbon reduction scenarios, CAM and CSAM.

4.3.3. Application of energy supply policies to MED model scenarios

These model runs reveal the single most important policy priority to be to incentivise the effective decarbonisation of the electricity system, because low-carbon electricity can then assist with the decarbonisation of other sectors, especially the transport and household sectors. In all the 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 (as explained above, 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 as soon as possible. The European Commission has an intention to establish a mechanism to stimulate the construction and operation by 2015 of up to 12 CCS demonstration plants, so that commercial CCS can be deployed from 2020 (as the MARKAL model currently assumes). However, the required mechanism has yet to be agreed, nor has the source been identified of the very considerable funds that will be required. The timescale for CCS deployment by 2020 is therefore beginning to look extremely tight, some would say infeasible, even if no large problems are uncovered during the demonstration process, which is by no means assured. The availability and uptake of CCS as projected by the model runs are therefore optimistic.

The UK Government is not proposing to build new nuclear power stations itself, but believes that energy companies should be able to with appropriate public safeguards (BERR 2008b). The Government is therefore proposing a number of measures to “reduce the regulatory and planning risk associated with investing in nuclear power stations” (BERR 2008b, p.124), without planning either to invest in new nuclear power stations or to give subsidies to those who do. The Government acknowledges that it is uncertain whether these measures will actually bring forward proposals for new nuclear power stations, because this would be a private investment decision dependent on such issues as “the underlying costs of new investments, expectations of future electricity, fuel and carbon prices, expected closures of existing power stations and the development time for new power stations” (BERR 2008b, p.129). These are all matters of considerable uncertainty. The scenarios envisage that only in CSAM has very significant investment in new nuclear plant (30 GW) taken place by 2035 (this would be equivalent to a new 3 GW power station opening every year from about 2025), with 9 GW projected in CAM, and 4GW in CLC by that date. It is probable that the 2035 carbon prices in these scenarios (£37, £97 and £133/tCO_2 in CLC, CAM and CSAM respectively) would provide the kind of price required for these investments, provided that the new generation of nuclear plant is economically and technically proven by about 2015.

This cannot be taken for granted, but seems rather more likely than the very challenging timetable for CCS to make its projected contribution in the model runs.

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 in order 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 by assumption (that the target set by the Renewables Obligation is met), otherwise the model would not choose renewable electricity to this level. Now Renewables Obligation (RO) targets have so far not been met – renewable generation (accounted against the RO) in 2007 was 4.9% (BERR 2008c, p.29) against a target for 2007-08 of 7.9%[25], a shortfall of 38%. While the RO has recently been reviewed and technology 'banding' been introduced in order to increase the incentive to install some technologies, the extent to which this will increase installation is uncertain.

Even with 15% renewable electricity in the MARKAL model runs, the maximum share of renewables in final energy demand (which also includes non-electricity energy consumed for transport and heat), 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. The UK Government launched a consultation in June 2008 on how the new EU targets might be achieved, recognising that new policies would need to increase the share of renewables in final energy demand by a factor of three over what current policies (already considered ambitious at the time they were introduced) were designed to achieve (BERR, 2008d, p.5).

For the UK the renewable potential to 2020 totals about 400 TWh (IEA 2008b, p.67), of which the largest components are from onshore wind (28.5 TWh), offshore wind (67 TWh), biomass for electricity (20.7 TWh) and heat (49.5 TWh), biogas (16.3 TWh), marine (58.9 TWh, from tide and wave energy), bio-fuels (domestic, 25.4 TWh), solar thermal (56.1

[25] See Ofgem Press Release 'The Renewables Obligation Buy-Out Fund (2007-2008)', October 7, 2008, http://www.ofgem.gov.uk/Pages/MoreInformation.aspx?docid=210&refer=Media/PressRel

TWh) and geothermal heat (53.7 TWh). This amounts to about 21% of the UK's projected final energy demand in 2020, so that nearly three quarters (or about 280 TWh) of this will need to exploited by 2020 if the UK is to meet its EU target of 15% of renewables in final energy demand by that date.

The BERR (2008d) consultation paper suggests a number of policies to seek to meet the 15% renewable target, including the incentivisation of renewable heat, financial support for small-scale heat and power technologies in buildings, reform of the planning system and ensuring grid access for new renewables, making full use of waste for energy and deploying bio-fuels in transport, as well as encouraging the development of electric vehicles. This is not the place to go into detail about these proposals or assess their prospects for delivering the target, not least because they are at this stage for consultation only. However, it is worth noting that the slow development of UK renewables to date, especially onshore wind, has been due to such issues as planning and grid access problems, rather than the level of remuneration, which is higher than in some other European countries that have achieved considerably greater deployment (IEA 2008b, p.105). These 'non-economic' problems are not likely to be easy to resolve.

If the UK succeeds in meeting the 15% EU renewables target, then it will be very well placed to exceed the renewables projections in the MARKAL scenarios. For example, renewable electricity in CAM in 2050 is projected to be only 16% of total electricity. However, if this share was already 35% in 2020, then it is likely that this will at least have been maintained, potentially allowing 380 TWh of renewable electricity to substitute for some other low-carbon source, for example nuclear or coal CCS. In CSAM renewable electricity is 39% of generation in 2050. If 35% had already been achieved by 2020, this seems an eminently feasible projection. In short, while the 2020 EU renewables target is extremely challenging, if it could be achieved, it would make the later carbon reduction targets seem much less daunting.

The policy analysis here has focused on the scenarios with increasing carbon targets. The only 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 uniquely takes up petrol hybrid and battery cars, and prefers battery and hydrogen LGVs to LGV diesel/biodiesel plug-ins, so that its use of bio-fuels is very small, in contrast to CCP, which makes much more use than any other scenario except CSAM of diesel/biodiesel

ICE cars. CCP also uses a very large amount of pellets for heating in the service sector, over as twice as much as in CAM, while CCSP uses practically none. Of course, not too much should be read into these specific differences. Rather their policy message 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 ensure that the full range of technologies has the opportunity to develop.

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Appendix A: Full UK MED Scenario Results

A1: Detailed results on Carbon Ambition Scenarios

B	**Base reference**	
CFH	**Faint-heart**	15% by 2020 ; 40% by 2050
CLC	**Low carbon reference**	26% by 2020 ; 60% by 2050
CAM	**Ambition**	26% by 2020 ; 80% by 2050
CEA	**Early action**	32% by 2020 ; 80% by 2050
CSAM	**Super Ambition**	32% by 2020 ; 90% by 2050

Primary Energy Demand (PJ)

	2000	35-B	35-CFH	35-CLC	35-CAM	35-CSAM	50-B	50-CFH	50-CLC	50-CAM	50-CSAM
Renewable electricity	20	187	183	183	178	191	203	208	226	284	843
Biomass and waste	121	263	299	316	618	1,089	252	301	611	1142	1724
Natural Gas	3,907	2,616	2,546	2,459	2,335	1,807	2,435	2317	2007	1170	573
Oil	3,039	2,403	2,361	2,311	2,022	1,363	2,165	2116	1295	386	137
Refined oil	-298	-193	-210	-235	-217	-200	0	0	0	128	175
Coal	1,500	2,762	2,708	2,593	1,848	747	3,156	3186	2396	1888	528
Nuclear electricity	282	31	31	93	245	790	-	0	375	764	1004
Imported electricity	52	9	63	88	88	88	32	103	103	103	103
Hydrogen	-	-	-	-	-	-	-	0	0	0	0
Total	**8,624**	**8,077**	**7,979**	**7,807**	**7,117**	**5,874**	**8,243**	**8230**	**7012**	**5864**	**5087**

Final Energy demand by fuel (PJ)

	2000	35-B	35-CFH	35-CLC	35-CAM	35-CSAM	50-B	50-CFH	50-CLC	50-CAM	50-CSAM
Electricity	1,176	1,377	1,303	1,272	1,234	1,341	1,479	1407	1517	1632	1865
Fuel oil	220	119	99	99	95	93	86	84	82	78	76
LPG	52	22	24	-	-	-	11	12	0	0	0
Gas	2,391	2,444	2,376	2,291	2,170	1,660	2,381	2263	1954	1148	578
Coal	75	158	152	154	2	2	218	234	125	2	2
Petrol	872	963	943	919	784	507	1,031	1008	589	311	230
Diesel	1,164	950	930	907	792	465	897	874	529	103	49
Jet fuel	30	39	39	38	36	35	37	37	35	34	34
Hydrogen	-	6	-	-	-	-	26	5	0	138	139
Ethanol/Methanol	-	32	62	62	232	389	32	66	236	393	393
Bio diesels	-	42	41	40	73	390	39	38	46	338	646

Manufactured fuel	75	23	3	3	3	3	25	3	3	3	3
Biomass	28	44	51	60	148	59	62	77	157	176	403
Heat	105	147	136	115	26	29	131	94	31	19	18
Others	-	-	-	-	-	-	-	0	0	0	0
Total	**6,189**	**6,367**	**6,159**	**5,960**	**5,594**	**4,972**	**6,455**	**6203**	**5304**	**4374**	**4434**

Final Energy demand by Sector (PJ)

	2000	35-B	35-CFH	35-CLC	35-CAM	35-CSAM	50-B	50-CFH	50-CLC	50-CAM	50-CSAM
Agriculture	51	61	59	54	48	47	67	63	54	49	44
Industry	1,473	1,516	1,456	1,422	1,321	1,274	1,538	1480	1368	1276	1209
Residential	1,961	1,979	1,927	1,838	1,666	1,233	1,920	1836	1582	891	832
Services	850	778	696	668	624	583	801	711	647	647	692
Transport	1,855	2,034	2,022	1,978	1,935	1,835	2,130	2112	1653	1511	1622
Total	**6,189**	**6,367**	**6,159**	**5,960**	**5,594**	**4,972**	**6,455**	**6203**	**5304**	**4374**	**4400**

Use of conservation (PJ)

	2000	35-B	35-CFH	35-CLC	35-CAM	35-CSAM	50-B	50-CFH	50-CLC	50-CAM	50-CSAM
Residential	-	-	-	-	-	-	-	0	0	0	0
Service	-	64	127	132	141	158	64	135	146	151	172
Industry	-	10	10	10	10	10	10	10	10	10	10
Total	**-**	**74**	**137**	**142**	**151**	**168**	**74**	**145**	**157**	**161**	**183**

Electricity generation mix (PJ)

	2000	35-B	35-CFH	35-CLC	35-CAM	35-CSAM	50-B	50-CFH	50-CLC	50-CAM	50-CSAM
Coal	396	1,144	438	-	-	-	1,296	54	0	0	0
Coal CCS	-	-	631	982	797	313	-	1196	976	816	222
Gas	487	50	50	50	50	50	-	0	0	0	0
Gas CCS	-	-	-	-	-	-	-	0	0	2	0
Nuclear	282	31	31	93	245	790	-	0	375	764	1004
Oil	16	-	-	-	-	-	-	0	0	0	0
Hydro	17	18	18	18	18	18	13	4	16	31	31
Wind	3	169	165	166	160	173	127	140	145	189	748
Biowaste & others	26	62	60	56	38	39	63	55	39	38	38
Imports	52	9	62	88	88	88	32	103	103	103	103
Marine	-	-	-	-	-	-	64	64	64	64	64
Solar PV	-	-	-	-	-	-	-	0	0	0	0
Storage	10	-	-	-	-	-	-	0	0	0	0
Total	**1,288**	**1,482**	**1,455**	**1,453**	**1,396**	**1,471**	**1,594**	**1616**	**1719**	**2007**	**2211**

Generation by plant type (PJ)

	2000	35-B	35-CFH	35-CLC	35-CAM	35-CSAM	50-B	50-CFH	50-CLC	50-CAM	50-CSAM
Base load	592	1,200	1,125	1,101	1,068	1,128	1,296	1250	1351	1582	1227
Non-base load	641	253	303	328	322	333	266	342	360	418	977
CHPs	45	30	28	24	6	10	32	24	8	7	7
Storage	10	-	-	-	-	-	-	0	0	0	0
Total	**1,288**	**1,482**	**1,455**	**1,453**	**1,396**	**1,471**	**1,594**	**1616**	**1719**	**2007**	**2211**

Electricity storage (PJ)

	2000	35-B	35-CFH	35-CLC	35-CAM	35-CSAM	50-B	50-CFH	50-CLC	50-CAM	50-CSAM
Storage heaters	46	52	49	44	40	26	41	34	23	12	17
Plug-in hybrid	-	-	-	-	-	18	41	41	125	136	104
Hydrogen storage	-	-	-	-	-	-	-	0	0	0	0
Pumped hydro	10	-	-	-	-	-	-	0	0	0	0
Total	**55**	**52**	**49**	**44**	**40**	**43**	**82**	**75**	**148**	**148**	**121**

Installed capacity by fuel (GW)

	2000	35-B	35-CFH	35-CLC	35-CAM	35-CSAM	50-B	50-CFH	50-CLC	50-CAM	50-CSAM
Coal	29	44	19	4	-	-	50	19	4	0	0
Coal CCS	-	-	24	37	30	12	-	46	37	31	12
Gas	24	10	11	12	13	15	20	8	13	26	39
Gas CCS	-	-	-	-	-	-	-	0	0	0	0
Nuclear	12	1	1	4	9	30	-	0	14	29	38
Oil	10	-	-	-	0	-	-	0	0	0	0
Hydro	1	2	2	2	2	2	1	0	1	3	3
Wind	0	16	16	16	15	16	12	13	14	18	65
Biowaste & others	2	15	13	12	12	11	5	3	3	4	3
Imports	2	2	4	4	4	4	3	6	10	8	11
Marine	-	-	-	-	-	-	5	5	5	5	5
Storage	3	1	1	1	1	1	1	1	1	1	1
Total	**84**	**91**	**90**	**91**	**87**	**92**	**98**	**101**	**103**	**126**	**177**

Installed capacity by plant type (GW)

	2000	35-B	35-CFH	35-CLC	35-CAM	35-CSAM	50-B	50-CFH	50-CLC	50-CAM	50-CSAM
Base load	36	48	46	47	41	45	64	64	58	70	52
Non-base load	41	39	41	41	43	44	31	34	43	54	124
CHPs	4	2	2	2	1	1	2	2	1	0	0
Storage	3	1	1	1	1	1	1	1	1	1	1
Total	**84**	**91**	**90**	**91**	**87**	**92**	**98**	**101**	**103**	**126**	**177**

Sectoral electricity demands (PJ)

	2000	35-B	35-CFH	35-CLC	35-CAM	35-CSAM	50-B	50-CFH	50-CLC	50-CAM	50-CSAM
Agriculture	16	16	15	15	15	14	16	15	15	14	14
Hydrogen	-	-	-	-	-	-	-	-	-	162	164
Industry	412	388	374	366	341	329	395	377	355	331	602
Residential	403	581	566	549	551	660	587	569	593	774	773
Service	326	342	295	287	273	252	360	311	295	279	275
Transport	20	39	43	44	45	76	112	125	250	223	191
Upstream	-	-	49	78	63	25	-	92	78	65	18
Total	**1,176**	**1,366**	**1,342**	**1,340**	**1,287**	**1,356**	**1,469**	**1,489**	**1,584**	**1,848**	**2036**

Sectoral Emissions (Million t-CO2)

	2000	35-B	35-CFH	35-CLC	35-CAM	35-CSAM	50-B	50-CFH	50-CLC	50-CAM	50-CSAM
Upstream	25	15	14	14	13	9	12	12	8	3	1
Agriculture	2	3	3	3	2	2	4	3	3	2	2
Electricity	181	240	121	40	22	12	262	49	21	17	5
Hydrogen	-	1	-	-	-	-	5	1	-	-	0
Industry	63	60	57	56	51	49	62	62	57	46	27
Residential	89	73	71	67	53	29	70	67	47	5	3
Services	26	22	20	19	17	16	22	19	16	12	1
Transport	140	146	143	140	121	75	147	143	85	32	19
Total	**526**	**560**	**429**	**338**	**278**	**191**	**583**	**355**	**237**	**118**	**59**

End-use Sectoral Emissions (Million t-CO2)

	2000	35-B	35-CFH	35-CLC	35-CAM	35-CSAM	50-B	50-CFH	50-CLC	50-CAM	50-CSAM
Upstream	25	15	19	16	14	9	12	15	9	4	1
Agriculture	5	6	4	3	3	2	6	4	3	3	2
Industry	127	128	90	67	56	52	133	74	62	50	29
Residential	151	175	122	83	62	34	175	85	54	13	5
Services	77	82	47	27	22	18	86	29	20	14	2
Transport	143	154	147	141	122	75	171	148	89	36	20
Total	**526**	**560**	**429**	**338**	**278**	**191**	**583**	**355**	**237**	**118**	**59**

CO2 and system costs

	2000	35-B	35-CFH	35-CLC	35-CAM	35-CSAM	50-B	50-CFH	50-CLC	50-CAM	50-CSAM
CO_2 emissions (MTCO2)	548.8	560.1	429.5	337.6	278.4	191	583.0	355.4	236.9	118.5	59
Marginal cost of CO2 (£2000/t)	-	-	13.4	37.3	96.7	133	-	19.5	85.4	168.6	299
Undiscounted energy system cost (£ billion)	69.8	227.3	228.1	226.2	224.8	234	259.1	261.6	267.0	276.0	288

Discounted energy system cost (£ Billion)	76.9	7.0	7.0	6.9	6.8	8	1.9	1.9	2.0	2.0	2
Transport b.v.km by vehicle type											
	2000	35-B	35-CFH	35-CLC	35-CAM	35-CSAM	50-B	50-CFH	50-CLC	50-CAM	50-CSAM
Car - Diesel/biodiesel ICE	70	147.4	143.1	139.1	116.7	122	188.7	184.2	68.7	65.0	183
Car - Diesel/biodiesel Hybrid	-	-	-	-	-	-	-	-	-	-	0
Car - Diesel/biodiesel Plug-in	-	-	-	-	-	-	-	-	-	-	0
Car - Petrol ICE	286	422.5	426.8	416.5	291.9	57	450.6	455.2	75.8	-	0
Car - Petrol Hybrid	-	-	-	-	-	-	-	-	-	-	0
Car - Petrol Plug-in	-	-	-	-	-	61	-	-	371.1	340.3	220
Car - E85	-	-	-	-	139.7	302	-	-	107.9	202.2	205
Car - Battery	-	-	-	-	-	-	-	-	-	-	0
Car - Hydrogen	-	-	-	-	-	-	-	-	-	-	0
Car - Methanol	-	-	-	-	-	-	-	-	-	-	0
Bus - Diesel/biodiesel ICE	6	-	-	-	-	-	-	-	-	-	0
Bus - Diesel/biodiesel Hybrid	-	8.5	8.5	7.9	7.9	3	-	-	-	-	0
Bus - Battery	-	-	-	0.4	0.4	5	8.9	8.9	8.9	8.9	9
Bus - Hydrogen	-	-	-	-	-	-	-	-	-	-	0
Bus - Methanol	-	-	-	-	-	-	-	-	-	-	0
HGV - Diesel/biodiesel	33	-	-	-	-	-	-	-	-	-	0
HGV - Diesel/biodiesel Hybrid	-	50.0	48.7	47.6	45.0	45	54.0	52.7	50.0	13.6	13
HGV - Hydrogen	-	-	-	-	-	-	-	-	-	35.0	35
LGV - Diesel/biodiesel	59	-	-	-	-	-	-	-	-	-	0
LGV - Diesel/biodiesel Hybrid	-	114.4	114.4	114.4	111.6	112	70.5	70.5	19.2	65.9	68
LGV - Diesel/biodiesel Plug-in	-	-	-	-	-	-	-	-	-	62.7	61
LGV - E85	-	-	-	-	-	-	-	-	-	-	0
LGV - Petrol	-	-	-	-	-	-	-	-	-	-	0
LGV - Petrol Hybrid	-	-	-	-	-	-	-	-	-	-	0
LGV - Petrol	-	-	-	-	-	-	61.4	61.4	109.3	-	0

Plug-in											
LGV - Battery	-	-	-	-	-	-	14.7	14.7	14.3	14.3	14
LGV - Hydrogen	-	-	-	-	-	-	-	-	-	-	0
LGV - Methanol	-	-	-	-	-	-	-	-	-	-	0
TW - Petrol	5	7.2	7.2	7.2	7.0	7	6.7	6.7	6.5	6.5	6
TW - Electricity	-	-	-	-	-	-	-	-	-	-	0
TW - Hydrogen	-	-	-	-	-	-	-	-	-	-	0
Rail - Diesel/biodiesel	0	0.0	0.0	0.0	0.0	0	-	-	-	-	0
Rail - Electricity	0	0.8	0.9	0.9	0.9	1	1.0	1.2	1.3	1.3	1
Rail - Hydrogen	-	0.1	-	-	-	-	0.4	0.1	-	-	0
Ship - Diesel/biodiesel	29	30.3	29.5	28.0	25.7	25	32.6	31.0	27.7	26.1	24
Air - Jet fuel	0	0.3	0.3	0.3	0.3	0	0.3	0.3	0.3	0.3	0
Air - Hydrogen	-	-	-	-	-	-	-	-	-	-	0
Air (int) - Jet fuel	-	-	-	-	-	-	-	-	-	-	0
Air (int) - Hydrogen	-	-	-	-	-	-	-	-	-	-	0
Total -	488	781.4	779.4	762.3	747.0	739	889.7	886.6	860.9	841.9	839

Transport fuel demand

	2000	35-B	35-CFH	35-CLC	35-CAM	35-CSAM	50-B	50-CFH	50-CLC	50-CAM	50-CSAM
Petrol	872	963	943	919	784	507	1,031	1,008	589	311	230
Diesel	933	913	894	875	765	438	853	834	496	74	24
Electricity	20	39	43	44	45	76	112	125	250	223	192
Hydrogen	-	6	-	-	-	-	26	5	-	138	139
Jet fuel	30	39	39	38	36	35	37	37	35	34	34
Bio-diesel	-	42	41	40	73	390	39	38	46	338	646
Ethanol/methanol	-	32	62	62	232	389	32	66	236	393	393
Total	**1,855**	**2,034**	**2,022**	**1,978**	**1,935**	**1,835**	**2,130**	**2112**	**1653**	**1511**	**1656**

Transport fuel demand by vehicle type (PJ)

	2000	35-B	35-CFH	35-CLC	35-CAM	35-CSAM	50-B	50-CFH	50-CLC	50-CAM	50-CSAM
Car - Diesel/biodiesel ICE	190	312	303	295	248	258	370	360	137	128	353
Car - Diesel/biodiesel Hybrid	-	-	-	-	-	-	-	-	-	-	0
Car - Diesel/biodiesel Plug-in	-	-	-	-	-	-	-	-	-	-	0
Car - Petrol ICE	865	988	998	974	683	136	981	992	168	-	0
Car - Petrol Hybrid	-	-	-	-	-	-	-	-	-	-	0

Car - Petrol Plug-in	-	-	-	-	-	67	-	-	377	347	227
Car - E85	-	-	-	-	325	704	-	-	239	443	449
Car - Battery	-	-	-	-	-	-	-	-	-	-	0
Car - Hydrogen	-	-	-	-	-	-	-	-	-	-	0
Car - Methanol	-	-	-	-	-	-	-	-	-	-	0
Bus - Diesel/biodiesel ICE	65	-	-	-	-	-	-	-	-	-	0
Bus - Diesel/biodiesel Hybrid	-	35	35	33	33	13	-	-	-	-	0
Bus - Battery	-	-	-	1	1	16	25	25	25	25	25
Bus - Hydrogen	-	-	-	-	-	-	-	-	-	-	0
Bus - Methanol	-	-	-	-	-	-	-	-	-	-	0
HGV - Diesel/biodiesel	402	-	-	-	-	-	-	-	-	-	0
HGV - Diesel/biodiesel Hybrid	-	377	368	359	339	339	375	366	347	98	96
HGV - Hydrogen	-	-	-	-	-	-	-	-	-	138	139
LGV - Diesel/biodiesel	215	-	-	-	-	-	-	-	-	-	0
LGV - Diesel/biodiesel Hybrid	-	195	195	195	191	191	115	115	31	107	110
LGV - Diesel/biodiesel Plug-in	-	-	-	-	-	-	-	-	-	82	84
LGV - E85	-	-	-	-	-	-	-	-	-	-	0
LGV - Petrol	-	-	-	-	-	-	-	-	-	-	0
LGV - Petrol Hybrid	-	-	-	-	-	-	-	-	-	-	0
LGV - Petrol Plug-in	-	-	-	-	-	-	101	101	184	-	0
LGV - Battery	-	-	-	-	-	-	14	14	13	13	13
LGV - Hydrogen	-	-	-	-	-	-	-	-	-	-	0
LGV - Methanol	-	-	-	-	-	-	-	-	-	-	0
TW - Petrol	8	8	8	8	7	7	7	7	7	7	7
TW - Electricity	-	-	-	-	-	-	-	-	-	-	0
TW - Hydrogen	-	-	-	-	-	-	-	-	-	-	0
Rail - Diesel/biodiesel	33	4	4	4	2	2	-	-	-	-	0
Rail - Electricity	20	39	43	43	44	43	46	59	62	62	62
Rail - Hydrogen	-	6	-	-	-	-	26	5	-	-	0
Ship - Diesel/biodiesel	29	30	30	28	26	25	33	31	28	26	24
Air - Jet fuel	30	39	39	38	36	35	37	37	35	34	0
Air - Hydrogen	-	-	-	-	-	-	-	-	-	-	0

Air - Bio-Kerosene	-	-	-	-	-	-	-	-	-	-	34
Total -	**1,855**	**2,034**	**2,022**	**1,978**	**1,935**	**1,835**	**2,130**	**2112**	**1653**	**1511**	**1589**
Demand Reductions (%)											
	2000	35-B	35-CFH	35-CLC	35-CAM	35-CSAM	50-B	50-CFH	50-CLC	50-CAM	50-CSAM
Agriculture	0%	0%	-4%	-12%	-21%	-24%	0%	-6%	-20%	-27%	-34%
Industry - Chemicals	0%	0%	-8%	-15%	-25%	-30%	0%	-7%	-23%	-32%	-40%
Industry - Iron & steel	0%	0%	-5%	-7%	-17%	-20%	0%	-5%	-15%	-22%	-30%
Industry - Non ferrous metals	0%	0%	-2%	-7%	-18%	-20%	0%	-5%	-15%	-23%	-25%
Industry - Others	0%	0%	-3%	-3%	-7%	-10%	0%	-3%	-6%	-10%	-12%
Industry - Paper & pulp	0%	0%	-2%	-5%	-8%	-10%	0%	-2%	-7%	-10%	-15%
Residential - Electricity	0%	0%	-3%	-5%	-6%	-9%	0%	-3%	-5%	-10%	-10%
Residential - Gas	0%	0%	-5%	-10%	-23%	-25%	0%	-5%	-20%	-30%	-38%
Residential - Heating	1%	0%	-3%	-8%	-17%	-23%	0%	-5%	-16%	-22%	-25%
Residential - Hot-water	1%	0%	-3%	-7%	-19%	-19%	0%	-5%	-17%	-22%	-22%
Services - Cooking	0%	0%	0%	-2%	-7%	-10%	0%	0%	-7%	-10%	-15%
Services - Cooling	0%	0%	0%	2%	0%	3%	0%	0%	0%	3%	3%
Services - Other electrical	0%	0%	-3%	-3%	-5%	-7%	0%	-2%	-5%	-10%	-13%
Services - Heating	0%	0%	-3%	-8%	-13%	-18%	0%	-3%	-11%	-18%	-23%
Services - Hot-water	0%	0%	-2%	-8%	-15%	-15%	0%	-3%	-12%	-17%	-20%
Services - Lighting	0%	0%	-2%	-2%	-5%	-5%	0%	-3%	-5%	-8%	-8%
Services - Refrigeration	0%	0%	0%	0%	0%	-2%	0%	0%	0%	-2%	-2%
Transport - Air domestic	1%	-1%	-1%	-1%	-9%	-9%	0%	0%	-4%	-7%	-7%
Transport - Bus	0%	0%	0%	-3%	-3%	-3%	0%	0%	0%	0%	0%
Transport - Car	0%	0%	0%	-3%	-4%	-5%	0%	0%	-3%	-5%	-5%
Transport - Rail freight	1%	-1%	-1%	-1%	-1%	-1%	0%	0%	-3%	-3%	-3%
Transport - HGV	0%	0%	-2%	-5%	-10%	-10%	0%	-3%	-8%	-10%	-10%
Transport - Air International	-	-	-	-	-	-	-	-	-	-	-
Transport - LGV	0%	0%	0%	0%	-2%	-2%	0%	0%	-3%	-3%	-3%
Transport - Rail passenger	0%	0%	0%	0%	0%	-2%	1%	-3%	-3%	-3%	-3%
Transport - Shipping	0%	0%	-2%	-8%	-15%	-17%	0%	-5%	-15%	-20%	-27%
MED parameters (B £2000)											

	2000	35-B	35-CFH	35-CLC	35-CAM	35-CSAM	50-B	50-CFH	50-CLC	50-CAM	50-CSAM
Change in consumer + producer surplus	-	-0	-3	-6	- 3	-26	-0	-5	- 20	-38	-52
Change in energy system costs	-	0	1	-1	-2	7	0	3	8	17	30
Increase in are under demand curve	-	-	-	0	-	0	0	0	-	0	0
Change in area under demand curve	-	-	-2	-7	-15	19	-	-2	-12	-20	23

Biomass/Biofuel in final energy (PJ)

	2000	35-B	35-CFH	35-CLC	35-CAM	35-CSAM	50-B	50-CFH	50-CLC	50-CAM	50-CSAM
Residential	8	-	-	-	88	-	-	-	80	-	0
Service	-	14	20	29	29	29	32	47	47	146	373
Transport	-	74	103	102	306	779	71	104	282	731	1005
Total	**8**	**87**	**123**	**131**	**423**	**808**	**102**	**151**	**409**	**876**	**1377**

Biofuels in transport sector (PJ)

	2000	35-B	35-CFH	35-CLC	35-CAM	35-CSAM	50-B	50-CFH	50-CLC	50-CAM	50-CSAM
Bus	-	2	2	1	3	13	-	-	-	-	0
Car	-	14	14	13	22	258	17	16	12	128	353
HGV	-	17	17	16	31	101	17	16	31	98	96
LGV	-	9	9	9	17	17	5	5	3	112	164
Rail	-	0	0	0	0	0	-	-	-	-	0
Total	**-**	**42**	**41**	**40**	**73**	**390**	**39**	**38**	**46**	**338**	**612**

Sources of Biofuel

	2000	35-B	35-CFH	35-CLC	35-CAM	35-CSAM	50-B	50-CFH	50-CLC	50-CAM	50-CSAM
Imported	-	58	87	86	119	190	71	104	112	243	263
Domestic	-	16	16	16	186	589	-	-	170	488	742
Total	**-**	**74**	**103**	**102**	**306**	**779**	**71**	**104**	**282**	**731**	**1005**

A2: Detailed results on 80% reduction sensitivity scenarios

CAM Ambition 26% by 2020 ; 80% by 2050

CEA Early action 32% by 2020 ; 80% by 2050

CCP Least cost path 80% post 2050 ; cumulative emissions (2010-2050) similar to CEA

CCSP Socially optimal least cost path

80% post 2050 ; cumulative emissions (2010-2050) similar to CEA ; 3.5% discount rate

Primary Energy Demand (PJ)

	35-CAM	35-CEA	35-CCP	35-CCSP	50-CAM	50-CEA	50-CCP	50-CCSP
Renewable electricity	178	189	180	214	284	281	299	488
Biomass and waste	618	918	528	282	1142	1135	1648	279
Natural Gas	2,335	2,050	2,171	2,388	1170	1181	613	1430
Oil	2,022	1,648	2,126	1,248	386	364	134	894
Refined oil	- 217	- 200	- 230	- 200	128	138	188	0
Coal	1,848	1,497	1,693	2,386	1888	1958	1343	2617
Nuclear electricity	245	461	364	295	764	719	997	308
Imported electricity	88	88	88	50	103	103	103	103
Hydrogen	-	-	-	-	0	0	139	0
Total	**7,117**	**6,650**	**6,919**	**6,663**	**5864**	**5878**	**5465**	**6118**

Final Energy demand by fuel (PJ)

	35-CAM	35-CEA	35-CCP	35-CCSP	50-CAM	50-CEA	50-CCP	50-CCSP
Electricity	1,234	1,309	1,249	1,246	1632	1640	1849	1528
Fuel oil	95	95	95	97	78	78	74	82
LPG	-	-	-	-	0	0	0	0
Gas	2,170	1,892	2,004	2,155	1148	1154	562	1317
Coal	2	2	91	120	2	2	2	131
Petrol	784	590	836	504	311	311	243	425
Diesel	792	649	824	353	103	95	48	312
Jet fuel	36	36	37	37	34	34	34	36
Hydrogen	-	-	-	218	138	114	136	279
Ethanol/Methanol	232	292	149	35	393	382	393	29
Bio diesels	73	302	76	14	338	403	582	12
Manufactured fuel	3	3	3	3	3	3	3	3
Biomass	148	90	137	77	176	100	405	87
Heat	26	29	32	32	19	15	19	34
Others	-	-	-	-	0	0	0	0
Total	**5,594**	**5,288**	**5,533**	**4,890**	**4374**	**4332**	**4349**	**4273**

Final Energy demand by Sector (PJ)

	35-CAM	35-CEA	35-CCP	35-CCSP	50-CAM	50-CEA	50-CCP	50-CCSP
Agriculture	48	47	49	55	49	49	42	58
Industry	1,321	1,305	1,322	1,389	1276	1276	1178	1376
Residential	1,666	1,427	1,596	1,436	891	867	825	822
Services	624	608	613	738	647	611	684	743
Transport	1,935	1,901	1,952	1,271	1511	1528	1586	1274
Total	**5,594**	**5,288**	**5,533**	**4,890**	**4374**	**4332**	**4315**	**4273**

Use of conservation (PJ)

	35-CAM	35-CEA	35-CCP	35-CCSP	50-CAM	50-CEA	50-CCP	50-CCSP
Residential	-	-	-	-	0	0	0	0
Service	141	141	149	64	151	151	172	64
Industry	10	10	10	10	10	10	10	10
Total	**151**	**151**	**159**	**74**	**161**	**161**	**183**	**74**

Electricity generation mix (PJ)

	35-CAM	35-CEA	35-CCP	35-CCSP	50-CAM	50-CEA	50-CCP	50-CCSP
Coal	-	-	-	-	0	0	0	0
Coal CCS	797	637	682	987	816	846	576	1091
Gas	50	50	50	50	0	0	0	0
Gas CCS	-	-	-	-	2	0	33	0
Nuclear	245	461	364	295	764	719	997	308
Oil	-	-	-	-	0	0	0	0
Hydro	18	18	18	18	31	31	31	16
Wind	160	171	163	180	189	186	205	407
Biowaste & others	38	39	40	40	38	38	38	39
Imports	88	88	88	50	103	103	103	103
Marine	-	-	-	17	64	64	64	64
Solar PV	-	-	-	-	0	0	0	0
Storage	-	-	-	-	0	0	0	0
Total	**1,396**	**1,464**	**1,403**	**1,636**	**2007**	**1988**	**2047**	**2028**

Generation by plant type (PJ)

	35-CAM	35-CEA	35-CCP	35-CCSP	50-CAM	50-CEA	50-CCP	50-CCSP
Base load	1,068	1,123	1,070	1,307	1582	1566	1606	1399
Non-base load	322	332	323	320	418	415	434	622
CHPs	6	9	10	9	7	7	7	8
Storage	-	-	-	-	0	0	0	0
Total	**1,396**	**1,464**	**1,403**	**1,636**	**2007**	**1988**	**2047**	**2028**

Electricity storage (PJ)

	35-CAM	35-CEA	35-CCP	35-CCSP	50-CAM	50-CEA	50-CCP	50-CCSP
Storage heaters	40	32	38	35	12	11	16	19
Plug-in hybrid	-	-	-	85	136	131	122	133
Hydrogen storage	-	-	-	-	0	0	0	0
Pumped hydro	-	-	-	-	0	0	0	0
Total	**40**	**32**	**38**	**120**	**148**	**142**	**138**	**152**

Installed capacity by fuel (GW)

	35-CAM	35-CEA	35-CCP	35-CCSP	50-CAM	50-CEA	50-CCP	50-CCSP
Coal	-	-	-	-	0	0	0	0
Coal CCS	30	24	26	38	31	32	26	43
Gas	13	13	10	20	26	28	27	29
Gas CCS	-	-	-	-	0	0	1	0
Nuclear	9	18	14	11	29	27	38	12
Oil	0	-	-	-	0	0	0	0
Hydro	2	2	2	2	3	3	3	1
Wind	15	16	15	17	18	17	19	36
Biowaste & others	12	12	14	3	4	2	2	3
Imports	4	7	5	7	8	10	8	14
Marine	-	-	-	1	5	5	5	5
Storage	1	1	1	1	1	1	1	1
Total	**87**	**92**	**87**	**99**	**126**	**127**	**131**	**145**

Installed capacity by plant type (GW)

	35-CAM	35-CEA	35-CCP	35-CCSP	50-CAM	50-CEA	50-CCP	50-CCSP
Base load	41	48	43	54	70	65	86	65
Non-base load	43	42	42	43	54	60	43	78
CHPs	1	1	1	1	0	0	0	1
Storage	1	1	1	1	1	1	1	1
Total	**87**	**92**	**87**	**99**	**126**	**127**	**131**	**145**

Sectoral electricity demands (PJ)

	35-CAM	35-CEA	35-CCP	35-CCSP	50-CAM	50-CEA	50-CCP	50-CCSP
Agriculture	15	15	15	15	14	14	13	15
Hydrogen	-	-	-	195	162	134	-	266
Industry	341	338	341	357	331	331	584	357
Residential	551	618	563	387	774	788	768	585
Service	273	270	263	332	279	278	265	342
Transport	45	59	58	144	223	218	208	220

Upstream	63	51	55	78	65	67	47	85
Total	**1,287**	**1,350**	**1,294**	**1,508**	**1,848**	**1,831**	**1,885**	**1,869**

Sectoral Emissions (Million t-CO2)

	35-CAM	35-CEA	35-CCP	35-CCSP	50-CAM	50-CEA	50-CCP	50-CCSP
Upstream	13	11	13	9	3	3	1	6
Agriculture	2	2	2	3	2	2	2	3
Electricity	22	19	19	26	17	18	13	23
Hydrogen	-	-	-	4	-	-	-	4
Industry	51	50	54	58	46	46	26	57
Residential	53	40	49	54	5	4	3	11
Services	17	16	17	19	12	14	1	18
Transport	121	95	127	66	32	31	20	56
Total	**278**	**233**	**282**	**238**	**118**	**118**	**67**	**179**

End-use Sectoral Emissions (Million t-CO2)

	35-CAM	35-CEA	35-CCP	35-CCSP	50-CAM	50-CEA	50-CCP	50-CCSP
Upstream	14	12	14	11	4	4	2	7
Agriculture	3	2	3	3	3	3	2	3
Industry	56	55	59	64	50	49	30	62
Residential	62	48	57	60	13	11	8	18
Services	22	20	21	25	14	16	3	22
Transport	122	96	128	75	36	35	22	66
Total	**278**	**233**	**282**	**238**	**118**	**118**	**67**	**179**

CO2 and system costs

	35-CAM	35-CEA	35-CCP	35-CCSP	50-CAM	50-CEA	50-CCP	50-CCSP
CO_2 emissions (MTCO2)	278.4	232.8	282.2	238.2	118.5	118.5	67.1	178.6
Marginal cost of CO2 (£2000/t)	96.7	119.4	86.3	39.4	168.6	173.2	360.4	66.1
Undiscounted energy system cost (£ billion)	224.8	228.4	226.4	202.7	276.0	275.5	281.4	226.8
Discounted energy system cost (£ Billion)	6.8	7.1	7.0	58.0	2.0	2.0	2.0	38.8

Transport b.v.km by vehicle type

	35-CAM	35-CEA	35-CCP	35-CCSP	50-CAM	50-CEA	50-CCP	50-CCSP
Car - Diesel/biodiesel ICE	116.7	167.5	137.5	-	65.0	69.7	163.7	-
Car - Diesel/biodiesel Hybrid	-	-	-	71.2	-	-	-	109.6
Car - Diesel/biodiesel	-	-	-	-	-	-	-	-

Plug-in								
Car - Petrol ICE	291.9	220.6	238.2	-	-	-	-	-
Car - Petrol Hybrid	-	-	-	204.8	-	-	-	127.0
Car - Petrol Plug-in	-	-	-	293.9	340.3	341.2	238.3	371.6
Car - E85	139.7	153.4	179.9	-	202.2	196.5	205.5	-
Car - Battery	-	-	-	-	-	-	-	31.2
Car - Hydrogen	-	-	-	-	-	-	-	-
Car - Methanol	-	-	-	-	-	-	-	-
Bus - Diesel/biodiesel ICE	-	-	-	-	-	-	-	-
Bus - Diesel/biodiesel Hybrid	7.9	3.0	3.2	3.0	-	-	-	-
Bus - Battery	0.4	5.3	5.1	5.5	8.9	8.9	8.7	8.9
Bus - Hydrogen	-	-	-	-	-	-	-	-
Bus - Methanol	-	-	-	-	-	-	-	-
HGV - Diesel/biodiesel	-	-	-	-	-	-	-	-
HGV - Diesel/biodiesel Hybrid	45.0	45.0	46.2	0.5	13.6	19.7	12.6	-
HGV - Hydrogen	-	-	-	46.9	35.0	28.9	34.6	54.0
LGV - Diesel/biodiesel	-	-	-	-	-	-	-	-
LGV - Diesel/biodiesel Hybrid	111.6	111.6	111.6	114.4	65.9	76.3	39.1	78.4
LGV - Diesel/biodiesel Plug-in	-	-	-	-	62.7	52.2	86.1	-
LGV - E85	-	-	-	-	-	-	-	-
LGV - Petrol	-	-	-	-	-	-	-	-
LGV - Petrol Hybrid	-	-	-	-	-	-	-	-
LGV - Petrol Plug-in	-	-	-	-	-	-	-	-
LGV - Battery	-	-	-	-	14.3	14.3	13.9	14.3
LGV - Hydrogen	-	-	-	-	-	-	-	50.2
LGV - Methanol	-	-	-	-	-	-	-	-
TW - Petrol	7.0	7.0	7.0	7.2	6.5	6.5	6.3	6.5
TW - Electricity	-	-	-	-	-	-	-	-
TW - Hydrogen	-	-	-	-	-	-	-	-
Rail - Diesel/biodiesel	0.0	0.0	0.0	0.0	-	-	-	-
Rail - Electricity	0.9	0.9	0.9	0.9	1.3	1.3	1.3	1.3
Rail - Hydrogen	-	-	-	-	-	-	-	-
Ship - Diesel/biodiesel	25.7	25.0	25.7	28.0	26.1	26.1	23.6	30.2
Air - Jet fuel	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Air - Hydrogen	-	-	-	-	-	-	-	-
Air (int) - Jet fuel	-	-	-	-	-	-	-	-
Air (int) - Hydrogen	-	-	-	-	-	-	-	-
Total -	747.0	739.3	755.6	776.6	841.9	841.9	834.1	883.3

Transport fuel demand (PJ)

	35-CAM	35-CEA	35-CCP	35-CCSP	50-CAM	50-CEA	50-CCP	50-CCSP
Petrol	784	590	836	504	311	311	243	425
Diesel	765	622	796	320	74	66	24	274
Electricity	45	59	58	144	223	218	208	220
Hydrogen	-	-	-	218	138	114	136	279
Jet fuel	36	36	37	37	34	34	34	36
Bio-diesel	73	302	76	14	338	403	582	12
Ethanol/methanol	232	292	149	35	393	382	393	29
Total	**1,935**	**1,901**	**1,952**	**1,271**	**1511**	**1528**	**1620**	**1274**

Transport fuel demand by vehicle type (PJ)

	35-CAM	35-CEA	35-CCP	35-CCSP	50-CAM	50-CEA	50-CCP	50-CCSP
Car - Diesel/biodiesel ICE	248	354	291	-	128	136	317	-
Car - Diesel/biodiesel Hybrid	-	-	-	91	-	-	-	128
Car - Diesel/biodiesel Plug-in	-	-	-	-	-	-	-	-
Car - Petrol ICE	683	517	558	-	-	-	-	-
Car - Petrol Hybrid	-	-	-	294	-	-	-	167
Car - Petrol Plug-in	-	-	-	322	347	349	246	382
Car - E85	325	357	419	-	443	430	448	-
Car - Battery	-	-	-	-	-	-	-	18
Car - Hydrogen	-	-	-	-	-	-	-	-
Car - Methanol	-	-	-	-	-	-	-	-
Bus - Diesel/biodiesel ICE	-	-	-	-	-	-	-	-
Bus - Diesel/biodiesel Hybrid	33	13	14	13	-	-	-	-
Bus - Battery	1	16	15	16	25	25	24	25
Bus - Hydrogen	-	-	-	-	-	-	-	-
Bus - Methanol	-	-	-	-	-	-	-	-
HGV - Diesel/biodiesel	-	-	-	-	-	-	-	-
HGV - Diesel/biodiesel Hybrid	339	339	349	4	98	140	91	-
HGV - Hydrogen	-	-	-	218	138	114	136	219
LGV - Diesel/biodiesel	-	-	-	-	-	-	-	-
LGV - Diesel/biodiesel Hybrid	191	191	191	195	107	124	64	128
LGV - Diesel/biodiesel Plug-in	-	-	-	-	82	69	120	-
LGV - E85	-	-	-	-	-	-	-	-
LGV - Petrol	-	-	-	-	-	-	-	-
LGV - Petrol Hybrid	-	-	-	-	-	-	-	-

LGV - Petrol Plug-in	-	-	-	-	-	-	-	-
LGV - Battery	-	-	-	-	13	13	13	13
LGV - Hydrogen	-	-	-	-	-	-	-	60
LGV - Methanol	-	-	-	-	-	-	-	-
TW - Petrol	7	7	7	8	7	7	7	7
TW - Electricity	-	-	-	-	-	-	-	-
TW - Hydrogen	-	-	-	-	-	-	-	-
Rail - Diesel/biodiesel	2	2	2	2	-	-	-	-
Rail - Electricity	44	43	43	43	62	62	62	62
Rail - Hydrogen	-	-	-	-	-	-	-	-
Ship - Diesel/biodiesel	26	25	26	28	26	26	24	30
Air - Jet fuel	36	36	37	37	34	34	-	36
Air - Hydrogen	-	-	-	-	-	-	-	-
Air - Bio-Kerosene	-	-	-	-	-	-	34	-
Total -	**1,935**	**1,901**	**1,952**	**1,271**	**1511**	**1528**	**1552**	**1274**

Demand Reductions (%)

	35-CAM	35-CEA	35-CCP	35-CCSP	50-CAM	50-CEA	50-CCP	50-CCSP
Agriculture	-21%	-23%	-20%	-10%	-27%	-27%	-37%	-13%
Industry - Chemicals	-25%	-28%	-25%	-17%	-32%	-32%	-42%	-22%
Industry - Iron & steel	-17%	-20%	-17%	-10%	-22%	-22%	-30%	-15%
Industry - Non ferrous metals	-18%	-20%	-15%	-10%	-23%	-23%	-28%	-13%
Industry - Others	-7%	-7%	-7%	-5%	-10%	-10%	-15%	-5%
Industry - Paper & pulp	-8%	-10%	-8%	-5%	-10%	-10%	-15%	-7%
Residential - Electricity	-6%	-7%	-7%	-48%	-10%	-10%	-15%	-50%
Residential - Gas	-23%	-23%	-23%	-50%	-30%	-30%	-40%	-50%
Residential - Heating	-17%	-20%	-17%	-13%	-22%	-22%	-20%	-13%
Residential - Hot-water	-19%	-19%	-19%	-13%	-22%	-19%	-20%	-12%
Services - Cooking	-7%	-10%	-7%	-5%	-10%	-12%	-17%	-5%
Services - Cooling	0%	0%	0%	0%	3%	3%	3%	3%
Services - Other electrical	-5%	-7%	-7%	-3%	-10%	-10%	-15%	-8%
Services - Heating	-13%	-15%	-13%	-8%	-18%	-19%	-23%	-10%
Services - Hot-water	-15%	-18%	-15%	-10%	-17%	-16%	-22%	-10%
Services - Lighting	-5%	-5%	-5%	-2%	-8%	-8%	-10%	-5%
Services - Refrigeration	0%	0%	0%	0%	-2%	-2%	-2%	0%
Transport - Air domestic	-9%	-9%	-5%	-5%	-7%	-7%	-7%	-4%
Transport - Bus	-3%	-3%	-3%	0%	0%	0%	-2%	0%
Transport - Car	-4%	-5%	-3%	0%	-5%	-5%	-5%	0%
Transport - Rail freight	-1%	-1%	-1%	-1%	-3%	-3%	-6%	-3%
Transport - HGV	-10%	-10%	-8%	-5%	-10%	-10%	-13%	0%

Transport - Air International	-	-	-	-	-	-	-	-
Transport - LGV	-2%	-2%	-2%	0%	-3%	-3%	-5%	-3%
Transport - Rail passenger	0%	-2%	-2%	-2%	-3%	-3%	-3%	-3%
Transport - Shipping	-15%	-17%	-15%	-8%	-20%	-20%	-27%	-7%
Transport - Two wheeler	-2%	-2%	-2%	0%	-3%	-3%	-5%	-3%
MED parameters (B £2000)								
	35-CAM	35-CEA	35-CCP	35-CCSP	50-CAM	50-CEA	50-CCP	50-CCSP
Change in consumer + producer surplus	-13	-19	-12	-9	-38	-37	- 48	- 7
Change in energy system costs	- 2	1	- 0	5	17	17	23	2
Increase in area under demand curve	-	-	-	-	0	0	0	0
Change in area under demand curve	- 15	- 18	- 12	- 5	- 20	- 20	- 26	- 5
	116%	92%	104%	50%	54%	55%	53%	68%
Biomass/Biofuel in final energy (PJ)								
	35-CAM	35-CEA	35-CCP	35-CCSP	50-CAM	50-CEA	50-CCP	50-CCSP
Residential	88	31	77	-	-	-	-	-
Service	29	29	29	47	146	70	375	56
Transport	306	594	225	48	731	785	941	41
Total	**423**	**654**	**331**	**95**	**876.16**	**855.54**	**1315.43**	**96.98**
Biofuels in transport sector (PJ)								
	35-CAM	35-CEA	35-CCP	35-CCSP	50-CAM	50-CEA	50-CCP	50-CCSP
Bus	3	13	1	1	-	-	-	-
Car	22	241	26	4	128	136	317	6
HGV	31	31	31	0	98	140	91	-
LGV	17	17	17	9	112	127	141	6
Rail	0	0	0	0	-	-	-	-
Total	**73**	**302**	**76**	**14**	**337.8**	**403.03**	**548.02**	**11.51**
Sources of Biofuel								
	35-CAM	35-CEA	35-CCP	35-CCSP	50-CAM	50-CEA	50-CCP	50-CCSP
Imported	119	127	122	48	243	248	257	41
Domestic	186	467	102	-	488	537	683	-
Total	**306**	**594**	**225**	**48**	**731**	**785**	**941**	**41**
	35-CAM	35-CEA	35-CCP	35-CCSP	50-CAM	50-CEA	50-CCP	50-CCSP

APPENDIX B: Carbon Emission Factors

A summary of carbon emission factors used to calculate implicit carbon tax in Section 4.3.2 can be found below:

	Conversion to CO2 (gross CV basis)	
Energy source	**Units**	**Kg CO_2 / unit**
Grid electricity	kWh	0.537
Natural gas	kWh	0.185
LPG	kWh	0.214
	litres	1.495
Gas oil	kWh	0.252
	litres	2.674
Fuel oil	kWh	0.268
	litres	3.179
Burning oil	kWh	0.245
	litres	2.518
Diesel	kWh	0.250
	litres	2.630
Petrol	kWh	0.240
	litres	2.315
Industrial coal	kWh	0.330
	tonnes	2,457
Wood pellets	kWh	0.025
	tonnes	132

Source: http://www.carbontrust.co.uk/resource/conversion_factors/default.htm