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Scenarios and Sensitivities on Long-term UK Carbon Reductions using the UK MARKAL and MARKAL-Macro Energy System Models

Research Report

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Dr Neil Strachan, Ramachandran Kannan
Kings College London

Steve Pye
AEA Energy and Environment

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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 UKERC Research Report encapsulates the final report for the DTI and DEFRA on the development of a new UK MARKAL & MARKAL-Macro (M-M) energy systems model. The focus of this final report is on the extensive range of UK 60% CO_2 abatement scenarios and sensitivity analysis run for analytical insights to underpin the 2007 Energy White Paper. This analysis was commissioned by the DTI to underpin the development of the 2007 UK Energy White Paper, and this technical report is a companion publication to the policy focused discussion of the modelling work (DTI, 2007).

Model development (enabled through the energy systems modelling theme of the UK Energy Research Centre (UKERC)) is summarised, notably the range of enhancements to improve UK MARKAL's functionality and analytical sophistication. These include resource supply curves, explicit depiction of energy supply chains, remote and micro electricity grids, substantial technological detail in the major end-use sectors (residential, services, industry, transport and agriculture), and a full data update including substantial stakeholder interaction. A major component of the development work was the integration of MARKAL with a neoclassical growth model (MARKAL-Macro), to facilitate direct calculation of macro-economic impacts from changes in the energy sector as well as endogenous behavioural change in energy service demands.

However, it is still important to acknowledge the limitations of these partial and general equilibrium dynamic optimisation energy system models. Cost optimization assumes a perfectly competitive market and neglects barriers and other non-economic criteria that affect energy decisions. Hence, without additional constraints, it may over-estimate the deployment of nominally cost effective energy efficiency technologies. The model has an incomplete ability to model firm and consumer behaviour. Additionally the spatial (as a UK aggregated model) and temporal approximations (seasonal and diurnal) provide less insight into the siting of infrastructures, and the supply-demand balancing of the electricity network. Further disadvantages from incorporating Macro include the omission of trade impacts and transitional costs and therefore is likely to represent a lower bound on GDP impacts.

Results focus on a selected set of MARKAL-Macro (M-M) model scenarios, utilizing an integrated set of UKERC assumptions and data:
- Base-case, CO_2 emissions in 2050 constrained to 60% of 2000 levels (C-60), and alternate CO_2 emission trajectory (SLT) implemented linearly from 2010;
- Resource import (high and low) price scenarios, from DTI projections;
- Technology scenarios: restricted innovation (limited to either 2020 or further to 2010 levels of improvement), no-nuclear, no-CCS or no-nuclear / CCS scenarios.

In all, over 50 full scenarios sets were run for this project. Results from additional scenario runs (including standard model runs) are used to further discuss key trade-offs between mitigation pathways. Key outputs included primary and final energy mixes, sectoral contributions to CO_2 reductions, detailed technology selection in the electricity and transport sectors, the role of demand side reductions, CO_2 prices, energy system costs and GDP impacts.

Presenting a set of model results paints a complex picture of how the UK energy system could develop under deep long-term CO_2 constraints. These runs illustrate possible technology pathways, energy system interactions and resultant energy and macro cost implications. However the MARKAL and M-M runs do not constitute forecasts, rather they are cost optimal solutions based on a set of integrated assumptions in a systematic what-if analysis of the future evolution of the UK energy systems to meet long-term CO_2 reduction targets. Furthermore the scenarios do not constitute a formal or structured assessment of the breadth of uncertainties in future UK energy scenarios, but illustrate the role of key drivers that are relevant to policy assessment of the economic, and technological implications of potential UK low carbon energy futures.

Principal findings
- A 60% reduction in UK CO_2 emissions entails radical changes in resource and infrastructure use, and investment in new technology portfolios.
- This long-term transition requires a strong CO_2 price signal with a central M-M model estimate of £105/TCO_2 by 2050 (within a range of £65/TCO2 to £176/TCO_2 for the key sensitivities covered in this report);
- The resultant impacts (from a relatively smaller energy sector) on the UK economy are more modest with a range of annual GDP losses in 2050 ranging from 0.3% to 1.5% (equivalent to £B7.5 to £B42). The higher cost estimates are strongly influenced by more pessimistic assessments of future low carbon technologies
- Energy system trade-offs are pervasive under alternate assumption sets. These include the use of natural gas vs. coal under low or high resources prices, upstream technological change vs. end-use energy reductions under innovation optimism, and electricity vs. transport CO_2 reduction pathways, based on the timing of emissions reduction requirements.
- These trade-offs illustrate endemic uncertainties in future resources, infrastructures, technologies and behaviour. One example, is that it is not possible to robustly project a dominant technology class within the future electricity portfolio.

System Evolution

In general the MARKAL and M-M model base-cases represent a low energy (and emissions) growth in the UK (from 6,152PJ final energy in 2000 to 6,272PJ in 2050). This is due to, even in the base case, pervasive technological change towards cost effective energy saving technologies (in the absence of an economy-wide CO2 constraint). Natural gas and coal constitute the dominant base-case primary energy fuels.

Under CO_2 constraint scenarios, further reductions in energy consumption are substantial, falling to around 5,250PJ in 2050. This intensity improvement reflects a range of mechanisms including upstream and end-use efficiency, use of technical conservation measures and a pure behavioural demand reduction in response to rising energy prices. These mechanisms combine with energy pathway and fuel switching in all sectors to meet CO_2 reduction of around 375 $MTCO_2$ by 2050 (to a level of 218 $MTCO_2$). Following a straight-line trajectory (SLT) to 2050 forces the model to abate earlier and implies more effort on a cumulative measure, with total SLT emission reductions rising to 7,205 $MTCO_2$, compared to approximately 6,460 $MTCO_2$ under the C-60 constraint.

In the CO_2 constrained scenarios, natural gas strengthens its position as the largest component (35%-40%) of primary energy (especially in end-use sectors). Coal use remains significant at around 20%, based primarily on CCS applications. Nuclear retains a share of base-load generation in many but not all constrained scenarios. Oil and refined oil use see significant reductions due to efficiency and fuel switching (to hydrogen) in various transport modes. Finally renewables see a significant growth in all scenarios (up to a 30% primary energy share), the rate of which is largely based on the availability of other zero-carbon and efficiency options.

All upstream and end-use sectors contribute to the stringent 60% reduction target. The electricity sector is a major source of carbon reductions. When electricity emissions are allocated to end-use sectors, industry and service sectors produce the deepest reductions at 24% and 27% respectively of year 2000 emissions. All hydrogen production is utilised by the transport sector, and transport is the last sector to decarbonise, retaining 55% of year 2000 CO_2 emission levels.

Technology Pathways

A 60% reduction in UK CO_2 emissions entails radical changes in resource and infrastructure use, and investment in new technology portfolios. In general, under alternate scenario assumptions there is a trade-off between emission reductions from the electricity sector (notably fuel switching and efficiency gains), the buildings and industrial end-use sectors (notably demand reductions, conservation and efficiency gains) and the transport sector (notably hybrids, hydrogen and bio-fuels).

Alternate scenarios generate alternate portfolios in electricity production. Notably, uncertainties in the future costs and characteristics of both new CCS and nuclear technologies mean it is impossible to robustly project that one technology is dominant. In addition, wind generation plays an increasingly important role. Without either nuclear or CCS the electricity portfolio transforms again to be dominated by offshore wind, supplemented by higher costs renewables (including marine) with base-load requirements met using natural gas and bio-gas CCGT plants. That the technology pathway evolution is inherently uncertain and path dependant is also illustrated in the SLT case, where the earlier CO_2 constraint results in a non-nuclear future, with emission reductions coming from more mature wind technologies and bio-fuels in transport.

In the base case, transport final energy consumption is already transformed in the absence of a carbon price signal, including modal shifts towards petrol and diesel hybrid vehicles. Post 2030, buses, then HGVs, and subsequently LGV's evolve into hydrogen vehicles, based on the relative costs of the technologies and importantly the infrastructure requirements per mode.

In the CO_2 constrained cases, consumption of transport fuels (petrol and diesel) is reduced further. An interesting (non-intuitive) finding is that hydrogen delivers lower levels of consumption than in the base case, as hydrogen production must be carbon neutral. Bio-fuels play an increasingly important role, with over 20% of all transport fuels by 2050.

In general there is trade-off between upstream emission reduction options and demand reductions, as seen in the cases with restricted upstream and technology options, as well as the "distance to target", as seen in the lower and higher resource price sensitivities. Conservation measures are taken up to their available limit, and combine with the purely behavioural change in energy service demands which cluster around 10-15% reductions and contribute significantly to lowering marginal CO_2 prices (e.g., comparing vs. standard MARKAL results).

Economic Impacts

Such a transformation of the UK energy system under a 60% CO_2 reduction policy necessitates a high carbon price signal. By 2050 the central constrained case generates a marginal CO_2 cost of £105/tCO_2 (or £385/tC). Without endogenous demand reductions (i.e., comparing the M-M model to the standard MARKAL model), this marginal price increases to £135/tCO_2 (or £495/tC). Scenarios with a greater or lesser distance to target (i.e. the low or high resource price cases) give a higher or lower CO_2 price. The highest marginal costs arise in those scenarios where innovation across a broad range of technologies has been restricted (up to £176/tCO_2 or £645 /tC).

In terms of energy systems cost projections using the M-M model, explanations are complicated by energy service demand reductions giving a smaller energy system in the CO_2 constraint cases vs. the increasing per unit costs of the energy sector. In the core C-60 case the energy system cost in 2050 is still £0.6 billion lower than the base case, although in the (2010) restricted innovation case costs rise to an increase of £7.2 billion in 2050. Without the complexity of overall demand reduction, the standard model generates abatement costs (scenario C-60) in 2050 of £B8.8 with a low estimate of £B2.1 if all optimistic technological assumptions are employed and a high estimate of £B19.8 if innovation is restricted to 2010 levels.

In terms of GDP impacts, the central CO_2 constraint case (C-60) gives an annual GDP reduction of 0.72% by 2050 (or a B£20.3 reduction from a projected UK GDP of B£2,807). The SLT case generates greater GDP losses (£B22.2) than the standard case – this is due to the cumulative emission reductions being greater (7,205 vs. 6,460 $MTCO_2$) and despite a smoother abatement path. The GDP reduction range in 2050 varies between 0.3% and 1.5% (£B7.5 to £B42.0) which is equivalent to other estimates for long-term CO_2 reductions (Stern, 2006). The higher cost estimates are strongly influenced by more pessimistic assessments of future low carbon technologies.

It is stressed that the M-M model is likely to give a lower bound to macro-economic costs, due to bottom-up optimism over future technologies and energy efficiency/conservation, together with non-consideration of trade impacts and transitional costs. Furthermore the simplicity of the M-M linkage with no government sector means that and recycling of revenues, cannot be investigated. Lastly the costs are for UK abatement with no option to purchase international emissions credits. The costs and availability of long-term emission credits is extremely uncertain and not considered in this analysis.

Future academic publications will present modelling insights on the full set of UK energy scenarios, focusing on global and policy drivers of technology pathways to a low carbon energy system. Future UK MARKAL modelling development will use enhanced spatial and temporal detail to further investigate the development of new infrastructures, operational details of the UK energy system and the impact of innovation. Additional modelling work will further disaggregate the role of consumer and firm behaviour in energy service demands. Finally additional UKERC scenario modelling will link analysis of UK policy objectives of low carbon and energy security.

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1. Introduction

1.1. Energy system modelling within the UK energy policy process

In response to the climate challenge set out by the Royal Commission on Environmental Pollution (RCEP, 2000), the previous version of the UK MARKAL energy systems model was utilized to advise on the technical options and costs of the UK moving to a low carbon energy future. This was as part of the wider Interdepartmental Analysts Group study via a two phased study (FES; 2002, 2003). This technical IAG analysis fed into the broader review of long-term UK energy policy (PIU, 2002). This systematically analysed energy technology options through development of three baseline and carbon constrained scenarios for the UK energy sector and detailed treatment of key uncertainties through extensive sensitivity analysis.

Since the publication of the 2003 Energy White Paper "*Our energy future – creating a low carbon economy*" (DTI, 2003), the UK Government has been assessing the key longer-term challenges for UK energy policy. Notably these include reducing carbon dioxide (CO_2) emissions to mitigate the impacts of climate change, ensuring that the UK has an energy resource that is both clean and secure with the move to increased dependence on imported energy, and maintaining low cost energy service provision to aid competitiveness of UK firms. The results of the Energy Review, described in "*The energy challenge*" (DTI, 2006a), were published in July 2006. This document set out the types of challenges that need to be addressed to ensure that the UK could move to a *low carbon* and *energy secure* economy. A new Energy White Paper, to be published in May 2007, will set out the policy framework and initiatives for ensuring that these long-term energy policy objectives can be met.

To support the activities under the Energy Review and proposals for the 2007 Energy White Paper, DTI and DEFRA commissioned a series of analyses with the new UK MARKAL and MARKAL-Macro models. Under the research portfolio of the UK Energy Research Centre (UKERC), these partial and general equilibrium energy systems optimisation models have been substantially developed and extended by the Policy Studies Institute (PSI) together with AEA Energy and Environment. The focus of the DTI/DEFRA analysis was to investigate and quantify long-term carbon constrained scenarios, focusing on characterisation of uncertainty in energy supply, technology pathways and cost implications.

This report serves as a technical explanation of the MARKAL and MARKAL-Macro (M-M) model analysis, to be included in the 2007 Energy White Paper, of the long-term impacts and associated uncertainties of a 60% reduction in CO_2 emissions by 2050. It is a companion report to the policy focused DTI report "*The MARKAL energy model in the 2007 Energy White Paper*" (DTI, 2007). Further policy focused MARKAL-Macro analysis, exploring alternate sensitivities and more stringent emission reduction targets is in Lockwood et al (2007) and DEFRA (2007).

1.2. Structure of report

This report describes the analysis undertaken using the UK MARKAL and M-M models, the key outputs generated from a wide range of scenarios, and the resultant policy insights into possible evolutions of the UK energy system. Two interim reports on the development of the UK MARKAL model framework (Strachan et al, 2005, 2006) detail the model structure and assumptions in greater detail, and are available at http://www.ukerc.ac.uk/content/view/295/592. The model documentation explains in detail the sources and rationale for the resources, technology classifications, energy service demand derivation and global model parameters (Kannan et al, 2007). Further model insights are reported in forthcoming conference and journal papers (e.g., Strachan et al, 2007a). Additionally, the UK MARKAL model continues to be enhanced and extended for future projects, including its spatial and temporal treatments of energy infrastructures (see Strachan et al, 2007b).

As a final report, the focus is on the specification of the model for the full range of scenarios and sensitivity cases, and an explanation of the model results and insights. This is a complex task given the number of scenarios (>50), the range of model outputs, and the multiple trade-offs and uncertainties in long term UK energy supply and demand.

Section 2 provides a summary of the UK MARKAL project design for the DTI-DEFRA analysis of long-term CO_2 reductions in the UK. This includes the structure of the MARKAL and M-M models (including recent development work), a summary of model strengths and weaknesses, the consideration of uncertainty, and information on key parameter characterisation. Due to the size and complexity of a model of the entire UK energy system, readers are referred to Appendices 1 and 2 as well as the previous project reports and model documentation for more information. In addition, the stakeholder review and model validation processes are summarized in Appendix 3. Section 3 sets out the extensive scenario set under this project, based on alternate data specifications, use of the partial or general equilibrium versions of the model, base-cases vs. CO_2 constrained cases, and alternate assumptions on classes of electricity technologies, scope of energy efficiency and progress in innovation.

Section 4 presents key model results, focusing on energy system and economy-wide costs, primary and final energy use, CO_2 emissions and prices, and electricity and transport technology portfolios. Given the very large number of scenarios (>50) and the range of outputs that MARKAL provides, additional results are provided in Appendix 4. Finally, Section 5 discusses model insights and conclusions, focusing on the trade-off between alternate technology pathways, the competing cost implications of alternate scenarios, and the inherent uncertainties in analysing possible UK energy futures over decadal timeframes.

2. Project design and overview of the UK MARKAL models

This section summarizes the principal characteristics of the current UK MARKAL and MARKAL-Macro (M-M) models. This includes the model structure, a summary of model strengths and weaknesses, and the consideration of uncertainty. Further background information to the development process is given in the 1st and 2nd interim MARKAL reports (Strachan et al, 2005, 2006) and in Appendices 1 and 2. Note that the full technical model documentation (Kannan et al, 2007) will be available separately, and is therefore not included in this report. Following on from this model description, the key parameters and assumptions for the DTI-DEFRA project are described. As data and assumptions are critical (as in all models); therefore the extensive validation, stakeholder consultation and model calibration processes are summarised in Appendix 3.

2.1. Modelling methodology

MARKAL (acronym for MARKet ALlocation) is a widely applied bottom-up, dynamic, linear programming (LP) optimisation model. It was developed in the late 1970s at Brookhaven National Laboratory and has been continually supported by the International Energy Agency (IEA) via the Energy Technology and Systems Analysis Program (ETSAP). It is being used by around 100 active teams in over 30 countries, and has a long track record of policy and academic research (e.g., IEA, 2006; Smekens, 2004).

The choice to use a particular energy-economic-engineering-environment (E4) model depends on the questions the analysis seeks to address and the quality of available data. The UK MARKAL model as a partial equilibrium energy system and technologically detailed model, is well suited to investigating the cost and physical trade-offs between long-term divergent energy scenarios. MARKAL's strengths and weaknesses and its ability to quantify uncertainties are discussed in sections 2.1.3 and 2.1.4.

Other models, often classified (IPCC, 2001) as various types of 'top-down' (models which evaluate the system from aggregate economic variables), have additional attributes including economic impacts, behavioural change, international trade and transitional costs. The general equilibrium MARKAL-Macro model is a hybrid that seeks to maintain the technological and sectoral detail of a bottom-up optimisation approach with the responsiveness of demands and resultant assessment of the economy-wide implications. It has been used to investigate long-term carbon reduction strategies in other countries (e.g., Chen et al, 2007), and is discussed in more detail in section 2.1.2 and Appendix 2.

2.1.1. Overview of the UK MARKAL model

MARKAL portrays the entire energy system from imports and domestic production of fuel resources, through fuel processing and supply, explicit representation of infrastructures, conversion to secondary energy carriers (including electricity, heat and hydrogen), end-use

technologies and energy service demands in the industrial, commercial, residential, transport and agricultural sectors. A highly simplified and partial reference energy system – focusing on the electricity component of the full model – illustrates how these components are linked to each other as in Figure 1.
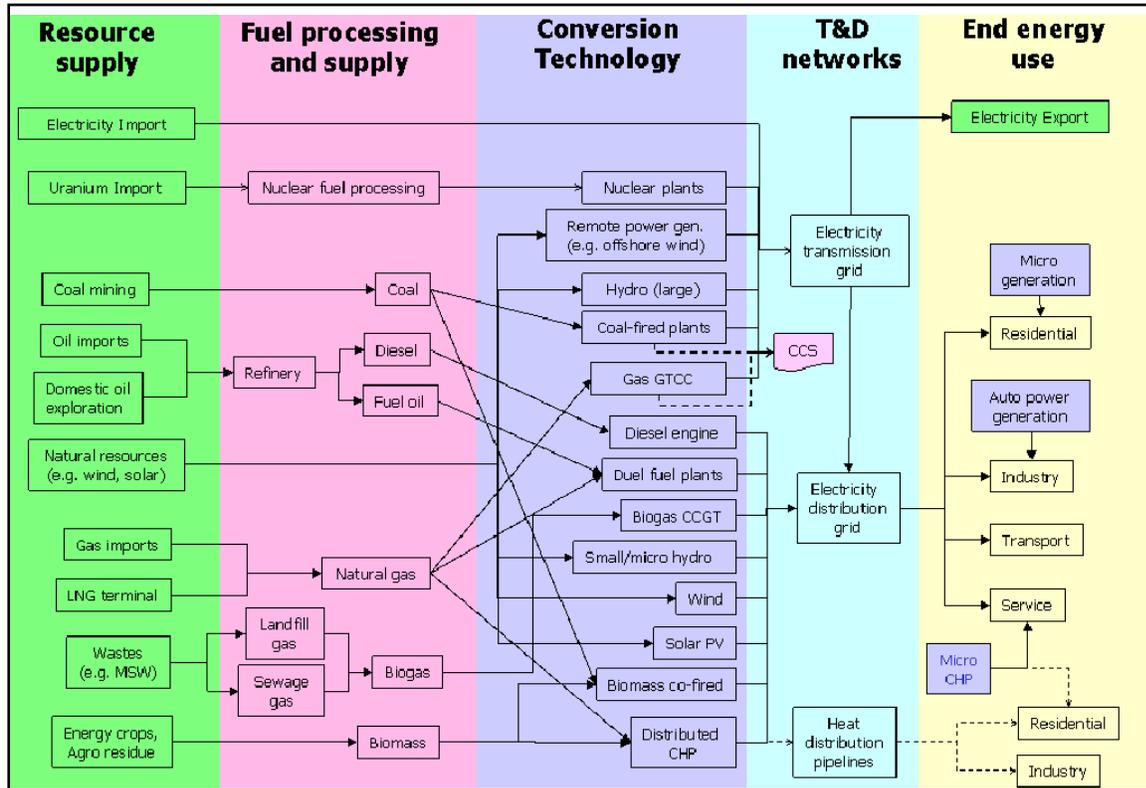
Figure 1: Highly aggregated and partial example of the UK MARKAL Reference Energy System (RES)

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.

The construction of the UK model entails definition of the specific characteristics of the UK energy system, including resource supplies, energy conversion technologies, end-use demands, and the technologies used to satisfy these demands. In particular, the current model is developed based on the previous model used in the Energy White Paper 2003 (DTI, 2003), and supplemented by stakeholder workshops and a wide range of peer reviewed data sources. Inputs into the model include base levels for global resource supply curves (DTI, 2006b), and detailed energy service demands in units of useful energy. These energy services demands were calibrated to DTI's published final energy consumption projections (see section 2.4.3).

In order to replicate the physical, regulatory and policy aspects of the whole UK energy system in MARKAL, many constraints are introduced to the model. These are designed such that the optimisation of the model database of technological pathways occurs under a realistic engineering and economic framework of the deployment of new infrastructures, fuels and technologies (see Section 2.2.5).

The model is calibrated in its base year (2000) to within 1% of actual resources supplies, energy consumption, electricity output and installed technology capacity. The principal calibration source is 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 (DTI 2006b). The model solves in 5-year time steps for an optimal evolution of energy pathways and technology deployment and use.

MARKAL generates a detailed set of outputs to characterise the evolution of the UK energy system. Key outputs include energy system costs, fuel and technology mixes, imports, exports and domestic production of resources, electricity generation and capacity investments, marginal costs of fuels including seasonal/diurnal detail of electricity and heat, environmental emission levels (notably CO_2 and SO_2), emission shadow prices, use of infrastructures, and refinery details. Furthermore, when the model is run in Macro mode, resultant demand levels are a key model variable. Furthermore the Macro variant generates detail on GDP, investment, and consumption at the economy level. Further explanation on model parameters and calibration for this analysis is detailed in section 2.2, with additional information on UK MARKAL model development in Appendix 1, and background information on the MARKAL model in Loulou et al (2004).

2.1.2. Development of the UK MARKAL-Macro model

MARKAL-Macro (M-M) was developed based on the pioneering work of Manne and Wene (1992). M-M hard-links a detailed energy systems model (MARKAL) with a simple neoclassical growth model. Hence M-M combines MARKAL's rich technological characterisation of energy system with a dynamic inter-temporal general equilibrium model. Using this approach, M-M allows both a sub-sectoral demand-side response to supplement supply-side technology pathway optimisation, as well as allowing direct analysis of the impacts of various energy and environmental policies on the growth of the economy.

The model maximizes the discounted utility function subject to a national budget constraint. In M-M, there are three other economic agents in addition to suppliers and consumers of energy (the energy market), as in MARKAL. These additional economic agents are producers, which supply other goods and services, consumers and a generic capital market. All these markets are assumed to operate in a single sector with perfect foresight. Demand changes respond to a single price elasticity and are asymmetric with price. However sub-sectoral demands will react differently dependent on the overall economic implications of their reductions (expressed via demand marginals). Figure 2 summarises the integration process, together with the key inputs and outputs from the MARKAL and Macro components respectively.
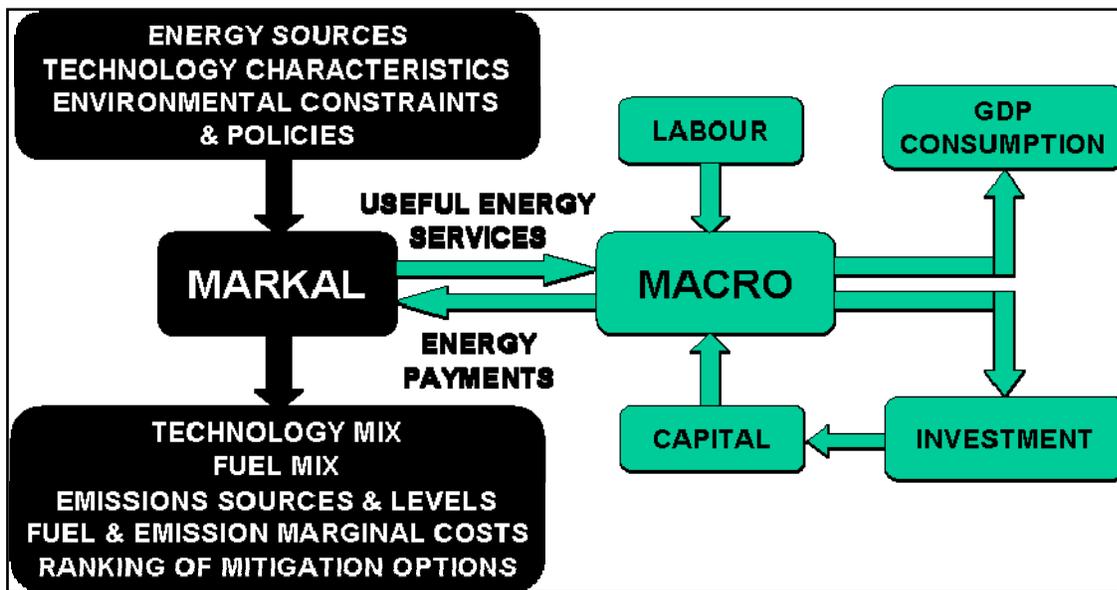
Figure 2: MARKAL-Macro overview schematic

In summary, M-M has four major features:
- An explicit calculation of GDP and other macro variables (consumption, investment)
- Demand feedbacks from changes in energy prices. In this formulation, although all sub-sectoral demands have the same price elasticity, they will respond differently depending on the total cost implications of altering demands for energy services. *All other things being equal, this additional system response and flexibility should produce lower policy costs*.
- Autonomous demand changes (e.g., with respect to increased aviation travel) to allow the M-M model to undertake scenario analysis where energy demands are decoupled from economic growth.
- Technological change and energy systems interactions within MARKAL as before.

Despite its relative simplicity (single region, no government sector), the practical implementation of a general equilibrium M-M model is difficult. Appendix 2 details the underlying equations for the Macro component, sample macro parameters for the UK, as well as the non-trivial procedure to implement within the UK MARKAL model.

2.1.3. Model strengths and weaknesses

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. However, that does not mean that MARKAL cannot be calibrated to the best available projection forecasts, at least in the near and medium term (see Appendix 3). Instead it offers a systematic tool to explore the trade-offs and tipping points between alternate energy systems pathways, and the cost, energy supply and emissions implications of these alternate pathways.

Principal advantages to be derived from using the MARKAL energy systems model include:

- Well understood least-cost modelling paradigm (efficient markets);
- Provides a framework to evaluate technologies on the basis of cost assumptions, to check the consistency of results and explore sensitivities to key data and assumptions;
- Transparent framework; open assumptions on data, technology pathways, constraints etc;
- Interactions within entire energy system (e.g. resource supply curves, competing use for infrastructures and fuels, sectoral technology diffusion);
- Ability to track emissions and energy consumption across the energy system, and model the impact of constraints on both
- As not constrained by past experiences or currently available technologies, the model can investigate long timeframes (in this case to 2050) and novel system configurations, thus providing information on the phasing of technology deployment.

And additional advantages from incorporating MARKAL MACRO include:
- Direct calculation of GDP and other macro variables;
- Demand-side behavioural response (to add to technical conservation, energy efficiency and exogenous changes in energy service projections).

Principal disadvantages from using such the MARKAL energy systems model include:
- 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.[1]
- Being deterministic the model cannot directly assess data uncertainties, which have to be investigated through separate sensitivity analyses;
- Limited ability to model behaviour (partially addressed by M-M);
- As a UK model there is no spatial disaggregation and hence less insight into the siting of infrastructures and capital equipment;
- There is an approximated temporal disaggregation, and hence possibly restricted insights into the supply-demand balancing of electricity, heat and other energy carriers;

And additional disadvantages from incorporating MARKAL MACRO include:
- Calibration and model operation time substantially increased due to movement from linear to non-linear optimization;
- Simplified general equilibrium approach neglects trade impacts, government sector and transitional costs and hence likely represents a lower bound on GDP impacts;
- Single and asymmetric price elasticity (applied to all demands which then adjust according to economic impact).

2.1.4. Consideration of uncertainty

A key attribute of the MARKAL optimisation process is a systematic approach to uncertainty. This is achieved through a "what-if" analysis that seeks to quantify sensitivities and tipping-points of moving between technology categories and energy pathways. This sensitivity

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[1] One example is the choice between two technologies with very similar costs; without constraints, the model could exclusively choose one technology and not the other (although in reality one might expect both to be used)

analysis is enabled through a broad set of scenarios (see section 3) that allow this decision space to be explored. In this DTI-DEFRA analysis the scenario sets are based on technology assumptions, global drivers of energy use, implementation of policy measures (CO_2 constraints) and alternate rates of innovation.

The alternate results detailed and discussed in sections 4 and 5 illustrate the complexity of insights as generated from a large energy system model. They should be viewed and interpreted in the light of generating robust insights over 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.

2.2. Project design and key parameters

The MARKAL and M-M models were set up with a core set of input parameters and model assumptions to run the range of scenarios for this DTI/DEFRA project. These are specified in more detail in Strachan et al (2006) and Appendices 1 and 2. However some key parameters and assumptions are worth describing further in this section. A summary of the main model parameters and assumptions are listed in Table 1.

Parameter	Value / Source
Time frame	2000-2050, in 5 yearly intervals
Discount rate	Global 10%: Market investment rate HURDLE RATE End-use sectors 25%: Increased payback period requirements
Fuel prices	DTI (2006b) Base import level; import and domestic stepped supply curves
Energy demands	DTI (2006b): Includes CCP and CCPR through 2020; low growth projection through 2070. Supplemented by information from DEFRA, BRE and DfT
Calibration	DUKES (2006): Final energy, primary energy, CO_2 emissions, electricity generation, fuel resources: aggregate (within 1%) and sectoral disaggregation (within 2%) DTI energy model: Sectoral energy and CO_2 emissions, within 1% in 2005 and 2% in 2010
Sectoral coverage	Industry (sub-sectors include chemicals, iron and steel, paper and pulp, non ferrous metals and other industry), services, residential, transport, agriculture, own energy industry use
Conservation	Demand technologies, energy savings devices (conservation); behavioural change (in M-M to some extent)
Load profiles	Actual year 2000 electricity and heat load profiles (National Grid, 2006)
Taxation and policy measures[2]	Included: CCL, hydrocarbon duty, transport fuel duty, LCP directive, renewables obligation (electricity & road), EEC, buildings

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[2] With the exception of the EU-ETS due to the uncertainties in projecting future carbon prices. The model is fixed to achieve at least 15% renewable generation by 2015 (or 2020 as M-M model employs ten-year increments).

	standards. Not included: EU ETS
Emissions	SO_2 & CO_2 additionally tracked by sector (electricity and H2 separately)
Emissions cap	CO2-60: 30% reduction from 2030; linear trend to 60% reduction from 2050 (from a year 2000 base value)
Technology treatment	Vintages for process, electricity, industrial transport, residential and commercial technologies Exogenous learning curves for early technologies in electricity, transport and hydrogen

Table 1: Summary description of core input parameters / assumptions

2.2.1. General structure

A range of key model inputs and energy system parameters are required to run the MARKAL and M-M models. The model is calibrated in its base year (2000), to match published UK statistics (DUKES, 2006) for final energy use (by fuel and sector), resource use, electricity generation and energy based CO_2 emissions. This entails a corresponding definition of residual technology capacities and use, and characterises when these plants would be retired and hence allow new technologies to be invested in as the model moves in 5 year time steps through to 2050[3]. Until the date of retirement, the total costs of new technologies must compete with the marginal costs of paid-off plants.

Upstream and agricultural sectors were included so that the model covers all energy use in the UK. All existing energy technologies and infrastructures are initially specified along with their operational life. All currently legislated major environmental and economic policies as of 2005 are included in the scenarios. All prices are in £(2000). The model then optimizes in 5 year time steps (through to 2050) and replaces technologies and infrastructures throughout all possible energy chains as they as they retire, taking into account:

- Changing energy resources supply curves (domestic and imported)
- Exogenous trends in energy service demands
- Changing technology costs (via vintaging and exogenous learning curves)
- Alternate energy chain configurations
- Physical constraints within the model
- Policy induced constraints within the model
- Taxes and subsidies
- (And in M-M) varying energy service demands

2.2.2. Energy prices

MARKAL requires exogenous guidance on upstream energy prices. In this updated version of UK MARKAL, domestic fossil and renewable resources, and fossil imports are depicted via supply curves rather than discrete values. Table 2 lists representative baseline, high case and low case fossil import prices in £2005 (DTI, 2006b). From these, multipliers calibrated

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[3] The UK MARKAL and M-M models optimize through to 2070 with an end of horizon treatment to account for yet later periods, although only results through to 2050 are presented in this report.

from baseline relative prices (adjusted to £2000) are used to translate these into prices for both higher priced supply steps as well as imported refined fuels. Systematic sensitivity analysis is carried out on these input prices (section 3). It is noted that more recent UK government projections of future energy prices have increased due to developments in world energy markets.

Year	Baseline			High Prices			Low Prices		
	Oil $/bbl	Gas p/therm	Coal $/GJ	Oil $/bbl	Gas p/therm	Coal $/GJ	Oil $/bbl	Gas p/therm	Coal $/GJ
2005	55.0	41.0	2.4	55.0	41.0	2.4	55.0	41.0	2.4
2010	40.0	33.5	1.9	67.0	49.9	2.4	20.0	18.0	1.4
2015	42.5	35.0	1.9	69.5	51.4	2.6	20.0	19.5	1.2
2020	45.0	36.5	1.8	72.0	53.0	2.6	20.0	21.0	1.0
2025	47.5	38.1	1.9	77.0	56.0	2.6	22.5	22.5	1.1
2030	50.0	39.6	2.0	82.0	59.0	2.8	25.0	24.0	1.2
2035	52.5	41.1	2.1	82.0	59.0	3.0	27.5	25.5	1.3
2040	55.0	42.6	2.2	82.0	59.0	3.0	30.0	27.0	1.3
2045	55.0	42.6	2.2	82.0	59.0	3.0	32.5	28.5	1.4
2050	55.0	42.6	2.2	82.0	59.0	3.0	35.0	30.0	1.5

Table 2: Exogenous base fossil fuel import prices

2.2.3. Energy service demands

An exogenous depiction is used for energy service or 'useful' energy demands, in physical units (e.g., billion vehicle kilometres for transport modes). MARKAL's final energy consumption (a model output based on energy service demands) are compared with aggregated sectoral energy demand projections in actual energy units from DTI (2006b). Convergence criteria between MARKAL and the DTI model predictions are discussed in Appendix 3. Note that only domestic transportation (shipping, and air) is included in model runs (detailed in section 4) in line with national emissions accounting.

Energy service demands are verified using additional sources including BRE buildings data (Shorrock and Uttley, 2003) and Department of Transport projections (DfT, 2005). These energy demands already account for legislated programs (for example the energy efficiency commitment (EEC) phase 1 and 2 through to 2020 (DEFRA, 2005a). Note that in actuality energy service demands are further broken down into specific end uses or sub-sectors. Further information is contained in Appendix 1, Strachan (2006) and Kannan (2007).

Note that under the M-M variant (see section 2.1.2 and Appendix 2), energy service demands are endogenous and respond from these base levels as final energy costs change, and according to the overall price elasticity and the individual demand marginals (See Appendix 2).

Changes in energy service demands vary between sectors, with annual growth rates shown in Table 3 below. Transport is the sector where the most significant increases in demand are

found, with other individual sub-sectoral instances of high demand growth (e.g., residential cooling from its current small base). The industrial sector sees relatively low growth in energy service demand, linked to the continuing restructuring of the UK economy.

		2000 - 2030	2030-2050			2000-2030	2030-2050
Industry	Chemicals	0.44%	0.19%	Service	Cooking	0.11%	0.00%
	Iron & steel	0.44%	0.19%		Cooling	1.50%	0.91%
	Non ferrous metals	0.45%	0.18%		Other electrical	0.41%	0.31%
	Other industry	0.44%	0.19%		Space heating	0.00%	0.00%
	Paper & pulp	0.44%	0.19%		Water heating	0.05%	0.07%
Residential	Cooling	9.13%	2.73%		Lighting	0.33%	0.42%
	Other Electrical	0.88%	0.52%		Refrigeration	0.04%	0.00%
	Space Heating	0.70%	0.04%		Air (domestic)	4.13%	4.30%
	Water Heating	0.50%	0.31%	Transport	Bus	0.97%	-0.10%
	Lighting	0.83%	0.49%		Car	1.09%	0.39%
	Refrigeration	0.84%	0.49%		Rail freight	0.94%	2.52%
	Cooking hob	0.83%	0.49%		HGV	0.93%	0.14%
	Cooking oven	0.83%	0.49%		LGV	1.60%	1.28%
	Chest freezer	0.72%	0.43%		Rail passenger	1.16%	2.76%
	Fridge freezer	0.86%	0.51%		Shipping (dom)	0.11%	0.51%
	Upright freezer	0.98%	0.57%		Two wheels	1.44%	-0.48%

Table 3: Service demand annual growth rates for end-use sectors, 2000-2050
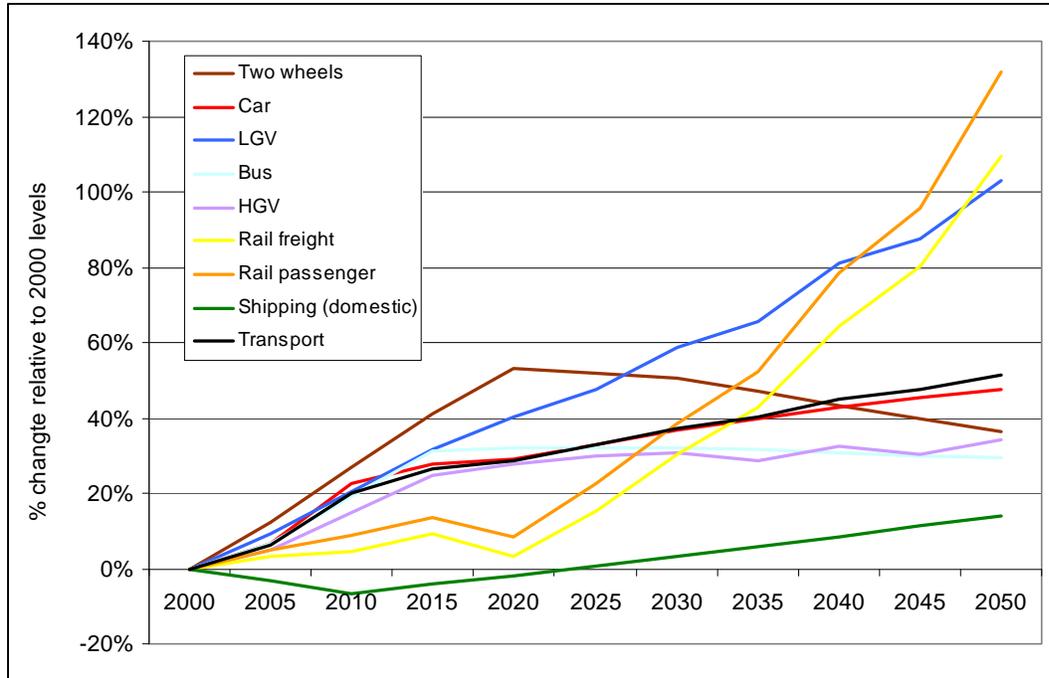
Figure 3: Demand growth trend for transport sector, 2000-2050

Overall, transport service demand rises from 485 billion vehicle km in 2000 to 734 B.v.km in 2050, an increase of approximately 50% (or annual growth rate of just over 1%).[4] There is significant variation between different transport modes. The largest relative increase comes from domestic air travel demand (not shown in Figure 3) which increases by over 550%.

2.2.4. Model system parameters

A range of system parameters need to be defined for the UK MARKAL model. These include the seasonal variation of electricity and heat demands, peaking constraint in the various electricity and heat grids (to account for instantaneous daily peaks plus the reserve margin), and a range of emission factors (EIA, 2005) for CO_2 and SO_2 which are tracked upstream based on input fuels, accounting for retrofitted control options. Sectoral emissions are also tracked (agriculture, electricity, industry, residential, services (commercial), transport, and upstream (refining and oil/gas extraction).

Another key system parameter is the discount rate for inter-temporal trade-offs. This global model parameter is the social time preference which accounts for time preference (both pure time preference and the element of possible catastrophe that wipes out return from investment), plus a value related to future income growth and hence declining marginal utility of future returns. The UK government uses a discount rate of 3.5% (HMT, 2006). However, in UK MARKAL technologies are specified with a higher technology-specific discount or hurdle rate to account for market risks and consumer preferences. In this

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[4] However, note this aggregated figure is skewed against larger vehicle modes (i.e. air, HGV etc)

analysis, upstream, electricity and other conversion technology investments use a discount rate of 10% to reflect current market instability, while end-use efficiency options must overcome a 25% hurdle rate to reflect documented barriers of risk or non-economic factors such as information availability (see Train, 1985). Discount or hurdle rates thus take one step in addressing non-cost drivers of technology take-up.

A final set of Macro parameters are detailed in Appendix 2. Key assumptions include base year UK GDP of B£(2000) 1035.3 (ONS, 2006), and projected annual GDP growth rates of 2% (equivalent to long term UK GDP growth rate). An aggregated elasticity of substitution (ESUB) between the energy aggregate and the labour-capital aggregate of 0.3 is used. This parameter is not available from statistics; but is derived from past ETSAP model estimate. For developed countries, lower end ESUB parameters (0.2 – 0.3) are more appropriate for models with detailed technological substitution and conservation in end-use sectors. Upper end sensitivities at 0.4 – 0.5 are more appropriate for less detailed models.

2.2.5. Treatment of energy efficiency

A key methodological issue is the treatment of energy efficiency. In addition to the 25% hurdle rate, further standardisation of the uptake of energy efficiency options in MARKAL's cost optimal framework is taken from DEFRA (2005a). This is to ensure that in the base case at least, historical rates of conservation uptake are continued. The model is then given long-term (post 2020) freedom in CO_2 constrained runs to select accelerated energy efficiency technologies and measures if it is cost optimal to do so. It is important to note the four types of demand response in the model:

- Exogenous depiction of energy service demand that are decoupled (higher: e.g., domestic aviation, or lower: e.g., some industrial sub-sectors) from UK overall economic growth;
- Energy efficient technologies: devices that produce energy carriers or meet energy demands at lowered levels of input fuel (e.g., condensing boilers), which are bundled into the overall MARKAL energy pathways;
- Energy conservation: devices that reduce demand for energy services (e.g., loft insulation), which are labelled *conservation* in the model;
- Behavioural change: responses to delivered energy prices (e.g., lowering home thermostat temperatures), which is only considered using the M-M model.

2.2.6. Model constraints

As a cost-optimising model, MARKAL requires constraints to ensure that the solution calculated is consistent with our understanding of how the UK energy system is developing in actuality. One set of constraints are linked to physical parameters such as the availability of types of storage capacity for sequestered CO_2. A further set is linked to representing legislated (as of 2005) policies. A final set responds to guide realistic market trends, including if the model was left to cost-optimise with total freedom, certain technologies could dominate with only modest costs advantages. Conversely, the purpose of using a model such as MARKAL is to gain some insights into longer term technological pathways and

associated costs. A balanced approach is required between realism and an over-specification of the model through too many constraints.

Example of constraints used in the model include:
- Constraints are included in limiting the gas and/or coal-based CCS technologies within the carbon storage limits;
- Limitations on certain fuel blends e.g. bio-diesel- in cars, co-firing in power plant
- Policy implementation e.g. Renewables Obligation (RO), Renewable Transport Fuel Obligation (RTFO);
- Conservation measures are limited to DEFRA's estimate under the Energy Efficiency Commitment (EEC);
- Physical constraints are imposed to smooth resource import/exports trends;
- Physical constraints are imposed to smooth the rate of growth or decline in power generation;
- Maintenance of lower shares of the transport fleet mix to reflect urban and rural conditions;
- Max & min limits to prevent 'complete' fuel switching in gas or electricity heating
- Use of existing stock of end-use appliances
- Limits on investment of new residential coal boilers, or new versions of existing power technologies (e.g. Magnox reactors)

2.2.7. Technology characterisation

A key input into the model is a realistic representation of future technology costs – which are enabled through data covering capital and operating costs, efficiency, availability, operating lifetime, and diurnal or seasonal characteristics. Fossil extraction, energy processes (e.g., refineries), infrastructures, nuclear technologies, transport, buildings, industrial and many electricity technologies utilise vintages to present improvements through time, while less mature renewable electricity and hydrogen technologies have an exogenously calculated learning rates based on the published literature (McDonald and Schrattenholzer, 2002) together with global technology uptake forecasts (IEA, 2006). The underlying principles guiding this process are as follows:
- Technologies were assumed to be developed globally and to benefit from advances in design, engineering and production;
- Costs and performance data were set to be representative of commercially deployed technologies enjoying the benefits of volume production, and of good installation and operation practices;
- Energy taxation and other financial mechanisms are incorporated explicitly at the appropriate point in the energy chain.

It is important to note that a "technology" in MARKAL refers to the entire range of variables in the model, including varied items including resource supply steps, pipelines, refineries, power plants, and end-use conservation technologies. The model has some thousands of technologies (where 'technology' refers to all model elements from resources to end-use appliances) each with a range of time stepped or time independent parameters. Connecting

all these technologies are over 500 energy carriers. Appendix 1 and Kannan et al (2007) provide additional detail.

3. Development of MARKAL scenario analysis

3.1. Selection of scenarios

Section 3 sets out the extensive scenario set under this DTI-DEFRA project. Given the complexity of projecting the evolution of the UK energy system over a 50-year period, a number of scenarios were combined to come up with a range of estimates. These include model runs using the standard MARKAL and MARKAL-Macro versions, and based on UKERC assumptions and DTI-DEFRA assumption sets. The total number of undertaken scenarios is illustrated in Table 4 below.

Model type / Assumptions	UKERC	DTI / DEFRA
Standard MARKAL	15	12
MARKAL-Macro	17	10

Table 4: Total DTI-DEFRA scenario set

A diverse scenario set was selected according to key issues as identified by DTI-DEFRA to explore the policy decision space around international and domestic drivers of UK energy use, particularly under long term domestic CO_2 reduction futures. These included alternate assumptions on classes of technologies, scope of energy efficiency, progress in innovation, global resource prices and additional policy assumptions. They are not intended to be an exhaustive set nor to account for a probability range of possible future energy systems. In particular, scenarios involving major unforeseen events were not modelled. Thus this scenarios set is not meant to provide 'forecasts' of what we expect to happen between now to 2050, but a systematic 'what-if' analysis of what in principle could deliver reductions in carbon emissions, what the trade-offs are between different mitigation pathways, and what the costs might be.

3.2. Assumption sets

UKERC assumptions
One set of results is based on the full UK MARKAL model, as developed under the direction of UKERC Energy Systems Modelling programme. The technology database has been developed on the basis of the literature review, sector review process, and stakeholder workshops, as summarized in Appendices 1 and 3, and comprehensively in Kannan et al (2007). In the base-case conservation technologies were constrained to DEFRA (2005a) estimates of efficiency uptake through 2020 with the model being given the freedom to choose cost-effective uptake in later years in the CO_2 constrained scenarios.

<u>DTI/DEFRA assumptions</u>

In addition to the above runs, DTI / DEFRA requested a set of model runs with a limited number of changes to the UKERC assumptions. These were separated out into high, central and low cost scenarios.

- Some of the data for electricity technologies was changed, to ensure consistency with the data used in the Energy Review electricity cost analysis (DTI 2006a). This included the use of central, low and high estimates of costs and performance characteristics. This also entailed the simplification of the nuclear fuel cycle with only one resource supply step.
- Assumption concerning conservation were changed, to reflect a more limited uptake of conservation as suggested by DEFRA. Conservation was limited to 25%, 50% and 75% of DEFRA's estimate in high, central and low cost scenarios
- Finally, the role of hybrid vehicles was restricted by adjusting future hybrid technology improvements and hence their fleet penetration

In this report, the focus is the on the presentation and analysis of results from the MARKAL-Macro (M-M) model, primarily using the UKERC set of assumptions. Results focusing on technology sensitivities on the standard MARKAL runs and outputs, together with M-M results with DTI technology assumptions are provided in Appendix 4.

Table 5 details the 27 model runs were undertaken using the M-M model, for the full UKERC model version and the DTI variant version.

Assumption set	Scenario	Scenario description
UKERC	M-BASE	Base (MARKAL-Macro)
	M-C60	60% CO_2 constraint applied as a 30% reduction in 2030 – straight line interpolation to 60% reduction in 2050
	M-C60SLT	60% CO_2 constraint applied as a straight line trajectory from 2010
	M-BASE_H	M-M base with high global resource prices
	M-BASE_L	M-M base with low global resource prices
	M-C60_H	As M-C60 with high global resource prices
	M-C60_L	As M-C60 with high global resource prices
	M-BASE_R10	M-M base with innovation limited to no technologies beyond a 2010 vintage
	M-BASE_R20	M-M base with innovation limited to no technologies beyond a 2020 vintage
	M-C60_R10	As M-C60 with innovation limited to no technologies beyond a 2010 vintage
	M-C60_R20	As M-C60 with innovation limited to no technologies beyond a 2020 vintage
	M-C60_NN	As M-C60 with no new nuclear
	M-C60SLT_NN	As M-C60SLT with no new nuclear
	M-C60_nCN	As M-C60 with no new nuclear nor CCS
	M-C60SLT_nCN	As M-C60SLT with no new nuclear nor CCS
DTI / DEFRA	DM-BASE_C	M-M base – DTI central costs
	DM-C60_C	60% CO_2 constraint applied as a 30% reduction in 2030 – straight line interpolation to 60% reduction in 2050
	DM-BASE_H	M-M base – DTI high cost assumptions
	DM-C60_H	As DM-C60_C but with high cost assumptions
	DM-BASE_L	M-M base – DTI low cost assumptions
	DM-C60_L	As DM-C60_C but with low cost assumptions
	DM-BASE_N	As DM-BASE_C but with no new nuclear
	DM-C60_N	As DM-C60_C but with no new nuclear
	DM-BASE_L	As DM-BASE_C but with improved renewable technology cost but restriction to 15% RO
	DM-C60_L	As DM-C60_C but with improved renewable technology cost but restriction to 15% RO

Table 5: Full set of MARKAL-Macro scenarios

In addition to differences in the core assumptions (UKERC vs. DTI/DEFRA), the scenarios explore the following issues:

- *Different CO$_2$ constraint levels* (although the focus of this analysis is on the 60% reduction in 2050). These scenarios explore differences in technology pathways and costs of moving towards a less stringent reduction.
- Use of a *straight line trajectory* (SLT), with CO$_2$ reductions in 2010, extrapolated to the 2050 reduction level (60%). These scenarios explore changes to technology choices where abatement actions are required earlier in the model time horizon.
- *Variation in energy prices*, with high and a low energy import resource price curves assumed. Given the uncertainties of prices levels of energy in future years, this is an important sensitivity to explore changes to the energy system due to variation in international drivers.
- *Limiting technological innovation*. Many assumptions have been made in the base case concerning how technologies will improve technically and have lower costs in future years. This scenario assesses a more pessimistic outlook, whereby costs and technical performance remain at similar levels as estimated in 2010 and 2020.
- *Limiting role of key low carbon technologies*. Nuclear and carbon capture and storage (CCS) could potentially play an important role in future years. These scenarios explore how the energy system responds to stringent constraints without these key technologies being available.

In the main, the above M-M scenarios reflect the important issues that DTI/DEFRA prioritised for exploration explore in this analysis to inform the policy discussions emerging from the Energy Review activities, which feed into the 2007 Energy White Paper publication. Appendix 4 discusses additional sets of scenarios that focus on technological sensitivity on classes of technologies, including grid-connected renewables, micro-generation and end-use efficiency.

4. Key Model Results

In this section and in Appendix 4, a full range of results from the main scenarios conducted to inform the 2007 Energy White Paper are presented and discussed. These focus on the base-cases and the CO_2 constrained cases to explore the costs of reducing UK economy-wide emissions by 60% by 2050.[5] This report expands upon the results presented in the companion policy report (DTI, 2007) which focus on a core set of results using the UKERC dataset and the general equilibrium M-M model.[6]

The following discussion focuses on key model results:
- UKERC M-M – base-case, CO_2 constrained and alternate emission trajectory (SLT)
- UKERC M-M – fuel price scenarios
- UKERC M-M – restricted innovation, no-nuclear, no-CCS no-nuclear scenarios

Results from additional scenario runs (including standard model runs) are used to further discuss key trade-offs between mitigation pathways.

Additional standard and M-M model results are discussed in Appendix 4:
- UKERC optimistic technology (by technology class)
- UKERC pessimistic technology
- UKERC alternate targets (60%, 40%, 20%)
- DTI M-M technology cost scenarios

These runs include additional metrics focusing on hydrogen production, the range of transport modes, and the interplay between imports, exports and domestic production of resources.

M-M and MARKAL generate over 500 distinct outputs for each scenario, although in this analysis the focus is on 16 primary metrics. These are grouped into the following sub-sections:
- System evolution
    - Final energy
    - CO_2 emissions
    - Primary energy by fuel
    - CO_2 emissions by sector
- Technology pathways
    - Electricity
    - Transport

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5 Relative to year 2000 levels (note, this is consistent with the 2003 Energy White Paper analysis). The UK carbon target under the proposed Climate Change Bill is relative to 1990 levels.

[6] Note that the M-M model makes explanation necessarily more complicated as the demand response means the size of the energy systems is changing in addition to the normal competition between fuels, supply pathways, demand technologies etc.

Note also that the M-M NLP optimization process is necessarily less precise that the standard LP solver meaning that some minor approximation can exist in the final solution (even using state-of-the-art commercial NLP solver).

o   End-use (conservation, demand reductions)
- Economic impacts
    - o CO_2 prices (marginal and average)
    - o   Energy system costs
    - o   GDP, investment, consumption

4.1 System evolution

4.1.1. Final energy time trends

Figures 4a, 4b, 4c, and 4d illustrate final energy[7] evolution through 2050 under the various base-cases and 60% CO_2 reduction scenarios. Several themes emerge that subsequent results expand upon. In particular, the model appears to behave logically with output metrics responding with the correct sign although varying magnitudes to changes in input assumptions. The energy systems approach captures the interplay between alternate technology pathways, as well as between upstream and end-use sectors as the UK energy economy decarbonises. An absolute 60% reduction in CO_2 emissions imposes radical changes in the resourcing, processing, conversion, distribution and use of energy, with all energy sectors undergoing significant changes. The resultant economic implications (discussed in section 4.3) are sizeable although moderated by the relative decline in the size of the energy sector as part of the economy, the role of technological innovation and demand-side reduction through efficiency, conservation and behavioural change.
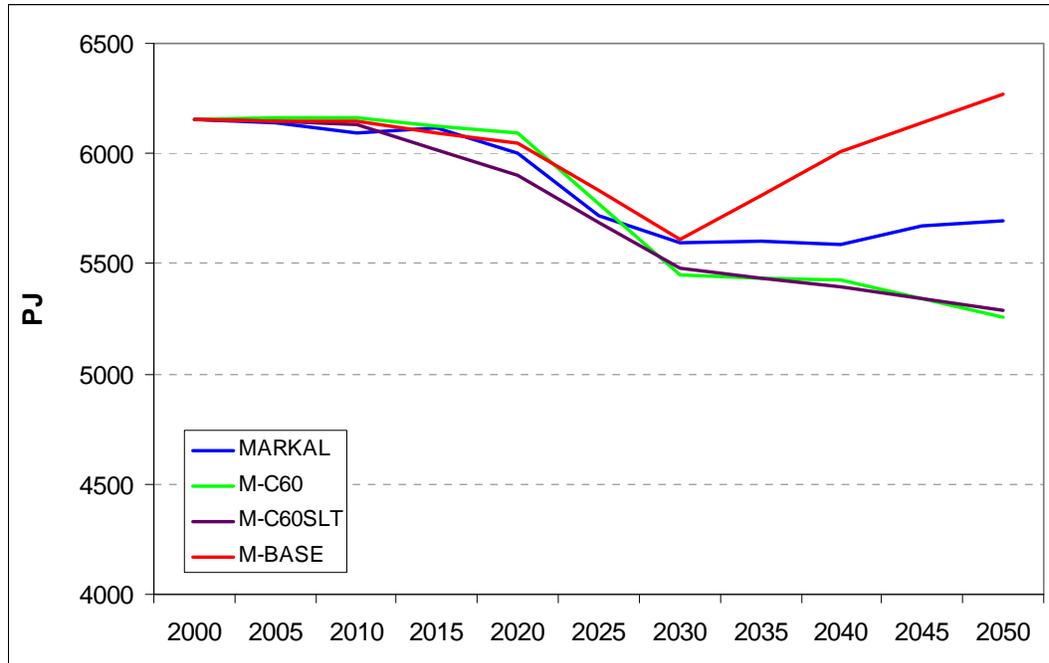

Figure 4a: Final energy – base and CO_2 constrained case

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[7] Note that non-marketed renewables (hydro, solar, wind, geothermal etc) only have their electricity output as a contribution to final energy

Under the general set of UKERC assumptions, the M-M model generates a low energy and CO_2 emissions growth baseline from 6,152PJ [8] in year 2000 to 6,272PJ in year 2050. The baseline is critical in defining the magnitude of changes required to meet a CO2 constraint (or other policy imposed outcomes. In the M-M and MARKAL models, low baseline growth (particularly in 2000-2030 where final energy falls) occurs due to modest estimates of energy service demand growth (see section 2) and considerable technological change occurring even in the absence of a carbon price signal. This includes the uptake of end-use conservation, implementation of higher efficiency plant and a proportion of renewable power in the electricity sector, and importantly a switch to hybrid vehicles (including private transport) followed by hydrogen vehicles in some transport modes (bus followed by LGVs and HGVs) (see Figure 4b). These profound changes are spurred by globally developed technologies, improved use of existing infrastructures, steady efficiency improvements in end-use energy patterns and steadily rising resource prices. The M-M model's later period growth (2030-2050) is higher due to its treatment of demand level technology options where capital costs and efficiency advantages in each category are gauged relative to a base technology and hence tends to be more sensitive to early-year considerations (see Appendix 2 for a full discussion).
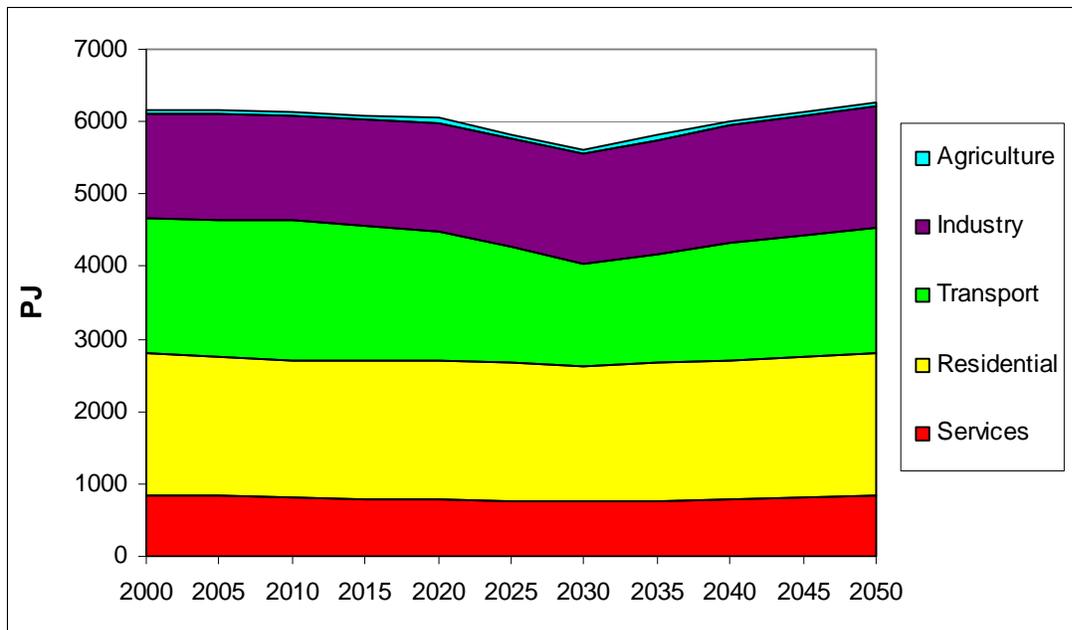
Figure 4b: Sectoral final energy consumption (Base case (M-BASE))

Higher or lower global fossil resource costs (Figure 4c) lead to lower (8.4% in 2050) or higher (3.0% in 2050) base-case energy consumption respectively. If innovation is limited (Figure 4d) to either 2020 or further to 2010 levels of improvement (in both vintages of new technology and learning rates for less mature technologies), base case final energy use is higher still, with an increase of 4.9% and 10.7% respectively. This reflects the lower efficiency of technologies due to restricted innovation combined with less access to new conservation measures and new renewable sources, and therefore the higher energy usage.

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[8] For conversion purposes, 1 petajoule (PJ) = 0.025 MTOE (million tonnes oil equivalent)
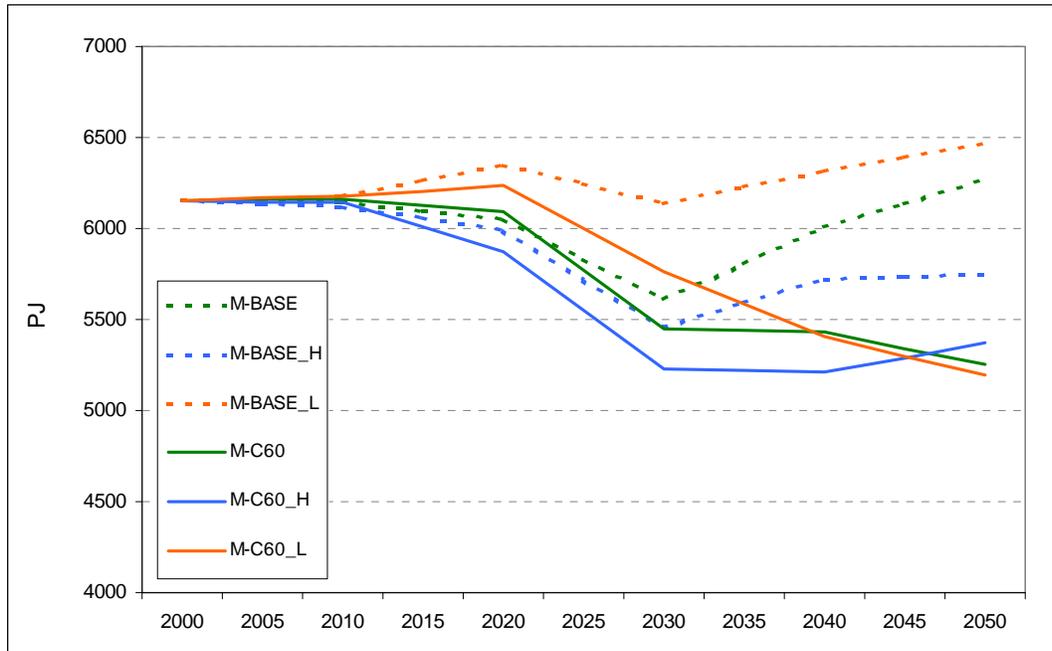
Figure 4c: Final energy – resource price scenarios
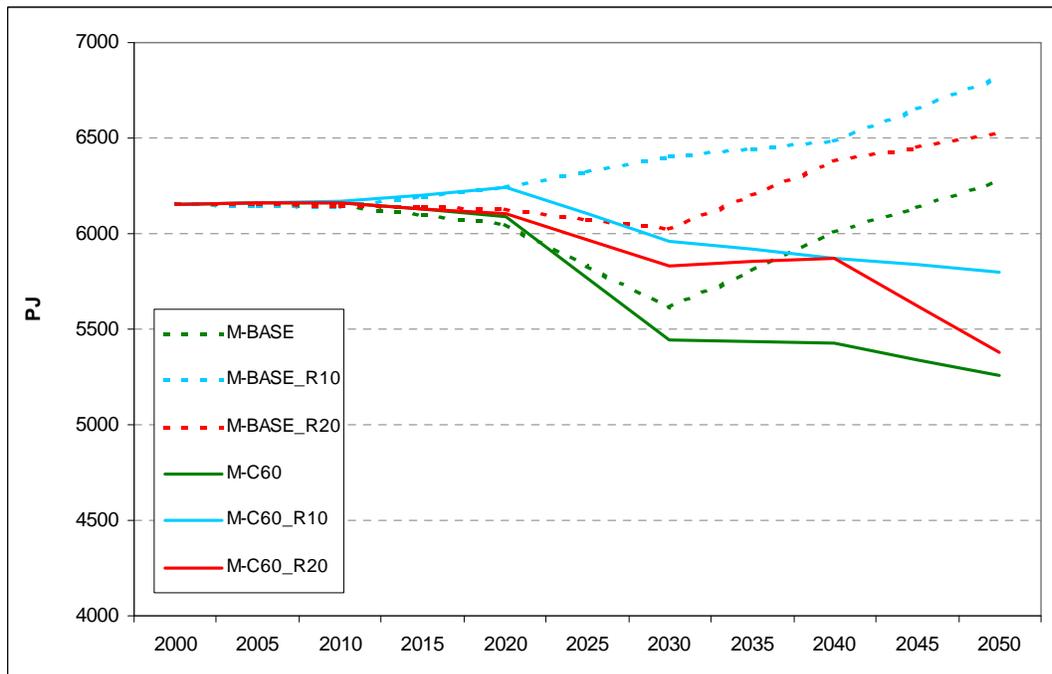
Figure 4d: Final energy – UKERC innovation scenarios

Under CO_2 constraints, the reductions in energy consumption are substantial, falling to around 5,250 PJ. The earlier imposition of the CO_2 constraint (SLT) results in energy reductions in 2010-2030, mainly in the transport and service sectors. Both high and low

price resource cases see energy consumption reductions similar to the central case (around 5,250PJ), with the level of 'effort' much greater in the low price case. The comparison is complicated by the changing economics of coal vs. gas under alternate resource prices assumptions. As the price component of natural gas is relatively larger than coal in most energy applications, higher efficiency gas is favoured under low price assumptions leading to slightly lower overall final energy use. For the technology scenarios, restrictions on major electricity technology classes (nuclear and CCS[9]) result in further end-use efficiency and demand reductions. However these reductions are not mirrored in the restricted innovation scenarios as here advanced efficiency and conservation technologies are limited thus imposing more pressure on fuel switching to meet the overall CO_2 constraint.

Figure 5 illustrate one ratio for final and primary energy – between primary and final energy for the base (BASE) and CO_2-60 (M-C60) cases respectively – illustrating the energy intensity of consumption across all sectors. This ratio initially falls [both with and without a constraint] due to upstream efficiency gains and the use (initially driven by the UK Renewable Obligation (RO) of non marketed renewable energy resources[10] (which like nuclear energy, only have their electricity production classified as primary energy (as in standard energy statistics reporting (DUKES, 2006). This latter effect is more important in the CO_2 constrained case towards the latter part of the modelling horizon. Section 4.1.3 gives further information on primary energy by fuel.
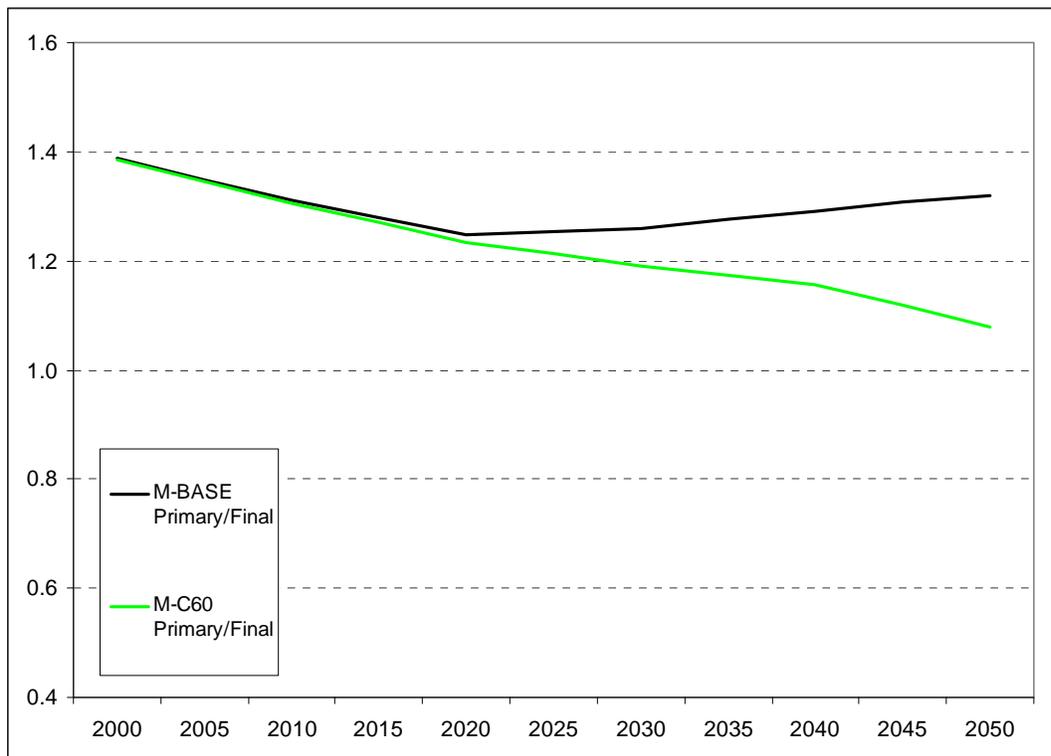
Figure 5: Primary and final energy comparison

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[9] Carbon capture and storage
[10] Marketed renewable resources are the range of biomass and waste options

4.1.2. CO_2 time trends

Figure 6 details carbon dioxide (CO_2) emissions from the respective M-M model runs, and compares this to the DTI Energy Review baseline (DTI, 2006). Appendix 3 details the convergence process between DTI projections and M-M model base results. Section 4.1.4 details sectoral CO_2 reductions for the various constraint cases.

To reiterate a key point, even in the base case (i.e., in the absence of an economy-wide CO_2 constraint), there is still pervasive technological change. Emissions may still fall in the base case as the model will invest in energy saving and/or lower carbon technologies so long as it is cost effective. This is the principal reason why the M-M model generates lower long-run energy and carbon projections than the DTI energy model which relies on econometric projections using currently available technologies.[11] In the central M-M fuel base case (M-BASE), there is some reduction in emissions to 2020, from 545 MTCO$_2$[12] to 489 MTCO$_2$. This is driven by cost effective potential for conservation measures and more efficient end use technologies[13], and the impact of near-term renewables (RO) and energy efficiency policies.
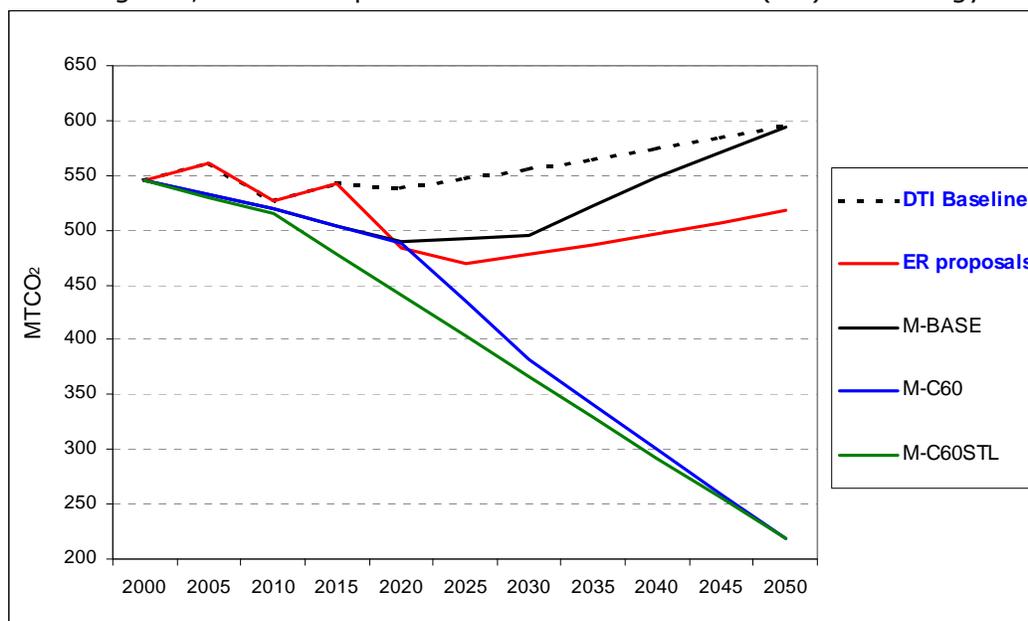
Figure 6: CO_2 trends and emission constraints

Under CO_2 constraints, two emissions paths are explored – one where the model achieves 30% by 2030, thereafter falling linearly to 2050 (M-C60) and where the model is constrained to achieve a 'straight line trajectory' (SLT) abatement path to 2050 (M-C60SLT). Under these CO_2 constraints the energy system is required to abate around 375

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[11] This approach allow the DTI energy model (and other econometric approaches) to better match near-term changes in energy use and supply.

[12] For conversion purposes, 1 TCO$_2$ = 44/12 TC

[13] MARKAL as a cost optimisation model with perfect foresight may overestimate this cost-effective abatement despite a higher hurdle rate in end-use sectors (25%), due to the impacts of imperfect knowledge and non-cost preferences

MTCO$_2$ by 2050, in order to meet a 60% reduction from 2000 levels (to around 218 MTCO$_2$). Following a straight-line trajectory (SLT) to 2050 forces the model to abate earlier and implies more effort on a cumulative measure, with total SLT emission reductions rising to 7,205 MTCO$_2$ as shown in Figure 7, compared to approximately 6,460 MTCO$_2$ under the non-SLT constraint (M-C60). The SLT trajectory has implications on the energy mix as earlier investments need to be made on available abatement options, and on costs due to the greater and earlier overall emissions reductions.
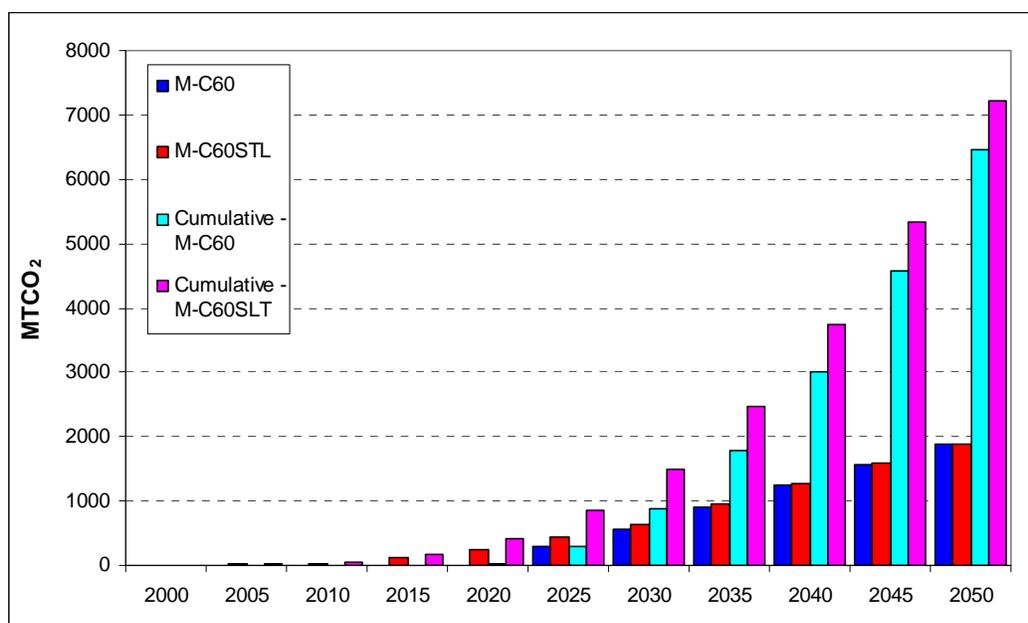
Figure 7: Annual and cumulative CO$_2$ emission reductions

4.1.3. Primary energy mix by fuel

Figures 8a and 8b detail the primary energy mix by fuel in the base year (2000) and in 2050 for the various scenarios. As per standard energy statistic reporting, only the electricity generation from nuclear and non-marketed renewables[14] is reported. In the base year, the negative component of refined oils, and the higher overall primary energy (8,626 PJ) reflects the export orientation of the UK oil and natural gas sectors, as discussed in Appendix 4. The base-case primary energy in 2050 (PJ) is lower than the year 2000 levels owing to moderate growth in final energy demand, a limited switch to renewable fuels (mainly through near term policies, including conservation measures through the Energy Efficiency Commitment (EEC) and the electricity (RO) and transport (RTO) renewables obligation) and a more substantial technological improvements throughout the energy system. A substantial primary energy reduction is consistent across the CO$_2$ reduction scenarios, which average around 60% of base-case primary energy consumption by 2050.

Natural gas and coal constitute the dominant base-case primary energy fuels, with the former used in high-efficiency direct-use applications in the residential, services and

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[14] Hydro, solar, wind, geothermal

industrial sectors, with next generation coal as the largest electricity generation and hydrogen production technology. In the CO_2 constrained scenarios, natural gas strengthens its position as the largest component (35%-40%) of primary energy, with its cost effective application in electricity generation boosted due to relative economic advantages of gas in the lower resource price case. Coal use remains significant at around 20% based primarily on CCS applications.

Nuclear retains a share of base-load generation in many but not all scenarios, largely due to the path dependent nature of long-lived technologies and plants dependent on the specific timing and cost effectiveness of CO_2 abatement options. Oil and refined oil use see significant reductions due to efficiency and fuel switching (to hydrogen) in various transport modes. The splits between oil and refined oil in high and low resources price cases is a reflection of whether higher cost UK oil reserves will be exploited in the medium- or long-term. Finally marketed and non-marketed renewables see a significant growth in all constrained scenarios, the rate of which is largely based on the availability of other zero-carbon and efficiency options. In both the no nuclear-CCS scenario and the 2010 limit innovation scenario, renewables reach a 30% primary energy share.
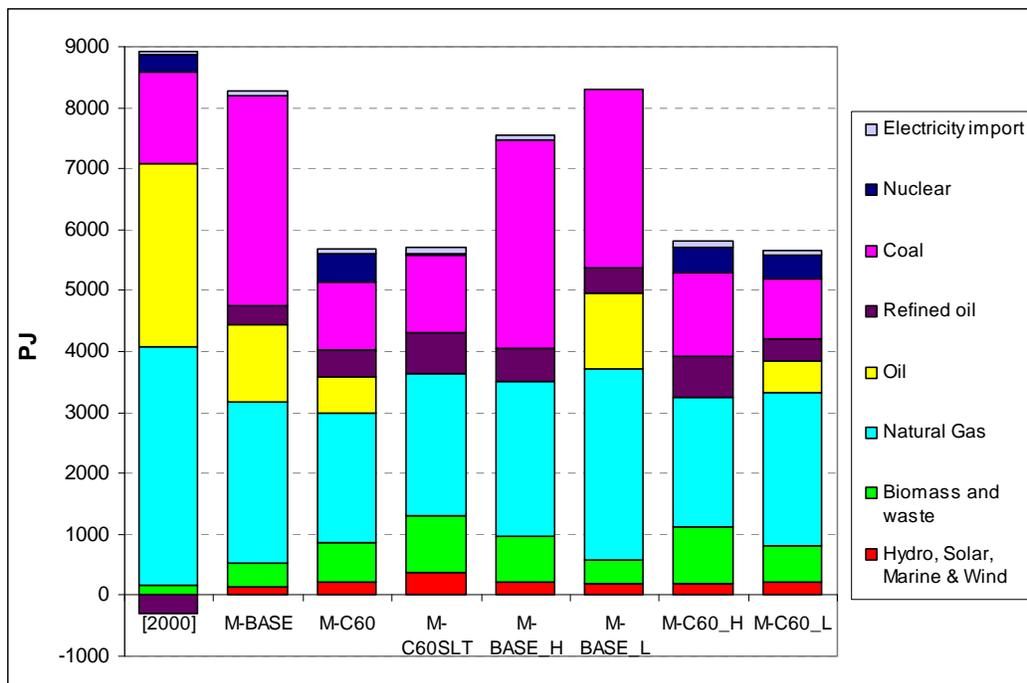
Figure 8a: Primary energy comparison – core and resource scenarios
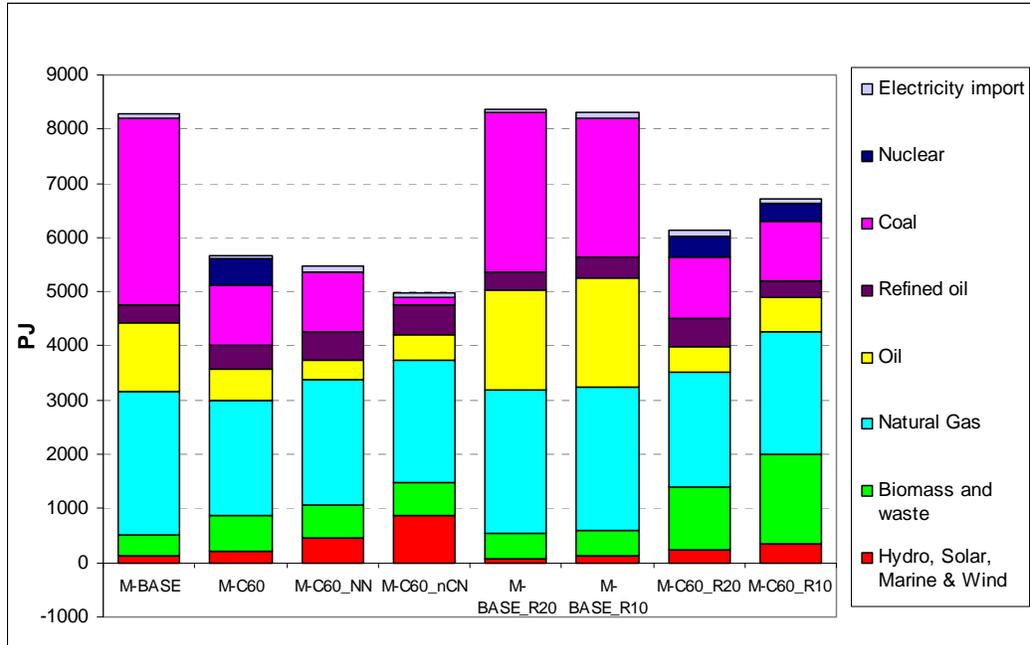
Figure 8b: Primary energy comparison – technology scenarios

4.1.4. Sectoral CO_2 emissions

In general for the CO_2 constrained scenarios, all upstream and end-use sectors contribute to the stringent 60% reduction target (from a 2050 base-case projection of 596 $MTCO_2$ to 218 $MTCO_2$). As illustrated in Figure 9a for the core CO_2 constrained case, the electricity sector is a major source of carbon reductions, complimented by fuel switching, efficiency conservation measures and demand reductions in the end-use sectors. The small increase in 2020 is a reflection of the model utilising existing carbon intensive capital before the constraint is implemented.
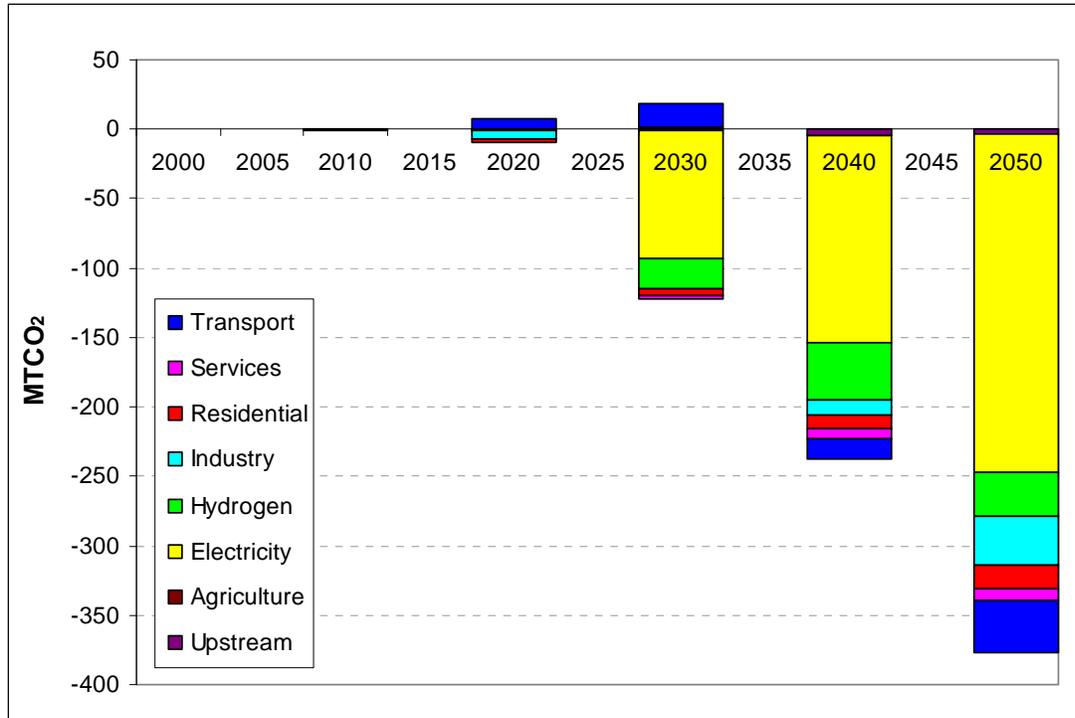
Figure 9a: Sectoral CO_2 emission reductions

Figure 9b shows the reduction in emission but with hydrogen and electricity reductions allocated[15] to their respective end-use sectors. In this model run, all hydrogen production is utilised by the transport sector, and hence shows a more realistic depiction of the role of the transport sector in the overall system decarbonisation. Transport is the last sector to decarbonise.

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[15] UK MARKAL tracks electricity and hydrogen production by sector
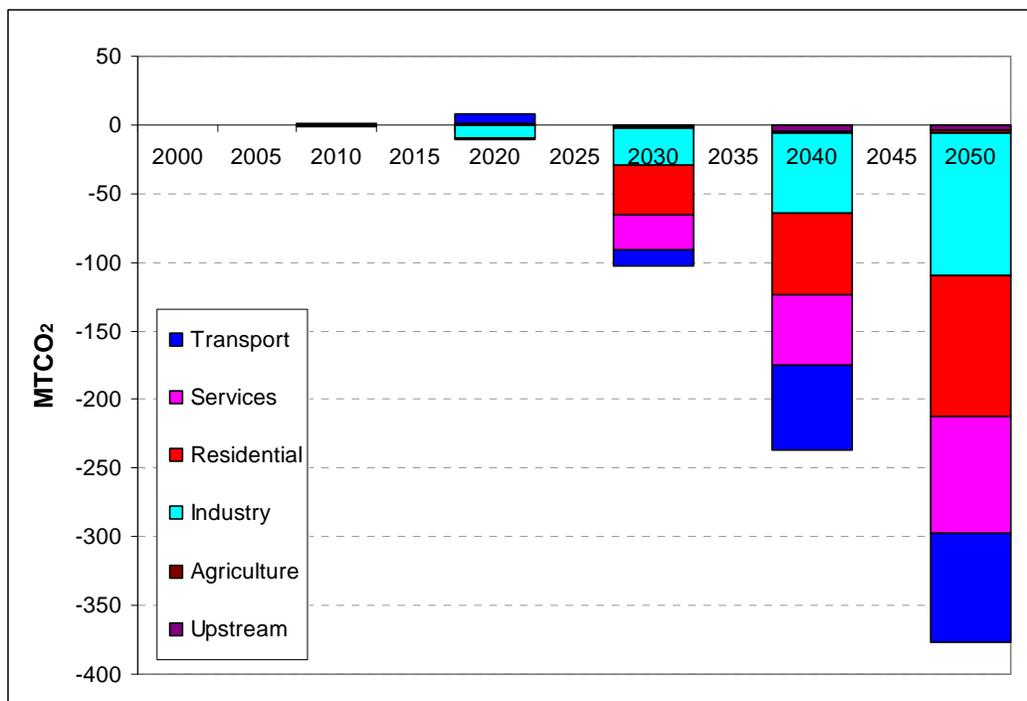
Figure 9b: End-use CO_2 emission reductions

As more clearly detailed in Table 6, transport in 2050 under the CO_2-60 constraint also has the smallest emission reductions relative to both the projected base case emissions and to actual year 2000 emissions. A combination of low demand service growth, demand reductions, fuel switching, and energy efficiency ensure that the industry sector has the largest relative emission reductions, followed by the services sector. Both of these sectors contribute more than their proportional share to the overall emissions cap.

Sector	2030	2050	2050 relative to year 2000
Upstream	95.6%	84.1%	52%
Agriculture	78.1%	53.3%	68%
Industry	78.1%	23.5%	24%
Residential	75.3%	39.4%	44%
Services	62.3%	19.6%	27%
Transport	91.5%	49.6%	55%
Total	**79.4%**	**36.7%**	40%

Table 6: Relative CO_2 sectoral emissions under constraint

Figure 10 details the percentage sectoral emissions for the range of CO_2 constrained scenarios. In general there is a trade-off between emission reductions between the electricity sector (notably fuel switching and efficiency gains), the buildings and industrial end-use sectors (notably demand reductions, conservation and efficiency gains) and the transport sector (notably hybrids, hydrogen and bio-fuels). The largest transport emission reductions are in the SLT case. Here, the 2010 imposition of the CO_2 constraint forces

earlier investment into zero-carbon transport infrastructures, and reduces the need to major late investments in zero-carbon electricity plants.
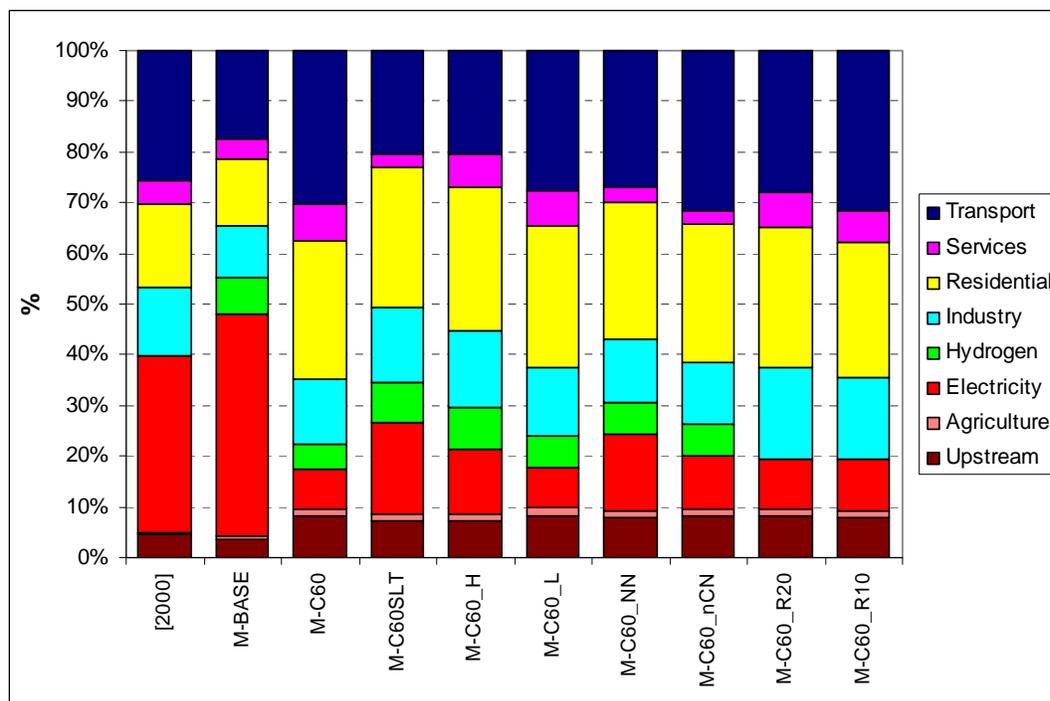
Figure 10: Percentage CO_2 by sector: 2050 comparison

4.2. Technology pathways

One of the main strengths of UK M-M is a detailed depiction of the technologies used to deliver the energy requirements of different sectors. A 60% reduction in UK CO_2 emissions entails radical changes in resource and infrastructure use, and investment in new technology portfolios. Key sectors of interest for the DTI-DEFRA project were electricity generation and transport, as both sectors hold significant scope for carbon emission reductions due to the many new and emerging technologies available over the model time horizon. Another key area is energy use reductions due to behavioural change, new efficient technology vintages and conservation measures.

4.2.1. Electricity generation

Figures 11a and 11b, detail electricity generation by major technology class, for the base and constrained cases. Under the base case (M-BASE), as shown in Figure 11a, the generation mix is dominated by gas and coal up to 2020. Nuclear generation reduces as existing plant are retired, and without a carbon price signal no new build is predicted. Post 2030, base case electricity portfolios see an overall growth, dominated by next generation base-load coal plants, together with a limited expansion in renewable technologies due to falling costs and the policy driver of the Renewables Obligation (RO). Coal dominates due

to the price advantage over more expensive gas, which tends to be used in more efficient direct use applications in the end use sectors. Note that in the M-M base case, there is no national carbon policy nor price signal. The M-M model's base-case electricity generation is higher than MARKAL as due to its differential costing routine, fewer efficient end-use technologies are adopted (see Appendix 2 for further information).
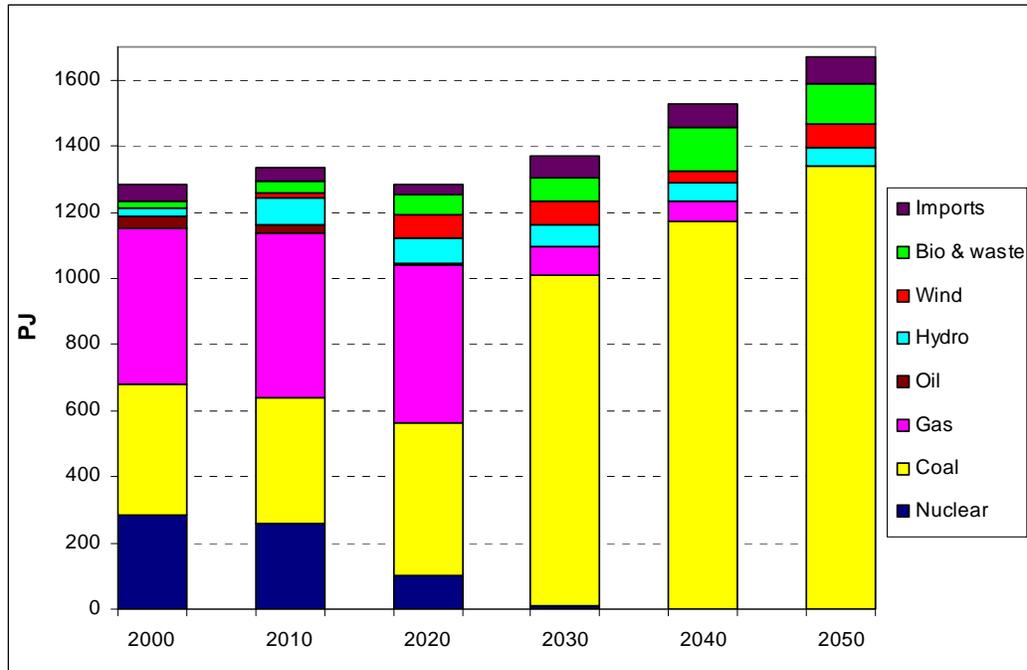
Figure 11a: Electricity generation: M-BASE scenario (2000-2050)

Under CO_2 constrained scenarios, the portfolio is dominated by next generation coal CCS plants (limited by available cost-effective UK storage capacity). Towards 2050 when the constraint tightens, there is a significant amount[16] of new generation nuclear plants. Uncertainties in the future costs and characteristics of both new and nuclear technologies mean it is impossible to robustly project that one technology is dominant. In addition, wind generation plays an increasingly important role. That the technology pathway evolution is inherently uncertain and path dependant is also illustrated in the SLT case, where the earlier CO_2 constraint results in a non-nuclear future, with emission reductions coming from more mature wind technologies and bio-fuels in transport (see Figure 12a).

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[16] Beyond the near-term there are no model constraints in the capacity per 5-year period the model can build (i.e., the model assumes no constraints based on the ability of the nuclear industry to build plants, planning process etc)
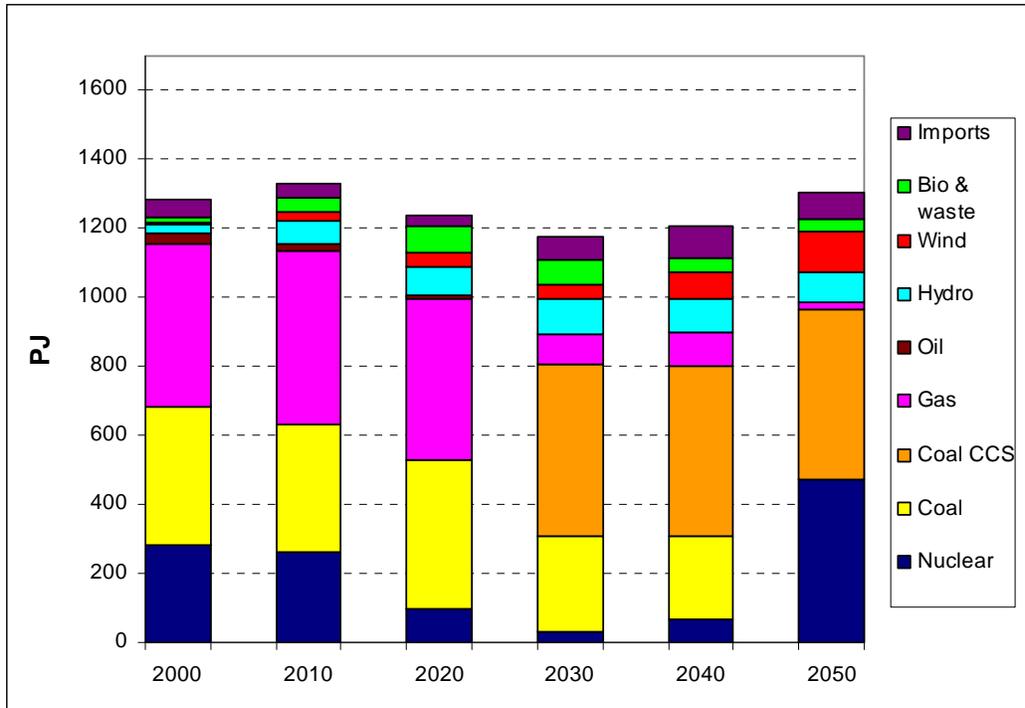
Figure 11b: Electricity generation: M-C60 scenario (2000-2050)

Figures 12a, 12b and 12 c detail a comparison in 2050 of the generation profile across the main scenarios. When comparing the standard model's CO_2 constrained solution, total electricity generation is markedly increased at 1,502 PJ vs. 1,305 PJ in the M-M model (see Figure 12a). This is due to the MARKAL model not having access to energy service demand reductions through behavioural change which thus substitutes greater emissions reductions on the upstream electricity sector via fuel switching to electric boilers and other buildings and industrial end-use technologies. One consequence of this is the introduction of previously higher cost marine renewable electric technologies.
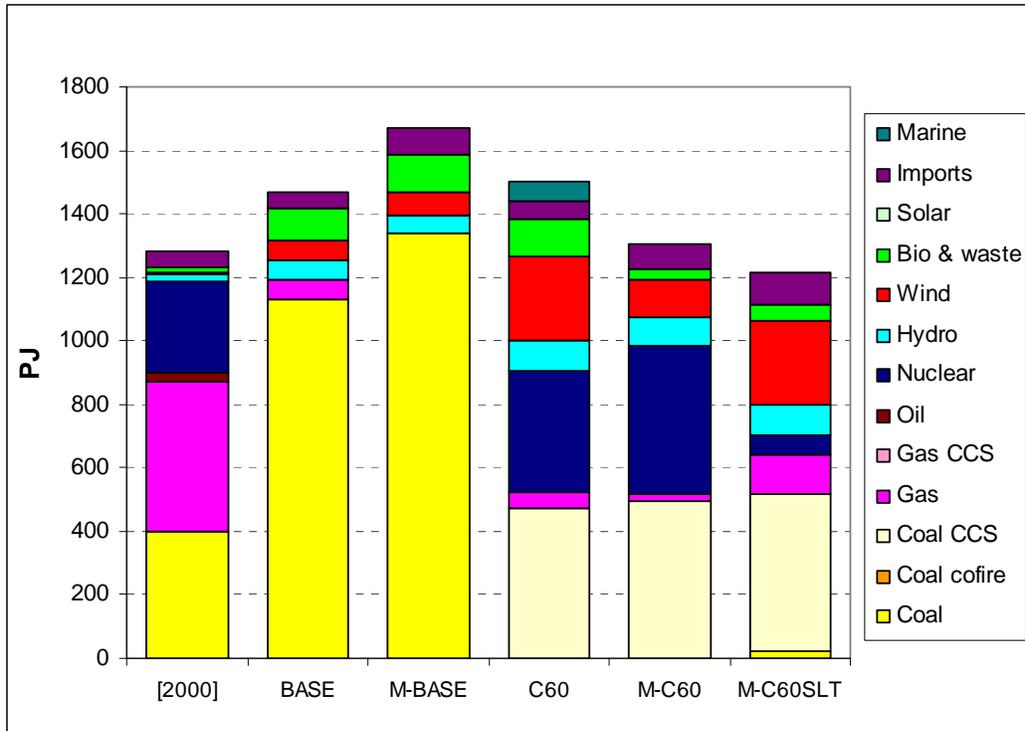
Figure 12a: Electricity generation: M-M and MARKAL - 2050 comparison

Figure 12b compares the central case with low and high resource cost scenarios. In the base cases, due to favourable natural gas economics in the low price scenario, CCGT generation also plays a role in meeting shoulder demands. High resource prices (M-C60_H), further reduce base case electricity generation through a general shift to more efficient technologies and end-use measures. In the low price scenario (M-C60_L), gas fired CCGT with CCS supplements the electricity portfolio due to favourable natural gas economics.
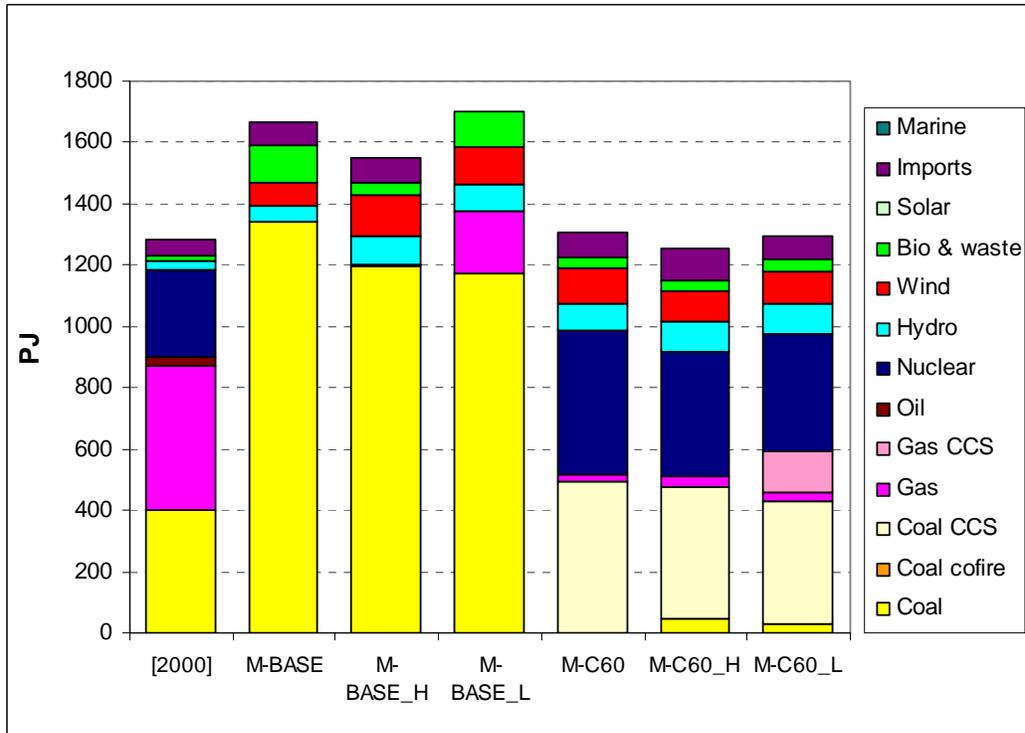
Figure 12b: Electricity generation: resource prices - 2050 comparison

When innovation is limited or major zero-carbon electricity technologies are restricted from the solution (e.g. nuclear and CCS) electricity generation declines (Figure 12c). Without either nuclear or CCS the electricity portfolio transforms again to be dominated by offshore wind [17], supplemented by higher costs renewables (including marine) with base-load requirements met using natural gas and bio-gas CCGT plants. Note that large shares (up to 61% in the no-CCS no nuclear cases) of UK electricity generation by (intermittent) wind necessitates a very large expansion of offshore wind capacity and remote electricity infrastructure. Note that the considerable constraints of this expansion are not accounted for in the model

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[17] Large shares (up to 61% in the no-CCS no nuclear cases) of UK electricity generation by (intermittent) wind necessitates a very large expansion of offshore wind capacity and remote electricity infrastructure. Note that the considerable constraints of this expansion are not accounted for in the model.
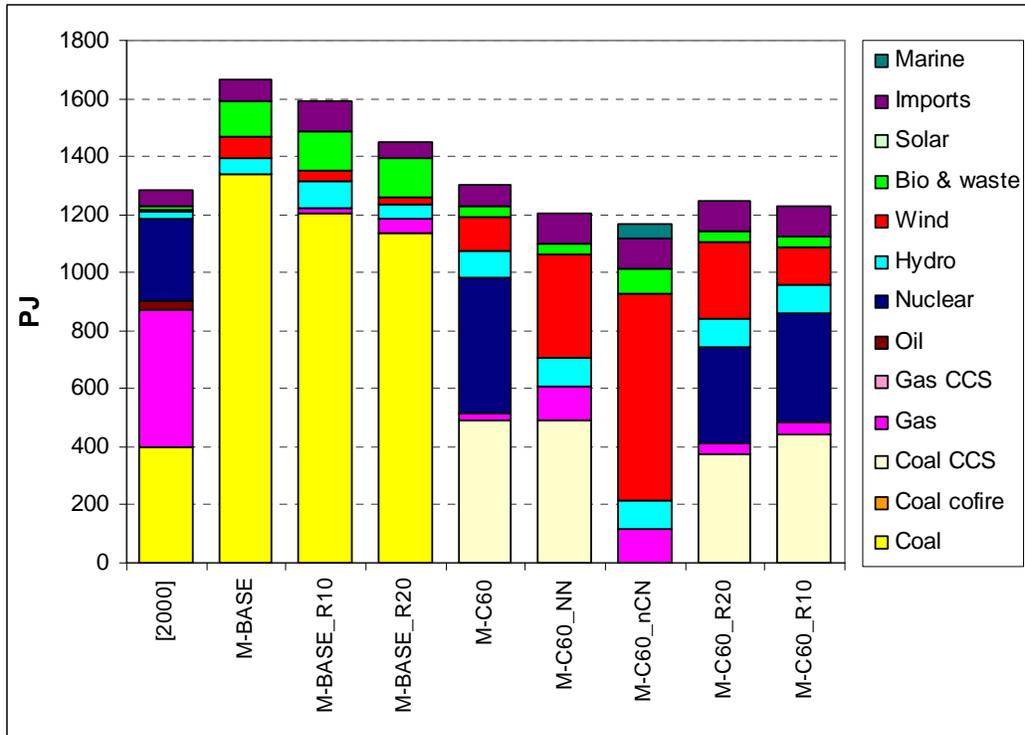
Figure 12c: Electricity generation: technology scenarios - 2050 comparison

A key message is the existence in all scenarios of a portfolio of electricity generation. No single technology dominates in a CO_2 constrained system, with a mix of fossil plant with CCS, nuclear, and renewables. Significant uncertainties exist on future technology costs (for all classes). Which technologies are chosen depends on relative economics and the path dependant nature of investments in long lived plants and infrastructures.

4.2.2. Transport

Figures 13a, 13b and 13c detail the transport fuel consumption in the base, CO_2 constraint and SLT CO_2 constraint cases. In the base case, the transport sector is already transformed in the absence of a carbon price signal. Despite some the higher of the projected energy service demand increases (see section 2.2.2), a move towards petrol and diesel hybrid vehicles in a range of modes from 2020 significantly reduces any growth in transport final energy consumption. Post 2030, buses, then HGVs, and subsequently LGV's evolve into hydrogen vehicles, based on the relative costs of the technologies and importantly the infrastructure requirements per mode (see Figure 13a).[18] Bio-fuels penetration in the base case is limited to that mandated under the RTO. The domestic aviation sector is a small but growing component of the overall transport energy demand and sees the least technological change owing to the limited technology substitution options.

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[18] Additional UK MARKAL modeling work further disaggregates the hydrogen infrastructure requirements (Balta-Ozkan et al, 2007)
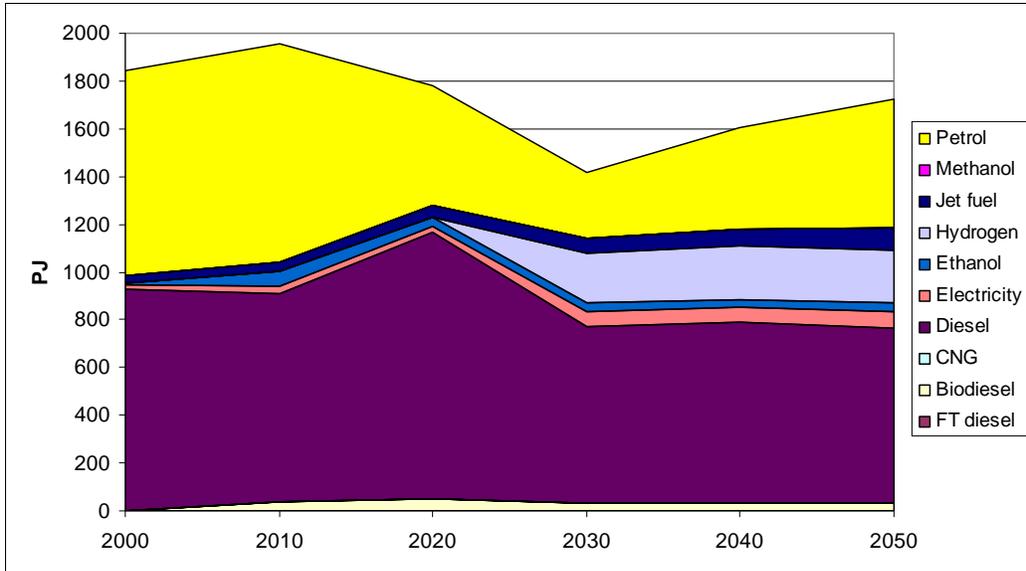
Figure 13a: Transport fuel consumption, M-M UKERC base case (M-BASE)

In the constrained case (M-C60), consumption of transport fuels (petrol and diesel) is reduced further as the sector moves towards a lower carbon objective (Figure 13b). In addition, in the M-M model we see the impact of increasing prices on the falling demand for fuels, decreasing in post-2030 (see section 4.2.3). An interesting (non-intuitive) trend to emerge is that for hydrogen, which shows lower levels of consumption than in the base case (M-BASE). However, hydrogen production in the base case is from fossil fuels; under the constrained case hydrogen is produced at a lower level but is carbon neutral (see Figure A17). Bio-fuels play an increasingly important role, with slightly higher levels of bio-diesel and ethanol, and the significant (20% of transport fuels) use of second-generation bio-fuels (Fischer Tropsch diesel) in 2050.
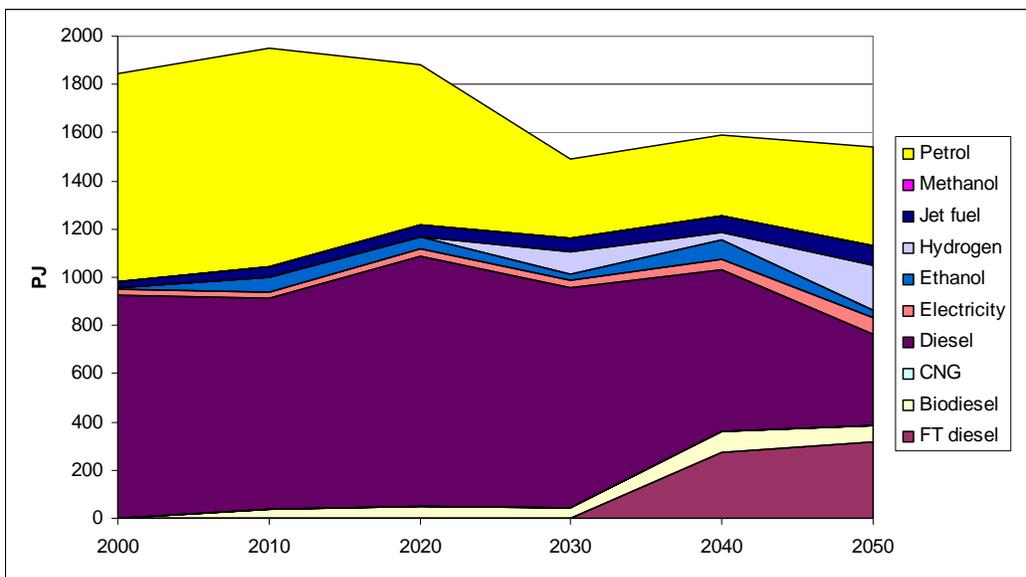
Figure 13b: Transport fuel consumption, M-M UKERC 60% constraint case (M-C60)
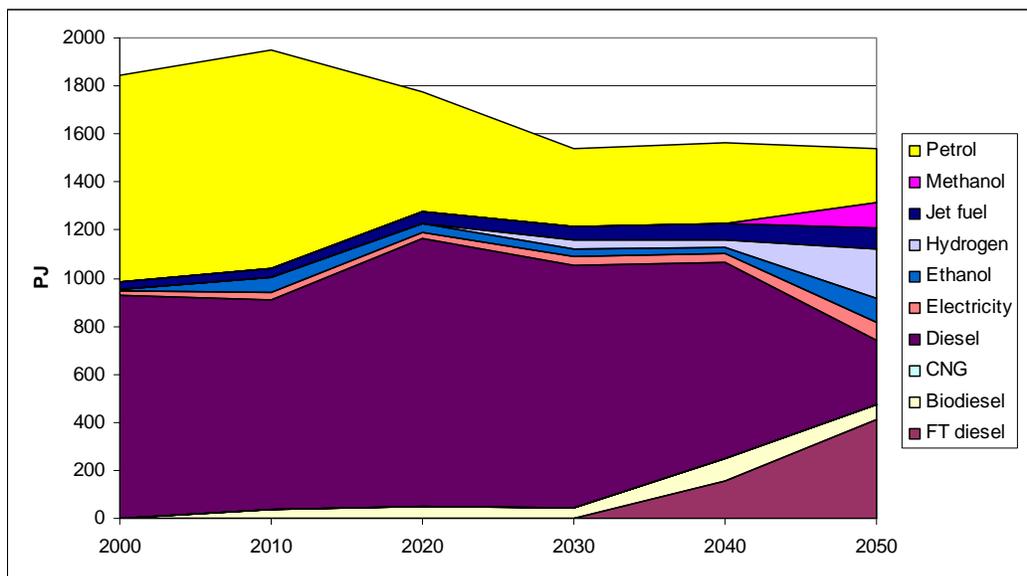
Figure 13c: Transport fuel consumption, M-M UKERC SLT 60% constraint case (M-C60SLT)

If the CO_2 constraint applied as a straight-line trajectory (SLT) (Figure 13c), as might be expected, petrol and diesel see greater reductions earlier in the time horizon. Methanol is also a fuel used in the later period. The SLT case mirrors the impact of what is happening in the electricity sector on the transport sector. With earlier reductions required in the earlier periods, nuclear does get chosen in the generation mix. Consequently, the transport sector contributes more to the decarbonisation effort, with increasing amounts of bio-fuels, and lower levels of conventional fuel consumption.

Note that technology share projections for cars (Figure A18a), as well as bus/HGV/LGV modes Figure A18b) are discussed in Appendix 4.

Table 7 details the year 2050 percentage share of transport fuels in the key constrained scenarios. It is clear that there is a continuing role for diesel, petrol and aviation fuel, even in a carbon-constrained system. This is at a much reduced level, with fuels being used in more efficient vehicles. For aviation fuel, there are few (cost-effective) alternatives in the model so continuing use at similar levels (as current use) would be expected.

Bio-fuels are important in providing low-carbon fuels to the transport sector under all of the variant scenarios. In earlier periods, levels are maintained by the road transport fuel obligation. In later periods, the levels of such fuels are constrained by resource availability. Fischer-Tropsch (FT) diesel is particularly important by 2050, at around the 20% level or greater in 2050. It is particularly important in the restricted innovation cases where limited progress on costs and technical performance mean that hydrogen is not taken up at all in the fuel mix in these scenarios. In the restricted innovation case (2010), ethanol plays an important role, with the uptake of flex-ethanol vehicles. As mentioned previously, hydrogen has a smaller role than in the base case, but the hydrogen used is produced from carbon-free production.

Fuel	M-BASE	M-C60	M-C60_H	M-C60_L	M-C60STL	M-C60_NN	M-C60_nCN	M-C60_R20	M-C60_R10
FT diesel	-	20.7%	26.3%	19.3%	26.5%	19.8%	13.5%	38.5%	33.6%
Bio-diesel	1.9%	4.3%	4.2%	4.7%	4.2%	4.7%	4.6%	5.9%	5.4%
CNG	-	-	-	-	-	-	-	-	-
Diesel	42.5%	24.7%	17.5%	30.0%	17.6%	29.4%	34.9%	22.8%	22.4%
Electricity	3.8%	4.5%	5.1%	4.7%	4.5%	4.8%	2.8%	2.8%	2.3%
Ethanol	2.2%	1.8%	7.6%	1.4%	6.5%	1.4%	1.6%	2.2%	21.7%
Hydrogen	13.0%	12.2%	13.6%	14.3%	13.6%	14.3%	13.9%	-	-
Jet fuel	5.5%	5.4%	5.4%	6.0%	5.6%	5.9%	5.8%	6.0%	5.5%
Methanol	-	-	5.9%	-	6.9%	-	-	-	-
Petrol	31.2%	26.4%	14.5%	19.7%	14.6%	19.7%	22.8%	21.6%	9.1%

Table 7: 2050 share of transport fuels by scenario

4.2.3. Demand-side response

There are a number of demand-side responses to the introduction of CO_2 constraints in the system. In cost-optimising across the energy system, the possibilities for carbon reduction in the demand end use sectors include fuel switching (e.g., moves to a new low carbon vehicle fleet in the transport sector), the use of more efficient *demand devices* that provide the end use energy services (e.g. move to condensing boilers stock in the residential sector), uptake of conservation measures resulting in lower demand for energy, and in the M-M version, endogenous reductions in the overall level of demand, due to behavioural changes from price feedback mechanisms.

Fuel switching and efficiency improvements can be seen in section 4.2.2 under some of the constrained scenarios. Generally there is a relative trade-off by scenario between upstream and downstream reductions. Although the electricity sector undergoes a major decarbonisation (in M-M C60 down to approximately 9% carbon emissions relative to the base year) this constitutes both changes in the electricity portfolio as well as fuel switching and demand reductions in the end-use sectors. Hence the role of demand side reductions is very considerable with industrial (27% of base year), services (27% of base year) and (to a lesser extent) residential (44% of base year emissions) sectors heavily decarbonising[19].

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[19] as detailed earlier in table 6

Table 8 details the uptake of conservation measures in residential, services and industry – these calibrated to DEFRA estimates through 2020, and held there in base cases – but post 2020 given freedom to choose in the CO_2 constraint cases if cost-effective to do so. In this cost-optimal solution, the model exhausts available conservation measures due to stringency of target (with a limited set of very high costs conservation measures not taken up. This is despite the use of a higher 25% hurdle rate, designed to partially account for market risk, information deficiencies and other market imperfections in the uptake of end-use conservation options. The exception is in the restricted innovation scenarios when many conservation measures are not available. See Appendix 4 for additional sensitivities on conservation assumptions with the standard model.

Scenario	Sector	2000	2010	2020	2030	2040	2050
All base cases	Residential	0.0	106.6	106.6	106.6	106.6	106.6
	Services	0.0	43.2	63.7	63.7	63.7	63.7
	Industry	0.0	10.2	10.2	10.2	10.2	10.2
	Total	**0.0**	**159.9**	**180.4**	**180.4**	**180.4**	**180.4**
Other CO_2 constrained cases	Residential	0.0	106.6	137.8	191.0	195.7	200.3
	Services	0.0	43.2	108.5	112.5	117.9	123.2
	Industry	0.0	20.5	38.9	63.9	87.8	111.7
	Total	**0.0**	**170.3**	**285.2**	**367.4**	**401.3**	**435.3**
CO_2-60 2010 innovation	Residential	0.0	107.6	107.6	117.3	121.6	121.6
	Services	0.0	43.2	49.0	49.0	52.1	52.1
	Industry	0.0	20.5	20.5	20.5	20.5	20.5
	Total	**0.0**	**171.3**	**177.1**	**186.7**	**194.2**	**194.2**
CO_2-60 2020 innovation	Residential	0.0	106.6	126.1	126.4	144.1	154.1
	Services	0.0	43.2	83.2	83.2	105.7	106.9
	Industry	0.0	20.5	38.9	38.9	38.9	38.9
	Total	**0.0**	**170.3**	**248.2**	**248.4**	**288.7**	**300.0**

Table 8: Conservation measure uptake in base and CO_2 constrained cases (PJ)

In addition to fuel switching, efficiency, and technical conservation, Figures 14a and 14b illustrates the purely behavioural change for reductions in demand (e.g., lowering a thermostat or driving less). Reductions in energy service demands cluster around 10-15% and contribute significantly to lowering marginal CO_2 prices (e.g., comparing vs. standard MARKAL results). In general there is trade-off between upstream emission reduction options and demand reductions, as seen in the cases with restricted upstream and technology options, as well as the "distance to target", as seen in the lower and higher resource price sensitivities.
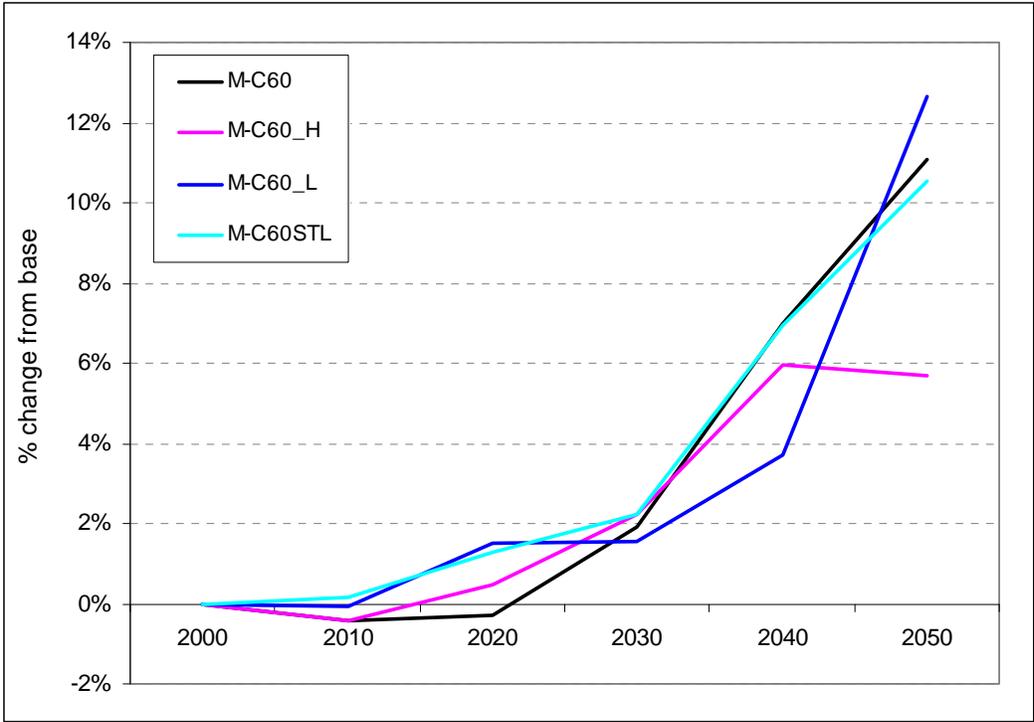
Figure 14a: Energy service demand reductions – core and resources cases
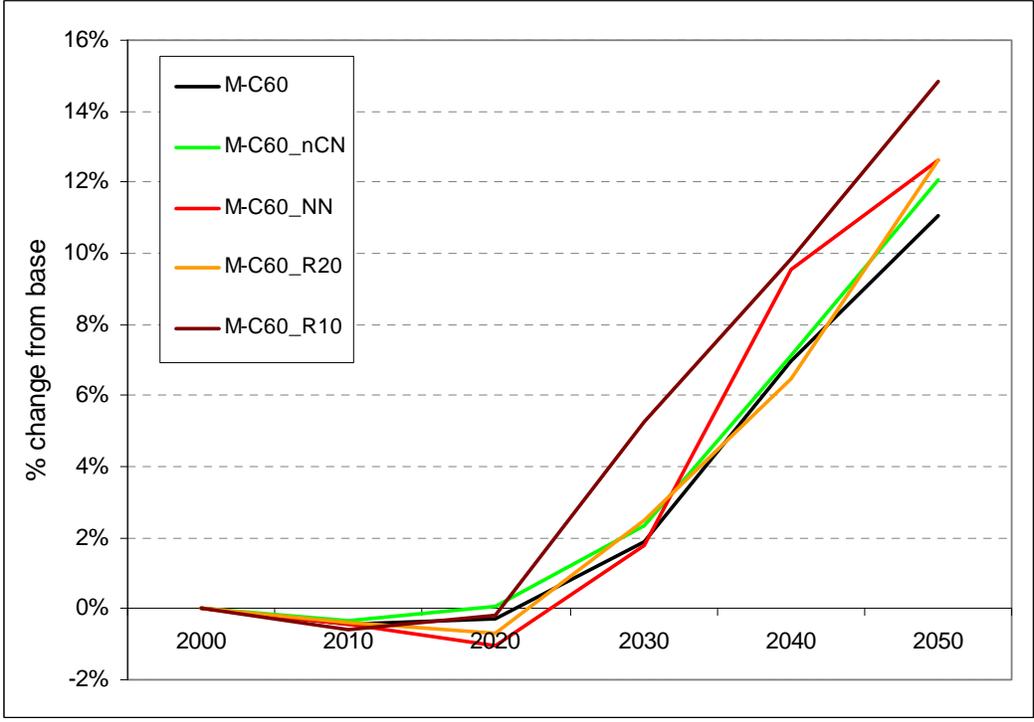

Figure 14b: Energy service demand reductions – technology cases

When examining demand reductions by sub-sector it is important to note that the stringency of the 60% reduction target ensures that significant behavioural change is taken

up in all cases. Although there is only one aggregated price elasticity for energy, this impacts different service demands based on their demand marginals. Sectors with lower demand marginals (partial derivative of demand relative to overall economic production) are reduced most in the CO_2 constrained runs. Low demand marginals are largely a reflection of the limited technological substitution options (making behavioural change from a high energy consumption baseline a more attractive option). e.g., in the transport sector the biggest demand reductions are in the rail, shipping and aviation sectors. A secondary effect is the model limitation of 50% reductions from base year demands, set to ensure unrealistic levels of demand reductions are not incorporated into the cost optimal solution. As some demands in 2050 are more than double the year 2000 level (and aviation higher still), this can impose a limit on overall demand reductions.

4.3. Economic impacts

4.3.1. Marginal costs of CO_2 abatement

Even considering the long time-frame and early announcement of the 60% CO_2 reduction policy, combined with the scope of technology and demand side options implemented in the M-M model, such a transformation of the UK energy system necessitates a high carbon price signal. As illustrated in Figures 15a and 15b, by 2050 the central constrained case generates a marginal CO_2 cost of £105/tCO_2 (or £385/tC)[20]. Without endogenous demand reductions (i.e., comparing the M-M model to the standard MARKAL model), this marginal price increases to £135/tCO_2 (or £495/tC).

Scenarios with a greater or lesser distance to target (i.e. the low or high resource price cases) give a higher or lower CO_2 price (although this is moderated in the low resource price case due to the relatively improved economics of switch natural gas vs. coal). Similarly, removing key mitigation technologies (nuclear, CCS) increases marginal prices. The highest marginal costs arise in those scenarios where innovation across a broad range of technologies has been restricted (up to £176/tCO_2). In these cases, the available abatement technologies used in reducing emissions are more expensive. Setting an earlier CO_2 constraint (SLT) gives modest intermediate CO_2 prices and a reduced marginal CO_2 price in 2050. The low level of the intermediate marginal prices is a reflection of the distance to target from the modest emissions baseline (see Figure 6) and the availability of low cost initial emissions reductions including conservation measures.

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[20] This equates to a marginal CO_2 price of €152/tCO_2 or €558/tC using an exchange rate of £1 = €1.45
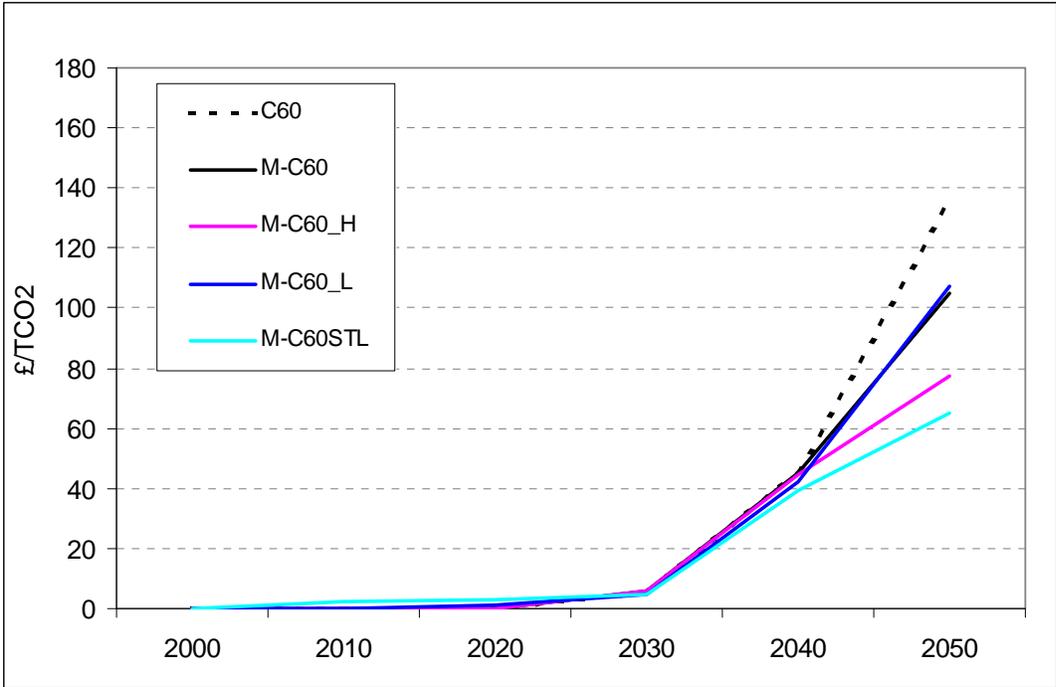
Figure 15a: Marginal costs (£/tCO$_2$) for MARKAL and M-M selected runs – core and resource cases
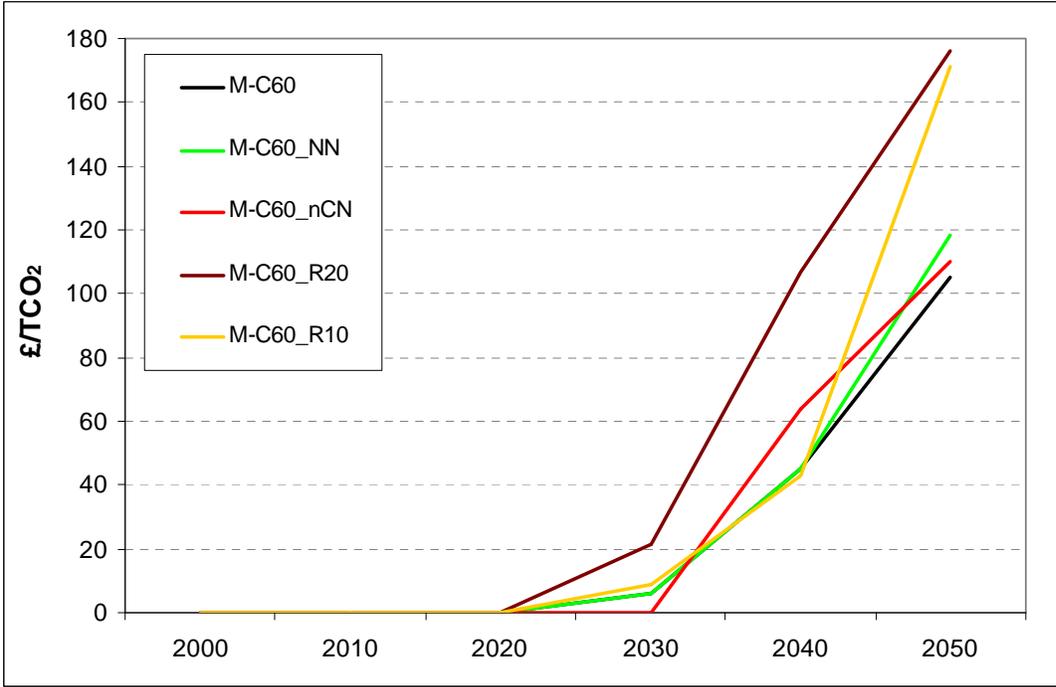
Figure 15b: Marginal costs (£/tCO$_2$) for MARKAL and M-M selected runs – technology cases

4.3.2. Average costs of CO$_2$ abatement

Average costs of abatement cannot be calculated in the M-M version due to system size being endogenous with the overall size of the energy system changing (see Figures 14a,b). Hence the concept of average costs of abatement is "meaningless" because the system size changes. Therefore the results from the standard MARKAL version are presented (Figure 16b). These are calculated by comparing the additional undiscounted system costs[21] of the carbon-constrained system with the base case, and dividing by overall emissions reductions.
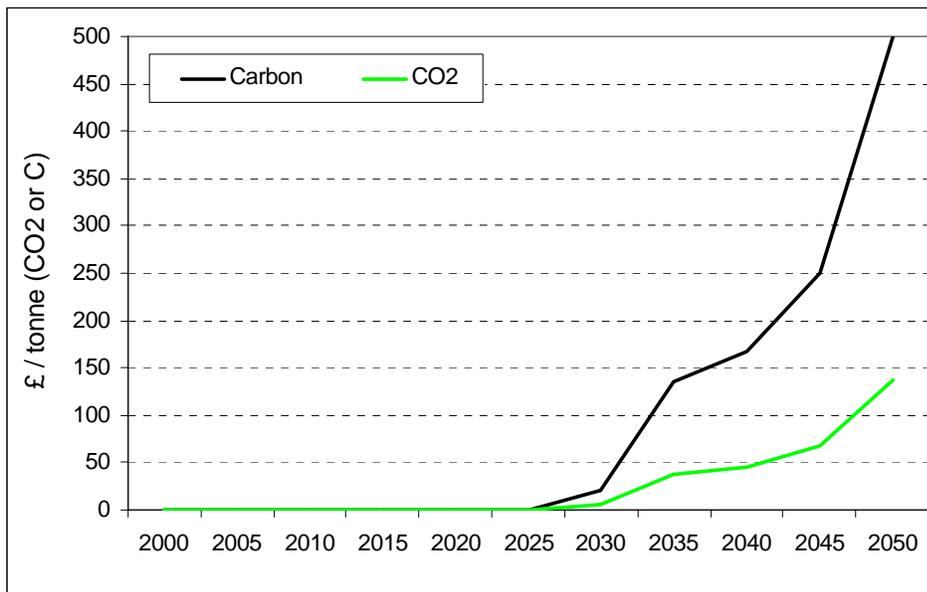
Figure 16a: Marginal costs of abatement using standard MARKAL (C60 scenario)

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[21] Further details of abatement costs by scenario for the standard model are detailed in Appendix 4.
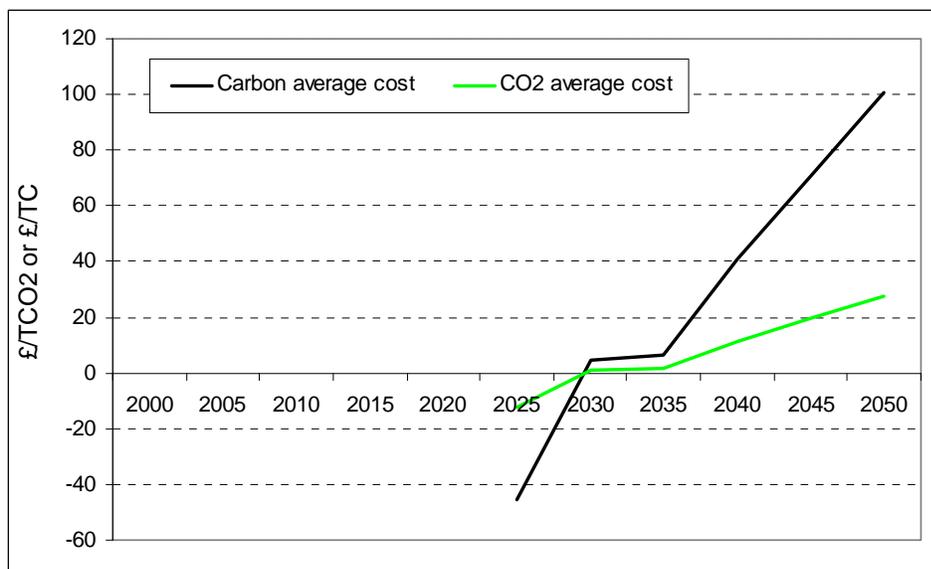
Figure 16b: Average costs of abatement using standard MARKAL (C60 scenario)

Costs of abatement are shown in the post-2020 period of the model, rising period-on-period as the system has to implement increasing abatement to meet more stringent reductions. Average abatement costs are estimated to be £27/tCO$_2$ in 2050 (or £100/tC). Comparing the average (Figure 16b) with the marginal emissions abatement curves (Figure 16a) shows much lower cost levels, indicating a cost distribution skewed towards lower cost reduction options, combined with fewer high costs abatement options as the model meets the tightening targets. The negative and very low average costs in 2025-2035 are a reflection of cost effective conservation options in the residential, services and industrial sectors, enabled through additional policies to address information barriers and other market barriers.

4.3.3. Total energy system costs

As illustrated in Figure 19, overall energy system costs are projected to grow more slowly than GDP, leading to a relatively declining share of the energy sector within the UK economy. However under the CO$_2$ constraint, radical changes in energy supply, transformation and use as detailed above have a major impact on this relatively smaller energy system.

In terms of energy systems cost projections using the M-M model, the situation is complicated by twin effects working against each other. Firstly, demand reductions due to behaviour shifts occur leading to a shrinking energy systems in the CO$_2$ constraint cases vs. the base-cases. Secondly however, the unit costs of the energy sector increase as higher costs fuels and technologies are utilized to meet the CO$_2$ cap. Thus the graphs of changes in energy systems costs (Figures 17a and 17b) tend to fall then rise as the higher unit costs outweigh the behaviour reductions. In the cores C-60 case the energy system cost in 2050 is still £0.6 billion lower than the base case. The low resource and high resource price cases entail higher and lower energy systems costs respectively, based on the distance to target

and hence mitigation effort required (noting gain the complicating factor of varying economics between coal and natural gas). The restricted innovation cases entail the highest energy systems costs, rising to an increase of £7.2 billion in 2050 if only 2010 improved vintages of technologies are available.
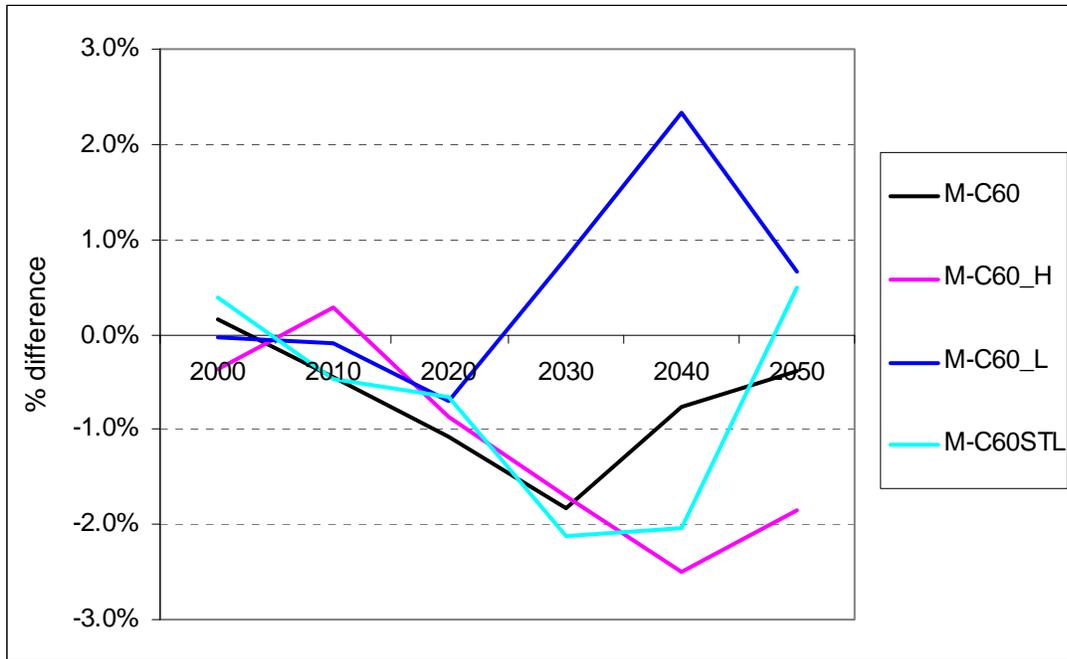
Figure 17a: Relative change from base in M-M energy system costs – core and resource scenarios
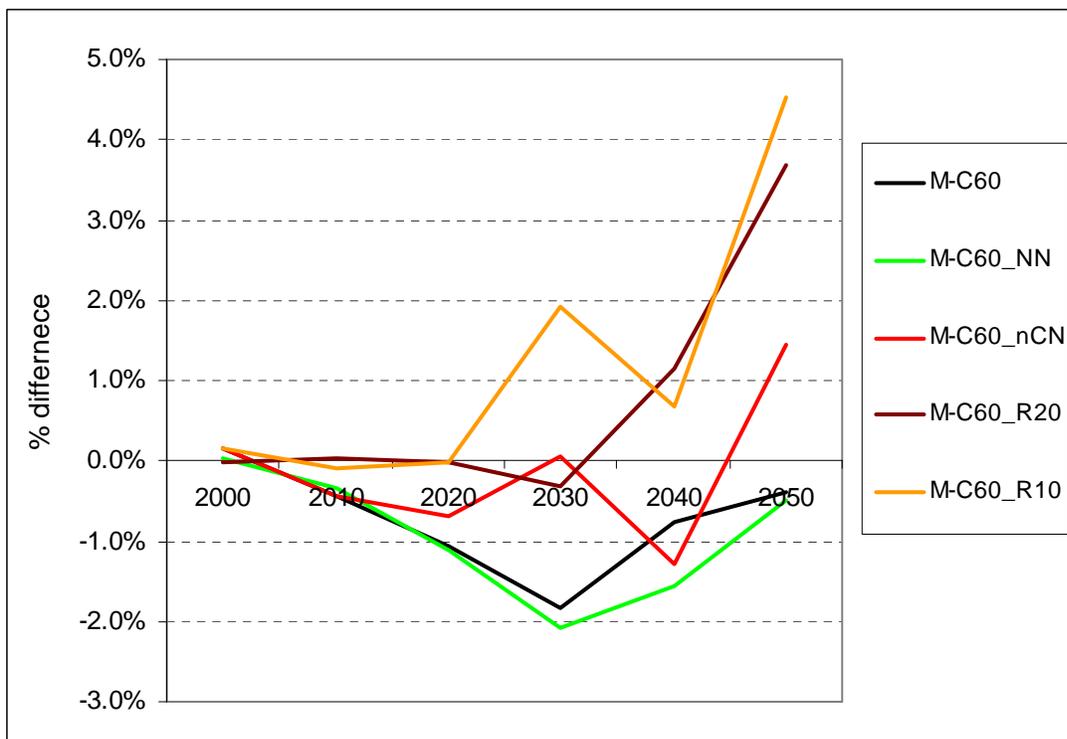
Figure 17b: Relative change from base in M-M Energy system costs – technology scenarios

The standard model does not have a behavioural demand reduction and hence its base and CO_2 case differences in energy systems costs directly correspond to abatement costs. Without the overall demand reduction, the standard model generates higher abatement costs, and a range of technology sensitivities results (see Appendix 4) are detailed in Figure 18. The central undiscounted abatement cost (C-60) in 2050 is £B8.8 with a low estimate of £B2.1 if all optimistic technological assumptions are employed and a high estimate of £B19.8 if innovation is restricted to 2010 levels. Similar to average CO_2 prices, negative costs in 2025-2035 are a reflection of cost effective conservation options in the residential, services and industrial sectors, enabled through additional policies to address information barriers and other market barriers.
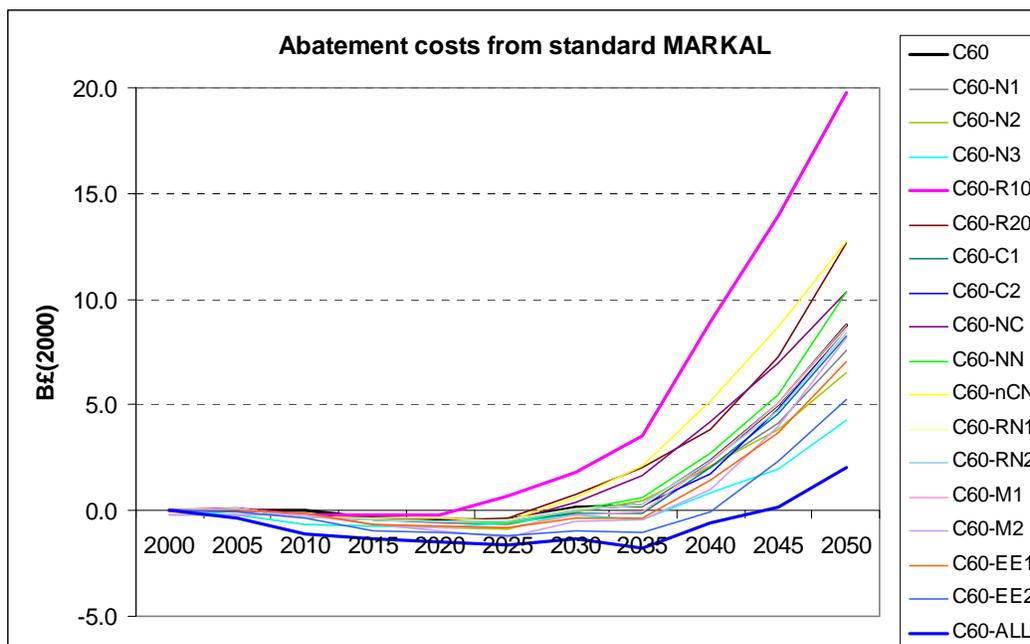
Figure 18: Abatement costs in technology scenarios via standard MARKAL

4.3.4. M-M parameters – Investment, GDP, consumption

As noted earlier, there is a relatively low energy system growth vs. growth rates of the rest of economy. Figure 19 illustrates base-case GDP growth (on the right hand axis) and energy system cost growth (on the left hand axis) for the resource case sensitivities (which show the most base-case variation). Base case GDP rises (in £2000) from around £1 trillion in 2000 to £2.8 trillion in 2050 with a much more modest growth in energy systems cots (with differences due to the diverging price of imported energy resources). This faster economic growth combined with improved energy intensity/efficiency leads to the energy sector's contribution to GDP falling from around 9% in 2000 to 5.5% in 2050.
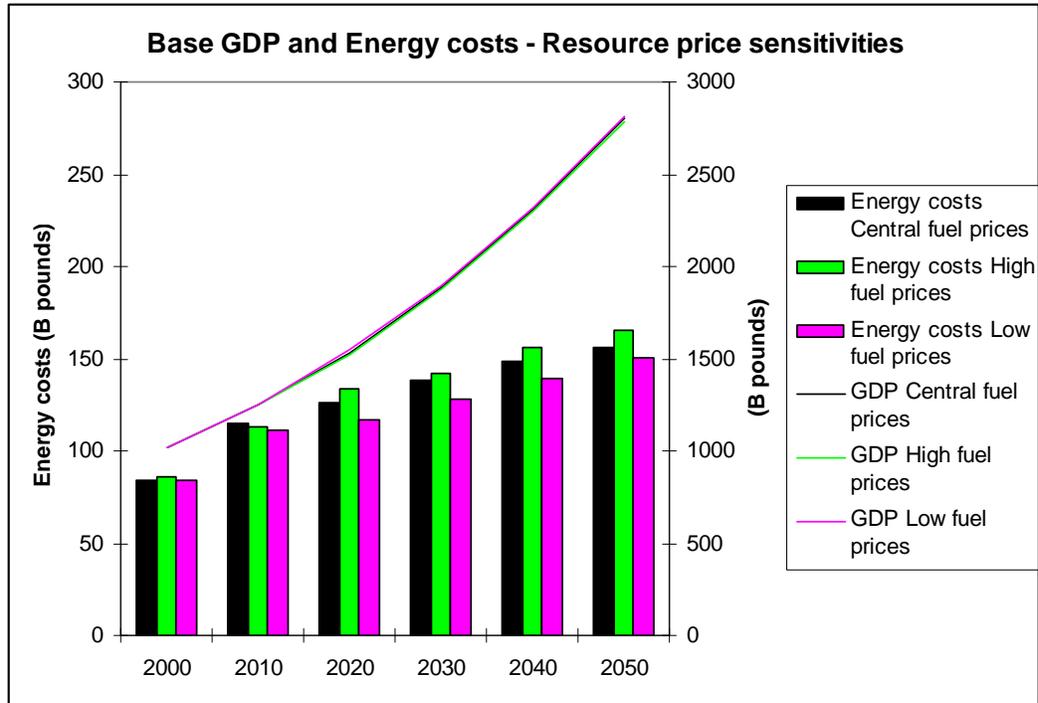
Figure 19: Base-case GDP and energy system cost trends – resource scenarios

Figures 20a and 20b details GDP impacts for the resource and technology sensitivity CO_2 constraint scenarios. It is stressed that the M-M model is likely to give a lower bound to macro-economic costs, due to bottom-up optimism over future technologies and energy efficiency/conservation, together with non-consideration of trade impacts and transitional costs. Furthermore the simplicity of the M-M linkage with no government sector means that and recycling of revenues, cannot be investigated. Lastly the costs are for UK abatement with no option to purchase international emissions credits. The costs and availability of long-term emission credits is extremely uncertain and not considered in this analysis.

MARKAL Macro implicitly has some measure of direct rebound effects as demand is reduced and the resulting price of energy service provision falls, then less efficient technologies can be taken up with resulting higher than expected energy consumption. However, strictly speaking the direct rebound effect in terms of reduced costs and additional energy service demands is not accounted for. Neither indirect nor economy-wide rebound effects are accounted for.
The central CO_2 constraint case (C-60) gives an annual GDP reduction of 0.72% by 2050 (or a B£20.3 reduction from a projected UK GDP of B£2,807). The SLT case generates greater GDP losses (£B22.2) than the standard case – this is due to the cumulative emission reductions being greater (7,205 vs. 6,460 MTCO$_2$ - see Figure 7) despite a smoother abatement path.

Under the resource scenarios two things are happening. First, there is alternate base-case energy use. Second there is alternate base case CO_2 emissions. In the higher fuel prices case, there is a lower base GDP where the economy is both less energy *and* CO_2 intensive.

Hence the distance to the CO_2 target is less and the GDP costs of meeting the constraint are lower. In the low fuel prices case there is a higher GDP and more energy use (and hence more energy reductions required). However the different costs between fossil fuel means the low fuel price case shifts from coal to natural gas (as gas fuel costs are a larger component vs. investment costs etc in the use of gas) - this means that CO_2 emissions are lower than the central case. Hence the low price case needs to reduce more energy but decarbonise relatively less than the central case - hence both effects wash out and GDP costs are similar (and both are higher than the high fuel price case)
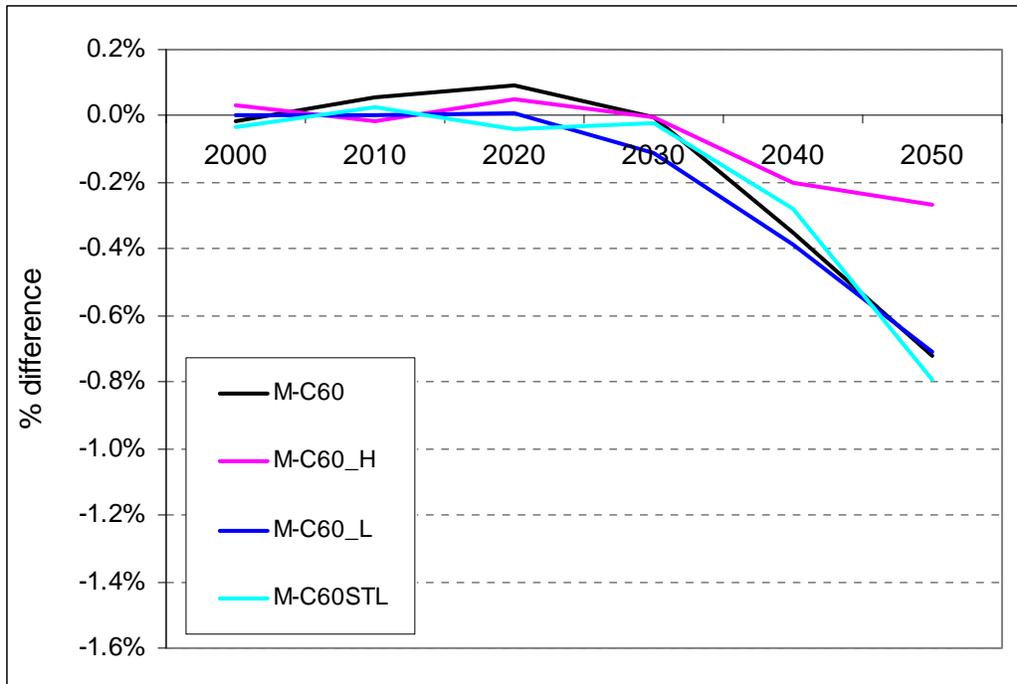
Figure 20a: GDP % changes – core and resource scenarios
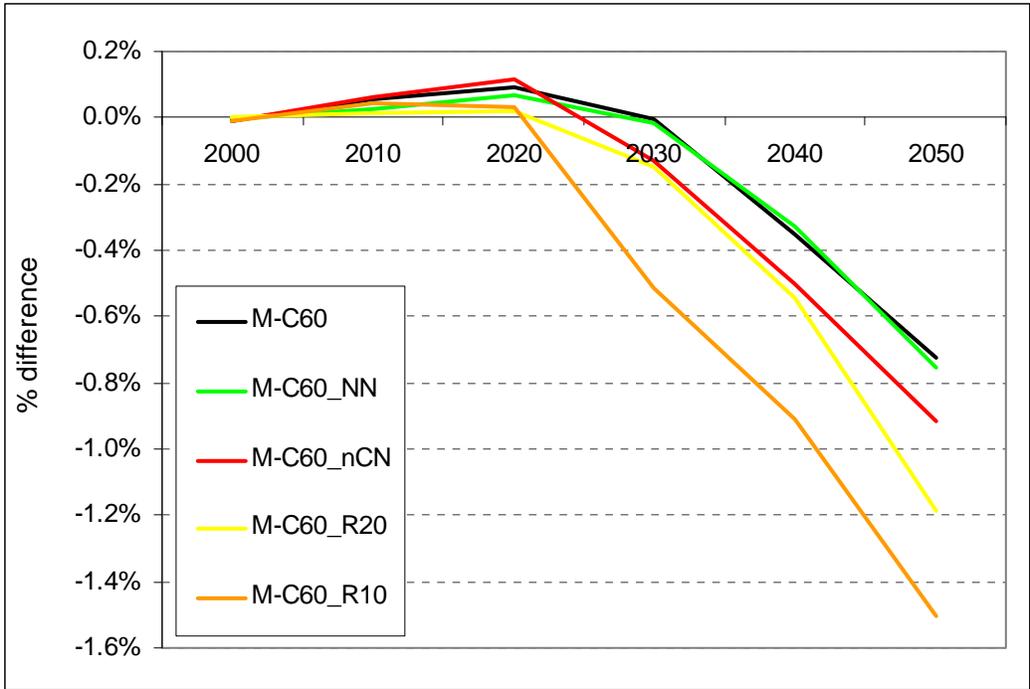
Figure 20b: GDP% change – technology based scenarios

The GDP reduction range in 2050 varies between 0.3% and 1.5% (£B7.5 to £B42.0) which is equivalent to other estimates for long-term CO_2 reductions (Stern, 2006)[22]. The higher cost estimates are strongly influenced by more pessimistic assessments of future low carbon technologies.

Finally, Figure 21 details the changes in the M-M models components of GDP, namely economy wide consumption and investment, as well as energy costs for the C-60 and C-60SLT scenarios. Increasingly, reductions in overall investment drive losses in GDP, with investment declines reaching around 3.0% in 2050. In this perfect foresight model, consumption prior to 2030 is slightly increased relative to the base-case before the imposition of the CO_2 constraint. As the CO_2 constraint tightens, energy costs rise (due to per unit energy cost increases), investment falls and GDP and consumption are also pulled down from base-case projection.

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[22] Note, the estimate in Stern (2006) were applicable to global reductions in CO_2 emissions
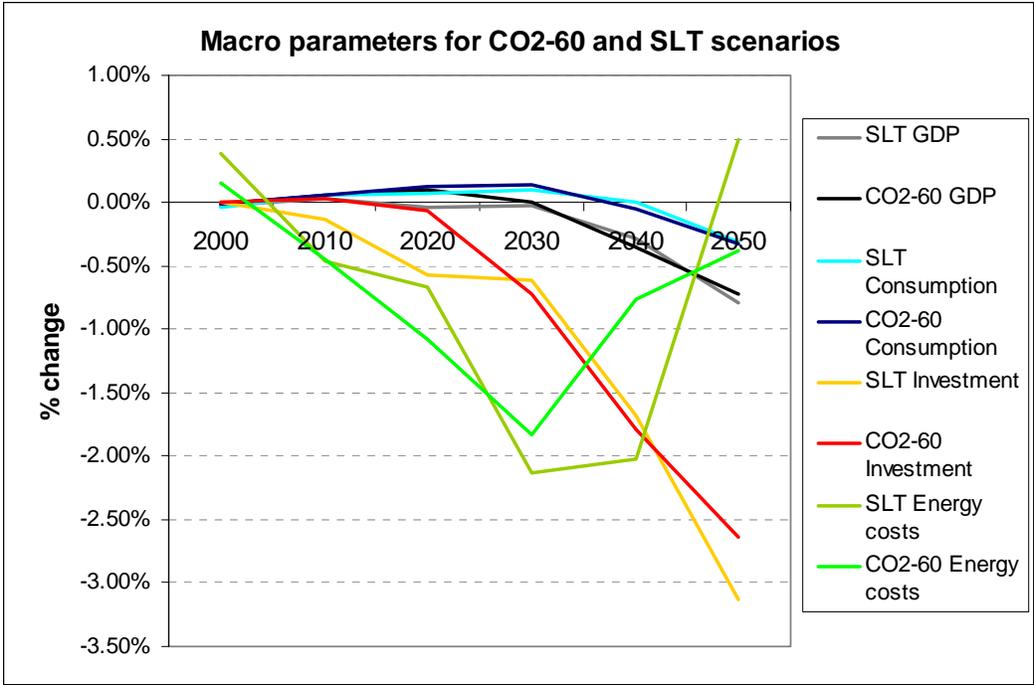
Figure 21: Investment, consumption and GDP

5. Insights and conclusions

The focus of this UKERC Research Report is on the extensive range of UK 60% CO_2 abatement scenarios and sensitivity analysis run for analytical insights to underpin the 2007 Energy White Paper. This technical report is a companion publication to the policy focused discussion of the modelling work (DTI, 2007).

Results focus on a selected set of M-M model scenarios, utilizing an integrated set of UKERC assumptions and data:
- Base-case, CO_2 emissions in 2050 constrained to 60% of 2000 levels (C-60), and alternate CO_2 emission trajectory (SLT) implemented linearly from 2010;
- Resource import high and low price scenarios, from DTI projections;
- Technology scenarios: Restricted innovation (limited to either 2020 or further to 2010 levels of improvement), no-nuclear, no-CCS *or* no-nuclear scenarios.

In all, over 50 full scenarios sets were run for this project. Results from additional scenario runs (including standard model runs) are used to further discuss key trade-offs between mitigation pathways. Key outputs included primary and final energy mixes, sectoral contributions to CO_2 reductions, detailed technology selection in the electricity and transport sectors, the role of demand side reductions, CO_2 prices, energy system costs and GDP impacts.

Presenting a set of model results paints a complex picture of how the UK energy system could develop under deep long-term CO_2 constraints. These runs illustrate possible technology pathways, energy system interactions and resultant energy and macro cost implications. However the MARKAL and M-M runs do *not* constitute forecasts, rather they are cost optimal solutions based on a set of integrated assumptions in a systematic what-if analysis of the future evolution of the UK energy systems to meet long-term CO_2 reduction targets. Furthermore the scenarios do not constitute a formal or structured assessment of the breadth of uncertainties in future UK energy scenarios, but illustrate the role of key drivers that are relevant to policy assessment of the economic, and technological implications of potential UK low carbon energy futures.

<u>Principal findings</u>

There are a number of key findings that emerge from the scenario analysis:
- A 60% reduction in UK CO_2 emissions entails radical changes in resource and infrastructure use, and investment in new technology portfolios.
- Cost-effective carbon reductions require action across all sectors, including increasing energy efficiency, reduced demand, fuel switching and the use of low carbon technologies. Restricting innovation into a range of low carbon technologies results in significantly higher marginal costs of abatement
- This long-term transition requires a strong CO_2 price signal with a central M-M model estimate of £105/tCO_2 by 2050 (within a range of £65/tCO_2 to £176/tCO_2 for the key sensitivities covered in this report);

- The resultant impacts (from a relatively smaller energy sector) on the UK economy are more modest with a range of annual GDP losses in 2050 ranging from 0.3% to 1.5% (equivalent to £B7.5 to £B42). The higher cost estimates are strongly influenced by more pessimistic assessments of future low carbon technologies
- Energy system trade-offs are pervasive under alternate assumption sets. These include the use of natural gas vs. coal under low or high resources prices, upstream technological change vs. end-use energy reductions under innovation optimism, and electricity vs. transport CO_2 reduction pathways, based on the timing of emissions reduction requirements.
- These trade-offs illustrate endemic uncertainties in future resources, infrastructures, technologies and behaviour. One example of this is that it is not possible to robustly project a dominant technology class within the future electricity portfolio.

<u>System Evolution</u>

In general the MARKAL and M-M model base-case represents a low energy (and emissions) growth in the UK (from 6,152PJ final energy in year 2000 to 6,272PJ in year 2050). This is because even in the base case (i.e., in the absence of an economy-wide CO_2 constraint), there is pervasive technological change towards cost effective energy saving and/or lower carbon technologies. Natural gas and coal constitute the dominant base-case primary energy fuels, with the former used in high-efficiency direct-use applications in the residential, services and industrial sectors, with next-generation coal as the largest electricity generation and hydrogen production technology.

Under CO_2 constraint scenarios, further reductions in energy consumption are substantial, falling to around 5,250PJ in 2050. This intensity improvement reflects a range of mechanisms including upstream and end-use efficiency, use of technical conservation measures and a pure behavioural demand reduction in response to rising energy prices. These mechanisms combine with energy pathway and fuel switching in all sectors to meet CO_2 reduction of around 375 MTCO$_2$ by 2050 (to a level of 218 MTCO$_2$). Following a straight-line trajectory (SLT) to 2050 forces the model to abate earlier and implies more effort on a cumulative measure, with total SLT emission reductions rising to 7,205 MTCO$_2$, compared to approximately 6,460 MTCO$_2$ under the C-60 constraint.

In the CO_2 constrained scenarios, natural gas strengthens its position as the largest component (35%-40%) of primary energy, with high efficiency end-use applications. Coal use remains significant at around 20%, based primarily on CCS applications. Nuclear retains a share of base-load generation in many but not all constrained scenarios. Oil and refined oil use see significant reductions due to efficiency and fuel switching (to hydrogen) in various transport modes. Finally renewables see a significant growth in all scenarios (with some up to a 30% primary energy share), the rate of which is largely based on the availability of other zero-carbon and efficiency options.

All upstream and end-use sectors contribute to the stringent 60% reduction target. The electricity sector is a major source of carbon reductions, complimented by fuel switching, efficiency conservation measures and demand reductions in the end-use sectors. When

electricity emissions are allocated to end-use sectors, industry and service sectors produce the deepest reductions at 24% and 27% respectively of year 2000 emissions. All hydrogen production is utilised by the transport sector, and transport is the last sector to decarbonise, retaining 55% of year 2000 CO_2 emission levels by 2050.

Technology Pathways

A 60% reduction in UK CO_2 emissions entails radical changes in resource and infrastructure use, and investment in new technology portfolios. In general, under alternate scenario assumptions there is a trade-off between emission reductions from the electricity sector (notably fuel switching and efficiency gains), the buildings and industrial end-use sectors (notably demand reductions, conservation and efficiency gains) and the transport sector (notably hybrids, hydrogen and bio-fuels).

Detail on electricity generation by major technology class was a key focus on the DTI scenario set. Alternate scenarios generate alternate portfolios in electricity production. Notably, uncertainties in the future costs and characteristics of both new CCS and nuclear technologies mean that it is impossible to robustly project that one technology will be dominant in future years. In addition, wind generation plays an increasingly important role. When innovation is limited or major zero-carbon electricity technologies are restricted from the solution (e.g. nuclear and CCS) electricity generation declines. Without either nuclear or CCS the electricity portfolio transforms again to be dominated by offshore wind, supplemented by higher costs renewables (including marine) with base-load requirements met using natural gas and bio-gas CCGT plants. That the technology pathway evolution is inherently uncertain and path dependant is also illustrated in the SLT case, where the earlier CO_2 constraint results in a non-nuclear future, with emission reductions coming from more mature wind technologies and bio-fuels in transport.

When compared to the standard MARKAL model's CO_2 constrained solution, total electricity generation is markedly increased at 1,502 PJ vs. 1,305 PJ in the M-M model. This is due to the MARKAL model not having access to energy service demand reductions through behavioural change which thus substitutes greater emissions reductions on the upstream electricity sector via fuel switching to electric boilers and other buildings and industrial end-use technologies. One consequence of this is the introduction of previously higher cost marine renewable electric technologies.

In the base case, transport final energy consumption is already transformed in the absence of a carbon price signal, including modal shifts towards petrol and diesel hybrid vehicles. Post 2030, buses, then HGVs, and subsequently LGV's evolve into hydrogen vehicles, based on the relative costs of the technologies and importantly the infrastructure requirements per mode.

In the constrained cases, consumption of transport fuels (petrol and diesel) is reduced further. An interesting (non-intuitive) trend to emerge is that for hydrogen, which shows lower levels of consumption than in the base case. However, hydrogen production in the base case is from fossil fuels; under the constrained case hydrogen is produced at a lower

level but is carbon neutral. Bio-fuels play an increasingly important role, with slightly higher levels of bio-diesel and ethanol, and the significant (20% of transport fuels) use of second-generation bio-fuels (Fischer Tropsch diesel) in 2050.

A range of demand-side responses trade off against electricity, transport and other CO_2 abatement mechanisms. In these cost-optimal solution, the model exhausts available conservation measures due to the stringency of the CO_2 target. This is despite the use of a higher 25% hurdle rate, designed to partially account for market risk, information deficiencies and other market imperfections in the uptake of end-use conservation options. In addition to efficiency and technical conservation, the purely behavioural change in energy service demands cluster around 10-15% and contribute significantly to lowering marginal CO_2 prices (e.g., comparing vs. standard MARKAL results). In general there is trade-off between upstream emission reduction options and demand reductions, as seen in the cases with restricted upstream and technology options, as well as the "distance to target", as seen in the lower and higher resource price sensitivities.

Economic Impacts

Even considering the long time-frame and early announcement of the 60% CO_2 reduction policy, combined with the scope of technology and demand side options implemented in the M-M model, such a transformation of the UK energy system necessitates a high carbon price signal. By 2050 the central constrained case generates a marginal CO_2 cost of £105/tCO_2 (or £385/tC). Without endogenous demand reductions (i.e., comparing the M-M model to the standard MARKAL model), this marginal price increases to £135/tCO_2.

Scenarios with a greater or lesser distance to target (i.e. the low or high resource price cases) give a higher or lower CO_2 price (although this is moderated in the low resource price case due to the relatively improved economics of switch natural gas vs. coal). Similarly, removing key mitigation technologies (nuclear, CCS) increases marginal prices. The highest marginal costs arise in those scenarios where innovation across a broad range of technologies has been restricted (up to £176/tCO_2).

From the standard model, comparing the average with the marginal emissions abatement curves shows much lower cost levels, indicating a cost distribution skewed towards lower cost reduction options, combined with fewer high costs abatement options as the model meets the tightening targets. The negative and very low average costs in 2025-2035 are a reflection of cost effective conservation options in the residential, services and industrial sectors, enabled through additional policies to address information barriers and other market barriers.

In terms of energy systems cost projections using the M-M model, the situation is complicated by twin effects working against each other. Firstly, demand reductions due to behaviour shifts occur leading to a shrinking energy system in the CO_2 constraint cases vs. the base-cases. Secondly however, the unit costs of the energy sector increase as higher costs fuels and technologies are utilized to meet the CO_2 cap. In the core C-60 case the energy system cost in 2050 is still £0.6 billion lower than the base case. The restricted

innovation cases entail the highest M-M energy systems costs, rising to an increase of £7.2 billion in 2050 if only 2010 improved vintages of technologies are available.

The standard model does not have a behavioural demand reduction and hence its base and CO_2 case differences in energy systems costs directly correspond to abatement costs. Without the overall demand reduction, the standard model generates higher abatement costs. The central undiscounted abatement cost (C-60) in 2050 is £B8.8 with a low estimate of £B2.1 if all optimistic technological assumptions are employed and a high estimate of £B19.8 if innovation is restricted to 2010 levels.

Under the CO_2 constraint, radical changes in energy supply, transformation and use as detailed above have a major macro-economic impact on a relatively smaller energy system (due to the energy sector's contribution to GDP falling from around 9% in 2000 to 5.5% in 2050).

The central CO_2 constraint case (C-60) gives an annual GDP reduction of 0.72% by 2050 (or a B£20.3 reduction from a projected UK GDP of B£2,807). The SLT case generates higher GDP losses (£B22.2) than the standard case – this is due to the cumulative emission reductions being greater (7,205 vs. 6,460 MTCO$_2$ - see Figure 7) despite a smoother abatement path.

The GDP reduction range in 2050 varies between 0.3% and 1.5% (£B7.5 to £B42.0) which is equivalent to other estimates for long-term CO_2 reductions (Stern, 2006). The higher cost estimates are strongly influenced by more pessimistic assessments of future low carbon technologies.

It is stressed that the M-M model is likely to give a lower bound to macro-economic costs, due to bottom-up optimism over future technologies and energy efficiency/conservation, together with non-consideration of trade impacts and transitional costs. Furthermore the simplicity of the M-M linkage with no government sector means that and recycling of revenues, cannot be investigated. Lastly the costs are for UK abatement with no option to purchase international emissions credits. The costs and availability of long-term emission credits is extremely uncertain and not considered in this analysis.

Future academic publications will present modelling insights on the full set of UK energy scenarios, focusing on global and policy drivers of technology pathways to a low carbon energy system. Future UK MARKAL modelling development will use enhanced spatial and temporal detail to further investigate the development of new infrastructures, operational details of the UK energy system and the impact of innovation. Additional modelling work will further disaggregate the role of consumer and firm behaviour in energy service demands. Finally additional UKERC scenario modelling will link analysis of UK policy objectives of low carbon and energy security.

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Appendix 1: Development of the 2007 UK MARKAL model

Since the 2003 EWP model analysis, the UK MARKAL model has been significantly revised and improved.[23] Since 2005, the model has been significantly revised by PSI under the UK Energy Research Centre, with contributory funding from DTI and DEFRA. AEA Energy and Environment have provided some support to this process, through funding from DTI/DEFRA. The aim of this programme of model development was to extend the functionality of the model, and to allow improved analysis of UK specific issues and underlying energy drivers.

Model revisions
Major updates to the model include:
- Comprehensive technology data review and update;
- Development of disaggregated end-use sectors notably industry, residential, service (commercial), transport and agricultural sectors
- Specification of resource supply curves for all domestic and imports;
- Specification and costing of fuel infrastructures on a sectoral basis, also facilitating sectoral tracking of fuels and emissions;
- Depiction of key energy processes including the refining sector, relevant hydrogen processes and biomass chains;
- Explicit treatment of mitigation options, including the nuclear fuel cycle, carbon capture and storage (CCS) options, and combined heat and power (CHP);
- Updating the electricity sector, including micro- and remote-grid representation;
- Re-estimation (from exogenous drivers) of energy service demands;
- Incorporation and integration of a Macro model to investigate demand responses and generate insights of GDP and consumption impacts (see section 2.1.2).

Table A1 details a complete listing of modelling extensions and updates through to the end of 2006.

Sector / Component	Completed extensions and updates
System parameters	Adjustment of the time frame and steps of the model, to run in five-year increments and through to 2070 Modularisation of the UK MARKAL model into specific sectors Development of logical and coherent naming conventions Finalisation of a complete set of consistent energy carriers Specification of model-wide assumptions on future technology vintages and costs Re-calibration of seasonal and diurnal demands

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[23] Analysis for the Carbon Abatement Technology strategy using the MARKAL model (DTI, 2005) led to interim improvements in the characterisation of carbon capture and storage technologies.

Fossil Resources	Cumulative supply curves for domestic oil, natural gas, coal Cumulative supply curves for imported uranium, natural gas, oil (partial) Export/import balance for coal, oil, oil products Tracking on imports/exports of electricity and natural gas via inter-connectors
Renewable Resources	Annual supply curves for domestic wind (by tranche), hydro, biomass (crops and agri-wastes), industrial and commercial wastes Resource availability for tidal, wave Imports of biomass, and refined bio-fuels
Hydrogen	Production (at differing scales) via SMR, coal gasification, biomass gasification, and electrolysis Transport via gaseous H_2 (pipelines, tube trailers, tankers), liquid H_2, hythane Hydrogen storage at alternate scales
Nuclear	Open and once through nuclear cycles, fusion Uranium enrichment, reprocessing for MOX fuels, waste product tracking
Refining	Depiction of current UK refining capacity New vintages of flexible refining plant Tracking of refined petroleum products
Biomass	Biomass chains including gasification, pyrolysis, fermentation, co-firing (with coal) derived fuels (e.g. 1st and 2nd generation bio-diesel) Second generation bio-fuel processes
Infrastructures	Explicit depiction of infrastructures to each end-use sector for each energy carrier (natural gas, oil, oil products, biomass, biogas, bio waste, other renewables, electricity, steam, LTH, hydrogen etc) Joint fuels (e.g. biogas-natural gas, petrol-ethanol etc)
Emissions	Tracking of CO_2 and SO_2 at input fuel stage, with downstream capture Tracking of emissions at sectoral level via dummy technologies on fuel flows
Other Key Process Technologies	Coal gasification, coke and coke oven gas, LNG terminals and infrastructure Secondary fuels (e.g., CNG, bio-diesel etc) coal-to-liquid, and gas-to-liquid processes Carbon capture and storage (CCS) - transportation and UK storage capacity in alternate reservoirs

Electricity	Explicit remote, centralized, distributed, auto-generation, and micro-generation grids to account for T&D costs
	Nuclear - Generation II, III, and IV technologies
	CCS – technology vintage and joint electricity/hydrogen production for coal and natural gas technologies
	Micro generation – fuel cells and other distributed generation (DG)
	Current and advanced vintages for coal, natural gas and oil technologies
	Dual fuel plants (bio-natural gas, gas-oil etc)
	Wind and hydro technologies by available resource
	Other renewable technologies (to match full resource depiction)
	Large and small CHP technologies
	Validation via stakeholder workshop
Industry	Full module rebuilding based on ENUSIM model database (ENUSIM, 2003)
	Introduction of energy service demands at sectoral level
	5 major sector disaggregation (Chemicals, Iron & steel, Non ferrous metals, Pulp & paper, Other industry)
	Classification of sectoral technologies by fuel type
	Classification of generic energy conservation opportunities
	Large vs. small industry disaggregation
Services (commercial)	Complete data update
	Energy service demand re-estimation
	Explicit representation of major appliances by efficiency class
	Historical and future conservation options
	Alternate fuels
	Integration with distributed generation
Residential	Complete data update
	Energy service demand re-estimation, based on existing and new build housing stock
	Explicit representation of major appliances by efficiency class
	Full depiction of historical and future conservation options
	Vintaging structure for space and water heating appliances
	Alternate fuels
	Integration with micro-generation and micro grids
Transport	Complete data update
	Further disaggregation of fuel chains to modes (Car, Bus, LGV, HGV, Shipping (domestic), Air (domestic), Two-wheelers, Rail passenger, Rail freight
	Additional technologies: Plug-in hybrids
	Additional modes: 2 wheelers
	Additional behavioural constraint algorithms
	Validation via stakeholder workshop
Additional	Inclusion of agriculture sector
	Inclusion of upstream energy use (refining, oil and natural gas extraction)

Table A1: Summary of completed UK MARKAL model extensions and upgrades

Model input parameters
As a data intensive energy systems model, MARKAL input data parameters describe technologies exhaustively. However, in the current UK MARKAL model, all the features are not used due to either lack of data availability or irrelevance to the UK context.[24] Furthermore some parameters are either specific to certain MARKAL variants or are optionally employed to investigate specific issues[25]. The majority of parameters are defined throughout all time periods (5 years steps from 2000-2070). A smaller number (e.g., lifetime) are time-independent. Technology types are organized by sets with differing ranges of potential parameters.

An important point is the use of input data parameterisation in the overall depiction of the UK energy system and the configuration of energy systems pathways. For want of a better term this is the "art" of energy modelling in that the modelling team must construct the characteristics of the current UK energy system, and give the model freedom to choose alternate energy configurations (for example in the use of new energy carriers such as hydrogen or the restructuring of energy infrastructures through distributed generation. An additional element to this is to constrain the system to represent UK-specific physical and current policy constraints. This allows the model to be calibrated to base-year (2000) energy metrics and to produce realistic analysis of future developments and interactions.

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[24] For example, endogenous progress ratios for less mature technologies are not employed as the relatively small UK market is assumed to be a price taker for globally developed technologies. As such exogenous rates of learning are used, based on the literature on progress ratios and IEA global technology forecasts.

[25] For example the costs of traded resources and goods in a multi regional model, or a global warming potential when investigating multi-gas mitigation

Table A2 below shows an overview of key input parameters used in the current UK model.

Parameters category	Specific Parameter Depictions	Notes on current usage or relevant examples
Demand (services) representation	Sectoral demand (e.g. residential, commercial, industrial, transport, agriculture)	Demand for energy services, e.g. residential lighting, heating, cooling etc; industrial chemicals, iron&steel etc; transport, cars, buses, domestic air etc
	Annual demand	
	Seasonal demand (e.g. night, day, winter, summers, …)	
	Peak load contribution	
Seasonal representation	Three annual seasons (summer, winter and intermediate)	Applies globally or technology/demand specific (e.g. to represent seasonal/daily availability of solar resources or seasonal demand for heating)
	Two diurnal periods (night and day)	
Technical data	Engineering characteristics of technology Applies to: Demand technology (heating/cooling, appliances, transport modes, generic industrial technologies…) Resource supply technology (fossil, renewable, nuclear,) Power generation technology (centralized, decentralized, base/peak load, storage, renewable, CHP, ….) Process technology (refineries, fuel processing, …) Infrastructure (grid, pipelines, LNG terminals, …)	
	Availability factors (annual and/or seasonal)	All technologies
	Unavailability factor (AF_TID)	
	Capacity factor (annual and seasonal)	
	Efficiency	
	Type of technologies, e.g. base load, peak load	Electricity and heat conversion only
	Technical life time	
	Year available	To vintage a technology. Mostly used in demand and power sector
	Existing/residual capacity (i.e. stock)	

Cost data	Applies to: Demand technology (heating/cooling, appliances, transport modes, generic industrial technologies…) Resource supply technology (fossil, renewable, nuclear,) Power generation technology (centralized, decentralized, base/peak load, storage, renewable, CHP, ….) process technology (refineries, fuel processing, …) Infrastructure (grid, pipelines, LNG terminals, …)	
	Capital cost (all upfront cost, including financing etc)	
	Fixed O&M cost	
	Variable O&M cost	
	Progress ratio (ETL-PROGRATIO)	
	Block investment	1 GW nuclear versus 10 GW investment
	Fuel cost with availability/supply curve	Applicable to primary energy resources and imported energy resources
Discount factor	Global discount	All technologies and resources
	Technology specific discount rate (to represent hurdle rate)	Technology specific
Infrastructure	Transmission losses	Electricity and fuels
	Distribution losses	
	Seasonal transmission efficiency (TRNEFF(Z)(Y))	Applicable to CHP plants
	Reserve capacity	Power generation and heat
	Contribution to peak load	
Emission factors	Type of emissions (e.g. CO_2, CO, SO_x, NO_x….)	Currently CO_2 is tracked
	Cap on emissions	Currently cap on CO_2
	Emissions from technologies	e.g. NO_x/SO_x from power plant
Constraints	To limit any technology	
	To limit an investment on particular technology	
	To limit output from a technology	
	To limit capacity of a technology	
	Phasing out existing stock of technologies	
	Limit on energy resources (annual and/or cumulative)	
	Control over share of technologies	e.g. share of particular technologies, Renewable Obligation Vs conventional or electric heating vs. gas heating
Tax and	To a technology	

subsides	To fuels	e.g. climate change levy
	To any emissions	e.g. carbon price
Macro parameters	GDP growth	Potential growth forecast
	Elasticity of substitution	Between nested investment and consumption and their aggregate to combined energy costs
	Demand marginal	To represent ease of altering specific energy service demands
	Demand decoupling factors	To account for existing demand decoupling from GDP growth (e.g. air travel is growing faster than GDP)
	Base year economic characteristics	GDP, energy costs, capital ratio, labour supply
Other MARKAL variants	Range of parameters related to: Multi-regional analysis material flows, elastic demands (including cross- demands) stochastic evaluation goal programming between different objective functions	

Table A2: Major input parameters

Appendix 2: Detailed description of MARKAL-Macro

MARKAL-Macro Methodology

MARKAL-MACRO (M-M) combines very rich technological characterization of energy system with a dynamic inter-temporal general equilibrium model. Using this approach, MARKAL-Macro allows both a sub-sectoral demand response to supplement technology pathway optimisation, as well as allowing direct analysis of the impacts of various energy and environmental policies on the growth of the economy.

M-M was developed based on the pioneering work of Manne and Wene (1992). M-M maximizes, under a pre-determined economic growth path, the discounted sum of utility derived from consumption. The basic input factors of production are capital, labour and energy service demands. The economy's outputs are used for investment, consumption and inter-industry payments for the cost of energy. Investment is used to build up the stock of (depreciating) capital, while labour is exogenous.

The demand levels and cost of energy is the link between MARKAL and the Macro module. Useful energy services that are given by MARKAL are aggregated to form the energy input in the production function of the Macro module. On the other hand, output can be used towards consumption, capital accumulation or energy service purchases, and this information is passed from the Macro module to MARKAL. With this connection between MARKAL and Macro, MARKAL-Macro can establish a baseline and resultant changes for energy consumption, carbon emissions, technology choices, and GDP.

MARKAL-Macro integrates a simple macro model within a technology rich framework. Despite its simplicity, this is one of the very few hard-linked top-down bottom-up modelling few approaches (other examples that undertake this linkage include MESSAGE and AIM). This single sector macro module has limits to its usefulness and hence insights it can give. There is no disaggregation of capital flows to different sectors nor international capital flows. This means that the model cannot look at competitiveness issues nor relative performance of industrial sectors. Similarly there is no government sector; this means that some policies with direct investments in energy, or conversely changes in government revenues, cannot be fully investigated. However, the model does allow a wide range of policies to be investigated including price instruments (trading, taxes, subsidies), technology and efficiency standards and technology/resource portfolios. Furthermore any macro-economic simplicity must be balanced against retaining MARKAL's technological richness and depiction of the energy system.

Even given the brevity of the macro formulation, the practical integration of the Macro component is non-trivial. A range of calibration and results analysis issues emerge, which are potentially time consuming. Furthermore, the model formulation requires procedural steps to accurately solve, including the derivation of realistic shadow prices, smooth technology penetration and the accounting of energy capital costs.

The strengths of M-M are is it retention of detailed energy systems analysis with (aggregated) endogenous demand and resultant calculation of macro variables (GDP, investment, consumption). Its weaknesses derive from its simplicity and include:

- A single region model hence no consideration of competitiveness and other trade issues;
- Not an macro-econometric model, hence gives no information on transition costs;
- No government sector, hence cannot investigate revenue recycling from taxation or auctioning permits
- Non-formal estimation of aggregated parameters (e.g. energy price elasticity ESUB)
- Consumer preferences are unchanging through the model horizon

M-M likely gives a lower bound to macro-economic costs related to long-term CO_2 reductions (e.g. compared to Stern (2006)), due to:

- M-M has lower energy sector growth relative to the overall economy as the UK continues to reduce its structural energy intensity. The energy sector in 2050 is only ~5% of the economy vs. ~8% in 2000
- Similar to the standard MARKAL model, M-M has optimistic future technology cost assumptions
- Similar to the standard MARKAL model, M-M employs a range of economy-wide energy efficiency measures
- M-M as a single region model does not quantify trade and competitiveness effects
- M-M as a single sector production module does not account for further transition costs
- M-M assumes costless substitution and behavioural change

In summary, MARKAL-Macro has four major features:

- An explicit calculation of GDP and other macro variables (consumption, investment) – this is a considerable improvement on the earlier (2003) MARKAL off-model calculations.
- Demand feedbacks from changes in energy prices. In this formulation, different demands will respond differently depending on the cost of altering demands for energy services. *All other things being equal, this additional system response and flexibility should produce lower policy costs*.
- Autonomous demand changes (e.g., with respect to increased aviation travel) to allows the Macro model to undertake scenario analysis where some energy demands are decoupled from economic growth.
- Energy systems effects within MARKAL as before (e.g., demand changes and resultant changes in technology mix or competition for fuel and infrastructures).

MARKAL-Macro governing equations
A compact structure ensures that only six principal equations govern the operation of the Macro model in M-M.

Equation 1 - Utility Function: The objective function of MARKAL-Macro is the maximization of the discounted log of consumer utility, summed over all periods, with an end of horizon term. The formulation is a non-linear (NLP) optimization, adding significantly to solution time.

$$UTILITY = \sum_{t=1}^{T-1}(udf_t)(\log C_t)$$
$$+ (udf_T)(\log C_T)/[1 - (1 - udr_T)^{ny}],$$
$$udf_t = \prod_{\tau=0}^{t-1}(1 - udr_\tau)^{ny},$$
$$udr_t = (kpvs)/(kgdp) - depr - grow_t,$$

Where:

Ct   : consumption in period t
kpvs   : the optimal value share of capital in the labour-capital aggregate.
kgdp   : the initial capital-to-GDP ratio
depr   : annual depreciation of the capital stock
growt : is the potential growth rate of the economy
udrt   : utility discount rate for period t
udft   : utility discount factor for period t

Equation 2 - Usage of Production: The output (production) of the economy via the Macro module is used for consumption, investment and energy costs (ECt represents the financial link between MARKAL and Macro)

$$USE: \quad Y_t = C_t + I_t + EC_t,$$

Where:

It   : investment in period t
ECt   : energy costs in period t

Equation 3 - Production Function: National production is from three substitutable inputs via a nested CES function. Under this formulation capital and labour substitute directly for one another, and then their aggregate is then substituted for a separable energy aggregate. (Ddm,t represent the physical links between MARKAL and Macro).

$$PRD: \quad \begin{aligned} & Y_t = \left[akl(K_t)^{\rho\alpha}(L_t)^{\rho(1-\alpha)} + \sum b_{dm}(D_{dm,t})^{\rho} \right]^{1/\rho}, \\ & L_0 = 1, \quad L_t = (1 + grow_{t-1})^{ny} L_{t-1}, \\ & \alpha = kpvs, \\ & \rho = 1 - 1/ESUB, \end{aligned}$$

Where:

akl, bdm   : coefficients determined by a base year benchmarking procedure
Kt   : the capital stock accumulated up to period t
Lt   : the labour in period t
Ddm,t   : the demand for energy services of type dm in period t
growt   : is the potential growth rate of the economy
ny   : number of years per period,

ESUB : the elasticity of substitution between the energy and the capital-labour aggregates

The benchmarking procedure for akl, bdm allows different energy demands to vary according to their reference or shadow prices. Values for bdm for each demand are found from the reference prices from a conventional MARKAL run. Via a first order optimality condition (Equation 3a) for the partial derivative of production with respect to demand, the marginal change in output is equal to the cost of changing that demand:

$[Y / D_{dm}]^{1-\rho} * b_{dm} = price(ref)_{dm}$

Once bdm is found, akl is the only remaining unknown variable in the production function which is then solved to find akl.

In practice this has two main results. First, different demands will be altered based on the cost of changing that demand. So if it is very expensive to reduce a particular demand, then this will be reduced relatively less. Secondly, great care is needed to have smooth (and certainly not zero) shadow prices which can occur due to over-constrained runs. This ensures that the marginal output (demand) responses are realistic.

Equation 4 - Capital Accumulation: Provides new capital through investment, accounting for depreciated capital

$$K_{t+1} = tsrv K_t + (ny/2)(tsrv I_t + I_{t+1}),$$
$$CAP: \quad tsrv = (1 - depr)^{ny},$$
$$I_0 = (grow_0 + depr)K_0,$$

Where:
tsrv : capital survival fraction
depr : annual depreciation rate
growt : potential growth rate of economy

Equation 5 - Terminal Conditions: A final equation ensures sufficient investment for replacement and constant growth of capital

$$TC: \quad K_T(grow_T + depr) \leqslant I_T.$$

Equation 6a and 6b - Linking Equations: MARKAL supply activities are linked to MACRO demand variables through 2 equations:

$$\sum_j supply_{j,dm,t} X_{j,t} = aeeifac_{dm,t} D_{dm,t}.$$

$$\sum_j cost_{j,t} X_{j,t} + c \sum_{tch} c_{tch} XCAP^2_{tch,t} = EC_t,$$

$$CAP_{tch,t+1} = expfCAP_{tch,t} + XCAP_{tch,t+1},$$

Where:

Xj : an activity of MARKAL supplying energy service demand of the form dm proportional to supplyj,dm

aeeifacdm : autonomous energy efficiency improvements factor

costj,t : the cost for each activity and period

CAPtch,t : the capacity for technology tch during period t

XCAPtch,t : the amount of capacity installed beyond the capacity expansion factor expf for technology tch in period t

Equation 6a allows an autonomous trend to be added to each demands for MARKAL Macro. This is especially key as demands are now an endogenous metric within the Macro module, and thus the autonomous component can calibrate demands to a previous MARKAL run or to forecast demands (converted into energy service demands). This process is also termed demand decoupling (as demands are decoupled from a linear relationship with economic growth).

Equation 6b is designed to smooth technology penetration and hence ensure the stability of the Macro run. The choice of its parameters is a matter of some consideration to define both the maximum technology expansion and also to have a realistic soft constraint to smooth that penetration. In addition this non-linear equation needs to be defined for each technology and is a non trivial modelling issue.

MARKAL-Macro linkage

There are a number of key differences between MARKAL and M-M

- The models have different objective functions - cost minimization vs. utility maximisation
- M-M demands are now an endogenous variable
- A differentiation costing mechanism is employed for end-use technologies. This correctly accounts for the energy sector's share of economic production, but gives a relatively differing input assumption set for demand technologies
- Lower bound changes to ensure non-zero and consistent demand marginals
- Some sectors has been simplified (notably residential with aggregated demand services for existing and new dwellings)
- M-M computational issues (non-linear optimization) means that the model matrix is collapsed into 10 year periods in order to solve in a reasonable time (<1 hour)

To successfully run MARKAL-Macro, a range of parameters need to be estimated and tested. In addition, the Macro run needs to calibrated to both potential GDP growth rates and energy demands – this is achieved via a specific demand decoupling factor (DDF) utility.

This process is in addition to the MARKAL base year (2000) calibration using national energy statistics.

First of all, the Macro variables need to be defined and in most cases are set from standard macroeconomic statistics. For other aggregated parameters, an estimated realistic value needs to be subjected to sensitivity testing. The labour index at time 0 is set to 1 and is the only variable to be specified completely exogenously. Table A3 details major Macro parameters, with typical values from Taylor (1995).

Parameter	Value	Comments
GDP0	B£ 1035.5	Base year (2000) UK GDP
GROWV	2%	Projected annual GDP growth rates are defined per time step
KGDP	2.4	Initial capital-to-GDP ratio
KPVS	24%	Optimal value share of capital (vs. labour)
ESUB	0.3	The aggregated elasticity of substitution is not available from statistics; hence ESUB is varied and results analyzed. Lower end estimates are more appropriate for models with detailed technological substitution and conservation options in end-use sectors
EC0	From MARKAL run	Energy costs in the initial period (2000)
DEPR	5%	Annual depreciation of the capital stock
DMTOL	0.5	Demand level tolerance – fraction by which the Macro demands can be lowered and sets a lower bound
IVETOL	0.5	Investment level tolerance – fraction by which the Macro investment can be lowered and hence sets a lower bound
DIFFDMDS	0 or 1	Flag to employ differential costing
QFAC	0 or 1	Flag for quadratic cost penalty factor
EXPF	15%	Percentage annual increase for quadratic cost penalty factor
SCALE	1000	Scaling factor to ensure M£ and B£ units are comparable

Table A3: Key macro parameters in DTI-DEFRA analysis

Three general issues are often encountered in setting up MARKAL-Macro runs. Firstly, only the energy-specific capital costs for a given technology need to be considered within ECt (to correctly account for only the energy related costs in the production function). This is generally done by using a utility (DIFFDMDS) to subtract the smallest INVCOST from all technologies fulfilling a given demand. The INVCOST's thus obtained now represent the differential costs of each technology, and not the full costs. Related to this energy cost estimation, the annualised capital cost of residual capacities needs to be included.

The second issue is to ensure that MARKAL's shadow prices of the demands (normally used as reference prices) are smooth and certainly non-zero. However, they often are heavily distorted in period 1, due to the heavy constraining usually employed to calibrate MARKAL to the energy statistics in the initial period. Users should inspect these shadow prices and make sure they are reasonably smooth over time without unrealistic spikes or drops, and adjust lower initial bounds if they are not.

The third issue in the calibration is to employ a Demand Decoupling Factor (DDF) utility to set-up the MARKAL-Macro reference scenario which matches both the user specified GDP growth rates and the demand levels of each demand category. This utility has been named DDFNEW. This DDFNEW utility will generate the demand decoupling factors (autonomous energy efficiency factors) and reference prices of each demand category, the potential GDP growth rates and the initial energy system cost needed by MARKAL-Macro database.

Appendix 3. Model validation and calibration

The UK MARKAL and M-M models are publicly available models, designed to have their assumptions, data sources and workings as transparent as possible. In addition to having the model reports and documentation placed on the UKERC website (see http://www.ukerc.ac.uk/content/view/142/112), a range of specific model validation and calibration exercise have been undertaken.

Stakeholder workshops

Three stakeholder workshops were held on road transport technologies (on 6th March 2006 at the Department of Transport (DfT)), on electricity generation technologies (on 10th April 2006 at DTI), and on new hydrogen infrastructure (on *date* 2007 at DfT). This prioritisation for feedback from industrial, government, NGO and academic experts represent the importance of the transport and power sectors classes for UK energy consumption, and the novel nature of an integrated hydrogen infrastructure. The data workshops were designed to elicit feedback on key model parameters, notably cost and efficiencies, and to explore alternate assumptions and supporting data sources. Detailed comments are available in Strachan et al (2005, 2006 and 2007b). The data validation process is ongoing with further UKERC and public stakeholder events scheduled for 3rd May 2007 and 21st June 2007 respectively.

Expert reviews

Four dedicated reviews on specific technology classes were carried out by domain experts. These were nuclear, hydrogen, biomass, carbon capture and sequestration (CCS). This process illustrated the importance of these technology pathways to the overall evolution of the UK energy system, as well as the significant uncertainties attached to each. The reviews were focused not only on parameter specification and data sources but also on the overall structure of the technology pathways and constraints of technology uptake and use. Detailed comments are discussed with in Strachan et al (2005, 2006). The review experts were:

- Nuclear – Dr Paul Howarth: Dalton Institute, University of Manchester
- Hydrogen – David Joffe: Imperial College (and member of the SuperGen UK Sustainable Hydrogen Energy Consortia)
- Biomass – Dr Ausilio Bauen: Imperial College (and principal investigator of the TSEC BIOSYS Consortia)
- Carbon capture and Storage (CCS) – Dr David Reiner: University of Cambridge (and member of the TSEC UKCSS Consortia)

An initial model peer review was carried out in May 2006 by Dr Gerard Martinus of ECN Netherlands, which is the largest MARKAL modelling group in the EU. In summary, the review (Martinus, 2006), found the new UK MARKAL model to be an adept tool for UK energy systems model analysis, with particular strengths in its modular structure, and strong focus on the power sector, the transport sector, and industrial sub-sectors. A number of short term priorities were suggested by this review:

1. Calibration of the model;
2. Incorporation of the MARKAL-Macro module;

3. Create a more balanced representation within the various sectors, notably with detailed residential and commercial sectors;
4. Addition of the agricultural sector;
5. Include coal-to-liquid, and gas-to-liquid for transport conversion processes;
6. Update and improve the documentation.

These improvements have all been completed for this 2007 model vintage as used for the DTI-DEFRA scenarios. In particular a full revamp of both the buildings sectors (residential and commercial) has considerably strengthened the model as an integrated energy systems tool.

Convergence with DTI energy model
A major calibration issue relates to the comparability between MARKAL, M-M and the DTI energy model outputs. A fundamental difficulty in comparing models and model outputs is their different structure.

UK MARKAL is an inter-temporal optimization model with perfect foresight whose strength is in evaluating long-term alternate developments of the integrated energy system, and the evolution of alternate technology pathways through time. The DTI energy model is a partial equilibrium model of the UK energy market. The demand side comprises over 150 econometric relationships of historic fuel demand for residential, transport, industry, service and agriculture sectors. The supply side comprises data on every major electricity producer and other energy producing industries. Its econometric structure means that its strength is in shorter-term forecasts of energy trends from a range of input demand, fuel price and other drivers.

MARKAL calculates energy service demands to a level of detail (e.g. appliance category, transport mode) using forecasts from DfT (DfT, 2005), BRE (Shorrock et al 2005), national statistics (e.g. historical housing build & demolition rates to derive residential service/appliances demand) and the ENUSIM model (ENUSIM, 2003 - with industrial growth rates checked against DTI). Thus derivation of final energy consumption from MARKAL is an output following an optimal selection of end-use technologies and conservation options as part of the overall solution. This is a major step and it is not surprising that there are differences between DTI and MARKAL.
- MARKAL has a time averaged representation of individual fuel prices, and also generates the cost optimal technology pathways based on a wide range of constraints designed to mimic physical factors and actual decision making.
- DTI has much less information on technological change – this quickly becomes important as in many end-use sectors the majority of end-use technologies have turned over by 2010, with greater technology shifts occurring in future years.
- When MARKAL calculates CO_2 emissions, this is then a further major step as the model now takes into account changes in upstream technologies, electricity generation, electricity vs. direct fuel combustion, fuel switching etc.

A further calibration issues arises in comparison the MARKAL and M-M model. It is stressed that they are different models; one partial and the other general equilibrium and with

different objective functions: energy system cost minimization vs. economy-wide utility maximisation. Further, M-M employs a differentiation costing mechanism for end-use technologies to correctly account for the energy sector's share of economic production – hence giving a relatively differing input assumption set for demand technologies. In addition, lower bound constraints are changed to ensure non-zero and consistent demand marginals. Finally due to computational issues (non-linear optimization) some sectors have been simplified (notably residential with aggregated demand services for existing and new dwellings), and the model matrix is collapsed into 10 year periods. As in the M-M model demands are now an endogenous variable, an iterative and separable convergence process is undertaken to match GDP to forecast GDP growth rates (2% as the long-run UK average), and energy demands to MARKAL (via exogenous demand decoupling to account for structural change in the energy economy). With the M-M and MARKAL base-cases matched, policy constraints (e.g., 60% CO_2 reduction target) can be imposed on both models

Therefore, in terms of calibration, MARKAL and M-M are exactly matched to DUKES (2006) figures for the base year (2000) for final energy demand (by sector), resource use electricity demand and CO_2 emissions. MARKAL's year 2000 energy consumption is 6158 PJ, which when including international air transport (469 PJ) and non-energy fossil fuel use (514 PJ), matches to actual total energy consumption of 170.56 MTOE or 7141 PJ. In future time periods the MARKAL model generates its own trends for these and all other metrics.
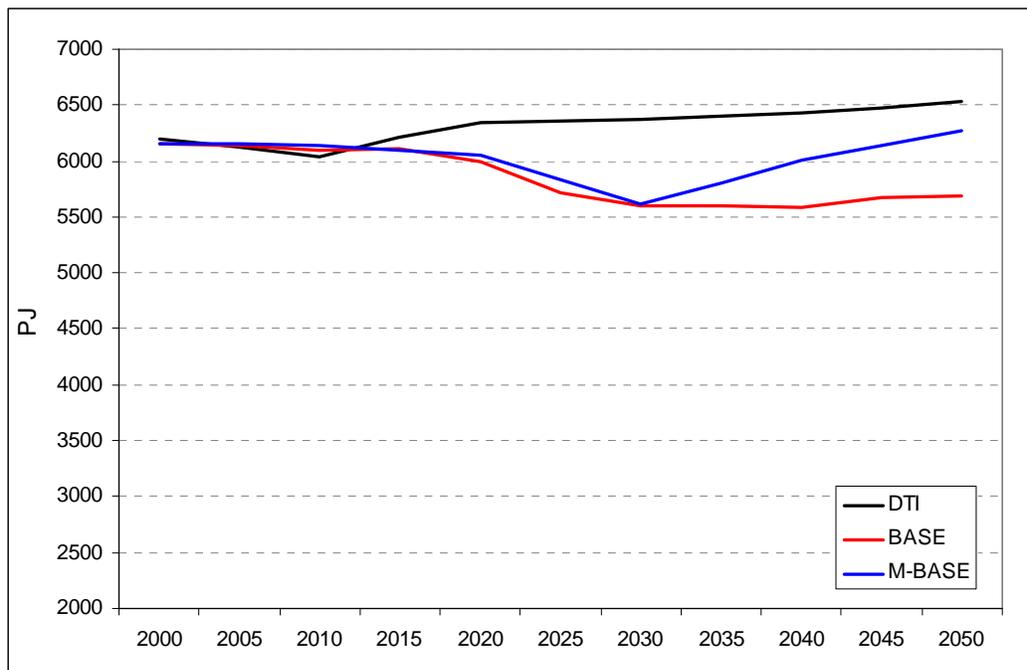
Figure A1: MARKAL (BASE), M-M (M-BASE), and DTI model final energy convergence

Focusing on final energy consumption, Figure A1 illustrates the comparison between UK MARKAL, M-M and the DTI energy model. The models converge within 0.3% in 2005 and 0.9% in 2010 for total final energy consumption. The smoother long-term trends from MARKAL's optimisation cannot mimic DTI's econometrically derived 10.6% residential

energy use drop from 2000-2005 or the 8.3% service sector energy use decline from 2005-2010. Short-term drivers such as spiking energy prices are likely the cause of this. In future years (post 2010) MARKAL gives lower energy use due to accelerated technological change (e.g., penetration of conventional transport hybrids). M-M is between the two due to moderated end-use efficiency uptake.
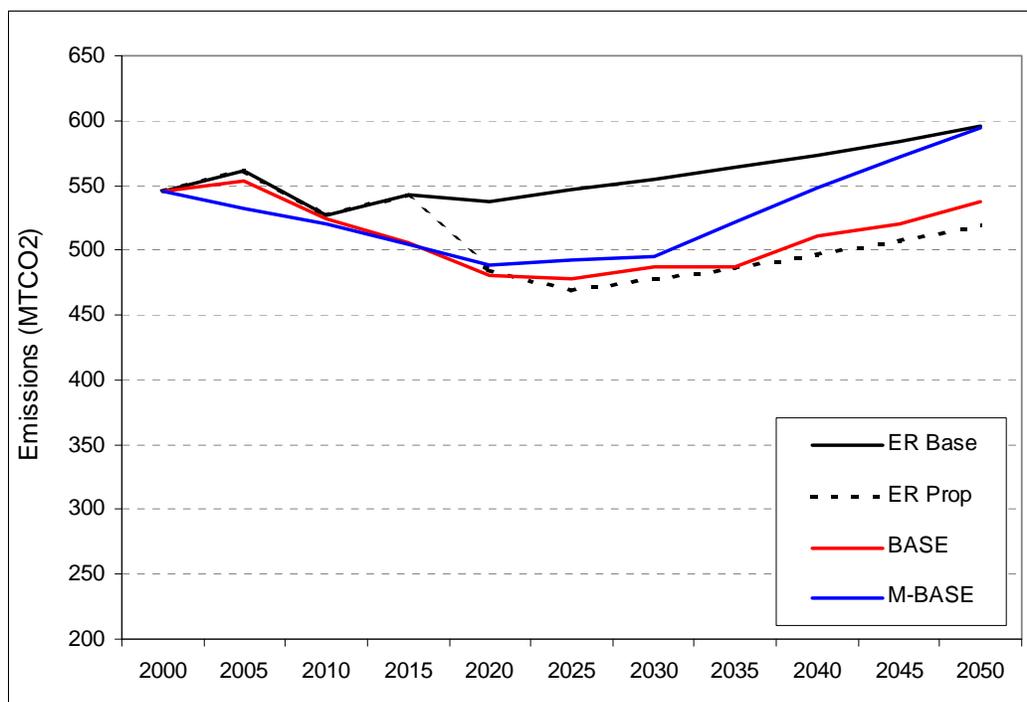
Figure A2: MARKAL (BASE), M-M (M-BASE), DTI model (Baseline and ER proposal) CO_2 emissions convergence

Focusing on total CO_2 emissions, Figure A2 illustrates the comparison between UK MARKAL. M-M and the DTI energy model. MARKAL generates an exact match to 2000 (DEFRA, 2005b) of 544.8 $MTCO_2$ or 148.6 MTC. MARKAL emissions in 2005 are higher than the 2000 levels, but 1.5% lower than DTI (and actual 2005 emissions).[26]   Again the discrepancy is likely due to short term drivers, e.g., high short-term natural gas prices leading to a shift to coal for electricity generation and industrial use. MARKAL, M-M and DTI emissions converges to within 0.5% in 2010. Again in future years MARKAL gives lower carbon emissions due to accelerated technological change (higher efficiency and fuel substitution), with M-M again between the two model due to moderated end-use efficiency take-up. Future year emissions coincide with the projections including measures identified under the Energy Review (ER).[27]

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[26] Note MARKAL converges with the DTI's earlier (April) projections for 2005 emissions.

[27] This does not mean that MARKAL selects the same measures as identified in the ER, but it does appear logical that a model which selects the cost optimal solution (provided non-cost barriers are addressed, and technologies fulfill their mitigation potential) provides baseline projections that are in agreement with the case where government policies seek to achieve this.

This issue of model convergence has come up before and dealt with in the 2003 Energy White Paper modelling exercise (FES, 2003), and more recent analyses of transport scenarios (FES, 2006). To quote from the latter study: *"We reviewed the new DTI energy demand data and associated scenario information, prepared for the current Energy Review and provided recently for the PSI/FES project, and compared it against the scenarios in the current MARKAL model. We compared input assumptions such as population and household numbers as it is difficult to compare the scenarios in terms of energy demand outcomes, due to the different modelling approaches and assumptions about technological progress and efficiency improvements. DTI projections tend to give higher energy demands than MARKAL. This is because the DTI projections are based on historical levels of efficiency improvement while MARKAL is based on bottom-up estimates of likely future efficiencies, and implicitly assumes all cost-effective measures (e.g. most energy efficiency measures) are taken up."*

The same situation applies here, and as long as the nearer-term projections from the MARKAL and M-M models are not widely different from the DTI model and/or any differences can be explained as above, the results are perfectly valid and indeed add additional insights.

Appendix 4: Further model results

In this Appendix, additional scenarios focusing on alternate technology assumptions are detailed. These scenario runs, exploring alternate assumptions, provide additional sensitivity analysis of key drivers but do not constitute a formal uncertainty analysis.

Further standard MARKAL results (UKERC assumptions): Technology sensitivities
Table A4 details the 27 model runs were undertaken using the standard MARKAL model, for the full UKERC version and the DTI variant version.

Assumption set	Scenario	Scenario description
UKERC	BASE	Base-case
	C60	CO_2 constraint applied as a 30% reduction in 2030 – straight line interpolation to 60% reduction in 2050
	C60_E1/E2	As C60 with advanced technology assumptions: end-use efficiency
	C60_N1/N2/N3	As C60 with advanced technology assumptions: nuclear
	C60_C1/C2	As C60 with advanced technology assumptions : CCS
	C60_M1/M2	As C60 with advanced technology assumptions: micro-generation
	C60_RN1/RN2	As C60 with advanced technology assumptions: grid renewables
	C60_NC	As C60 but with no CCS
	C60_NN	As C60 but with no new nuclear
	C60_nCN	As C60C but with no new nuclear nor CCS
	BASE-R10	Base case with innovation limited to no technologies beyond a 2010 vintage
	BASE-R20	Base case with innovation limited to no technologies beyond a 2020 vintage
	C60-R10	CO_2 constraint with innovation limited to no technologies beyond a 2010 vintage
	C60-R20	CO_2 constraint with innovation limited to no technologies beyond a 2020 vintage
DTI / DEFRA	D-BASE_C	Base-case with central DTI cost assumptions
	D-C60_C	60% CO_2 constraint applied as a 30% reduction in 2030 – straight line interpolation to 60% reduction in 2050
	D- C60SLT_C	60% CO_2 constraint applied as a straight line trajectory from 2010
	D-BASE_H	Base-case with high DTI cost assumptions
	D-C60_H	As C60_C but with high cost assumptions
	D-C60SLT_H	As C60SLT_C but with high cost assumptions
	D-BASE_L	Base-case with low DTI cost assumptions

	D-C60_L	As C60_C but with low cost assumptions
	D-C60SLT_L	As C60SLT_C but with low cost assumptions
	D-BASE_N	Base-case with no new nuclear nor CCS
	D-C60_N	As C60_C but with no new nuclear nor CCS
	D-C60SLT_N	As C60SLT_C but with no new nuclear nor CCS

Table A4: Full set of standard UK MARKAL scenarios

A number of technology sensitivity runs were undertaken to assess the impact of varying key technology assumptions, and the impacts that this might have on primary energy demand, sectoral CO_2 emissions, electricity generation profile and abatement costs.

The different sensitivities assessed include:
- Restricted innovation of technologies (pessimistic outlook): C60-R10, C60-R20
- Optimistic nuclear and CCS costs and resource assumptions, and restrictions on the use of these generation technologies: C60_N1/N2/N3, C60_C1/C2, C60_NC, C60_NN, C60_nCN
- Optimistic micro-generation assumptions: C60_M1/M2
- Optimistic renewables assumptions: C60_RN1/RN2
- Optimistic energy efficiency assumptions for technologies / conservation options: C60_E1/E2

Restricted innovation

Two scenarios have been run to assess the impact of restricting innovation of technologies (post 2010 and 2020), thereby reducing improvements in technical performance and reductions in costs. This has been done by:
- Future technology vintages beyond 2010 or 2020 are not permitted. This results in costs and performance of technologies restricted to 2010 and 2020 levels
- Conservation in the base cases is limited to Defra's 2010 or 2020 estimated potential and held at that level throughout the model horizon
- Conservation in the CO_2 constraint cases post 2010 and 2020 are limited to approximately 25% and 50% of BRE's maximum estimated potentials.

<u>Advanced, restricted nuclear and CCS</u>
There is systematic uncertainty surrounding the future costs of nuclear and CCS technologies. Within any reasonable uncertainty analysis, model results do not show a robust preference for either of these base-load technologies.

<u>Nuclear generation sensitivities</u>
Three sensitivity runs were undertaken that reflected a more optimistic outlook of the costs associated with nuclear generation. They are important to undertake to assess how moderate changes in assumptions can lead to significant changes. The scenarios developed here illustrate the tipping points in the generation options for the electricity sector e.g. between CCS and nuclear.
The constrained scenarios included:
- **C60-N1** - the uranium supply curve is flattened at the second step to reflect the deep uncertainty of available resource supplies. Costs of resources are therefore fixed at step 2, and do increase above such costs.
- **C60-N2** – as above, plus a 30% reduction in enrichment costs (which is considered well within the uncertainty range for this parameter
- **C60-N3** – as for C60-N2, plus a 30% reduction in nuclear capital costs. This latter estimate takes already optimistic nuclear technology costs down to the best possible estimates (based on IEA and NEA industry estimates).

<u>CCS sensitivities</u>
Two constrained sensitivity runs on optimistic CCS assumptions included:
- **C60-C1** - CCS capital costs reduced by 30%
- **C60-C2** - CCS potential storage capacity increased by 30%

With significant capital investment assumed for this type of plant, a reduction in capital costs was considered to see what impact this might have on levels of technology penetration. Such sensitivity is appropriate given the significant uncertainties in cost assumptions. Rates of CCS were being restricted by limits on storage capacity; this was increased under the second sensitivity run to assess the impact this would have on the electricity generation mix.

<u>Nuclear / CCS restrictions</u>
Under the constrained base case (C60), both new nuclear and CCS technologies are shown to be important for electricity generation. An interesting sensitivity is to assess how the energy system, if constrained, reduces CO_2 emissions when two important low carbon electricity generation types are excluded from the model options. This provides insights into the other technologies that might be available, for example, if new nuclear build did not go ahead, and what the implications are for costs.

Three constrained sensitivity runs were undertaken:
- **C60-NN** – no new nuclear build
- **C60-NC** – no CCS for either coal or gas-based electricity generation
- **C60-nCN** – no availability of new nuclear build nor CCS

Micro-generation

Assessment of assumptions of the costs of micro-generation were undertaken, focusing on adjusting the progress of such technologies in cost and performance terms over time. Two sensitivity runs included:

- **C6O-M1** - this accelerates micro-generation learning rates (and hence capital cost reductions) to 100% of the potential learning. The full potential learning comes from McDonald and Schrattzenholzer (2002). This oft-quoted paper surveys and synthesizes studies of energy technology learning. These learning rates are then applied to global technology penetration under the most recent IEA GTP.
- **C6O-M2** - this further accelerated learning case uses the same 100% potential based on these learning rates and world technology uptake. This is added to by most optimistic technology floor prices (in 2020-2025) from industry estimates (World Associated for Distributed Energy or WADE). These estimates cover gas, oil, coal, waste and biomass engines and micro-turbines.

Grid renewables

These scenarios investigate improved renewables costs for wind, marine, solar, biomass, geothermal, waste and hydro electricity technologies. Note that the current specification in the constrained base case is already optimistic on renewables costs, and calibrated to available UK sources approximates to 50% the potential learning rate from the literature.

Such scenario runs are important to consider the range of costs assumptions given the significant uncertainties associated with the renewable technologies. Two model runs consider improved renewable cost assumptions:

- **C6O-RN1** - this accelerated renewables earning rates (and hence capital cost reductions) to 75% of the potential learning. The full potential learning comes from McDonald and Schrattenholzer (2002)
- **C6O-RN2** - this accelerated learning to 100% of the potential based on these learning rates and world technology uptake. There are some departures from trends post 2030 (in solar, marine, and wind) to ensure realism in long-term costs

Efficiency

These scenarios undertook a parametric assessment of improved investment costs of end-use and efficiency and conservation measures. This included conservation measures and new end-use appliances rated A or AA. A corresponding rise in capacity bounds was made where applicable, although only upper bounds were adjusted to ensures no forcing of efficiency. Note that that residential and services conservation bounds are removed post-2020 in constrained runs.

Two sensitivity runs included:

- **C6O-E1** – 15% improvements in investment costs of key efficiency and conservation technologies in the residential, services and industrial sectors.
- **C6O-E2** - 15% improvements in investment costs of key efficiency and conservation technologies in the residential, services and industrial sectors.

Standard model results

Primary energy consumption in 2050 has been compared across all scenarios to assess the impact of changing a range of assumptions.
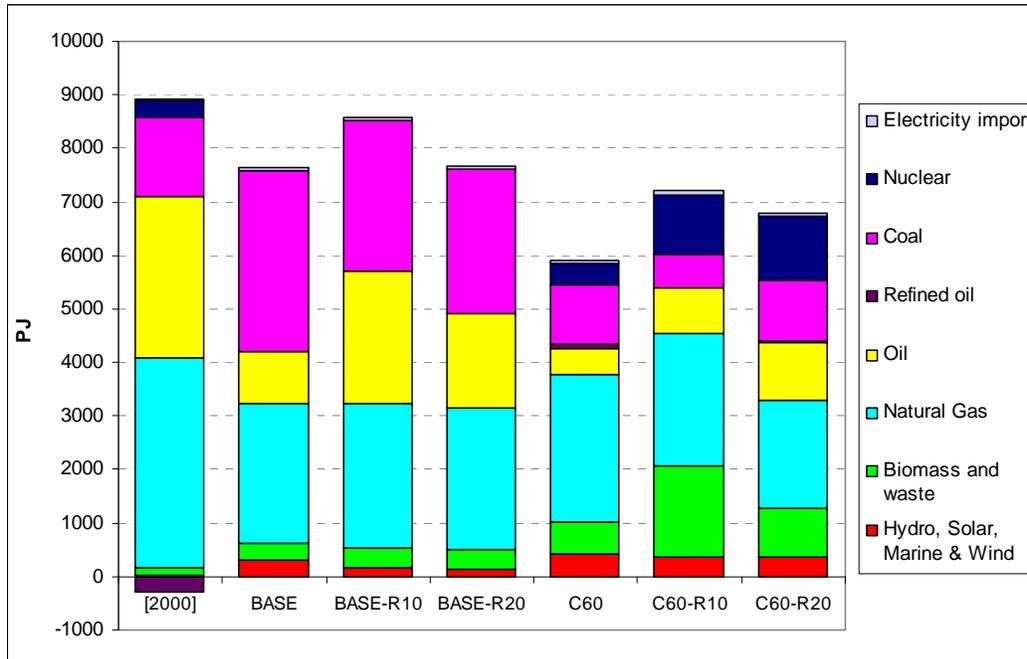
Figure A3: Primary energy in 2050: C60 and restricted innovation scenario comparison (2050)

Under the restricted innovation cases, primary energy consumption tends to be higher due to the use of less efficient technologies, and therefore the need for increased levels of energy use. Under the base cases, it is primarily the 2010 restricted case (BASE-R10), where significant increases can be seen relative to BASE. The increase is largely supplied by the refining sector. Under the constrained cases, the increases cannot be met by oil due to the cap on carbon emissions; instead the energy sector uses increased amounts of nuclear electricity and biomass. Higher levels of oil use (relative to C60) reflect the fewer low carbon transport options.
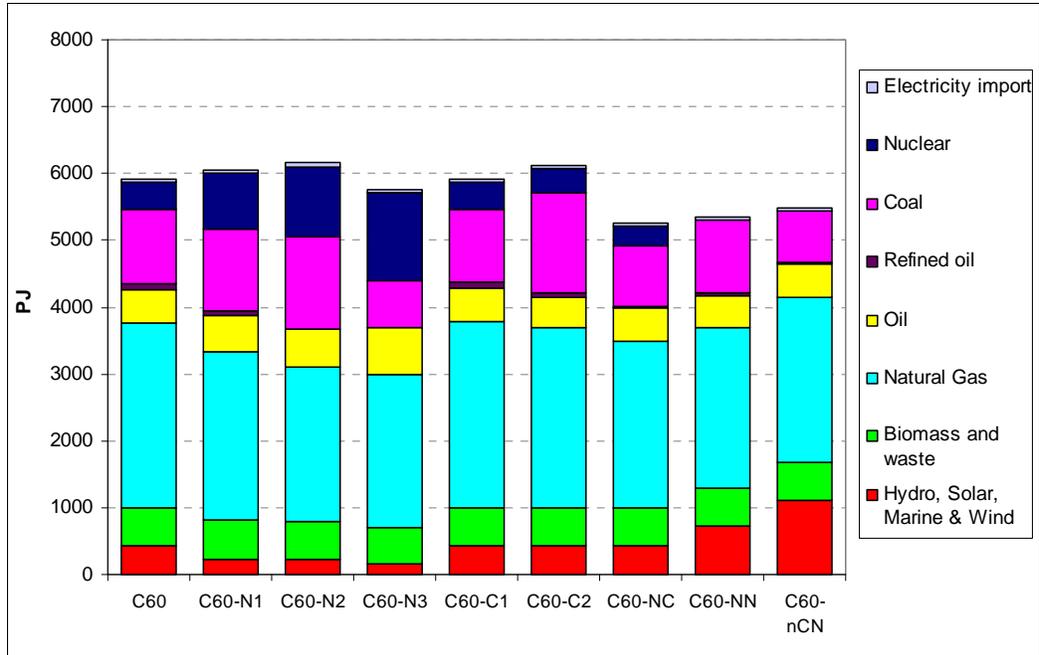
Figure A4: Primary energy in 2050: C60 and nuclear / CCS scenario comparison (2050)

Under the "optimistic" assumption scenarios for nuclear, the share of primary energy from nuclear electricity increases. This is at the expense of natural gas and coal use in the electricity generation sector. "Optimistic" assumption scenarios for CCS show an increased share of coal. Where nuclear is excluded from the generation options, the share of renewables increases. There is limited change in the share of primary energy from biomass., perhaps reflecting its limited role in electricity generation within these scenarios.

Few changes can be seen in Figure A5 (relative to the constrained baseline – C60). The obvious change is the reduction in overall primary energy consumption where more optimistic assumptions are made concerning energy efficiency options.
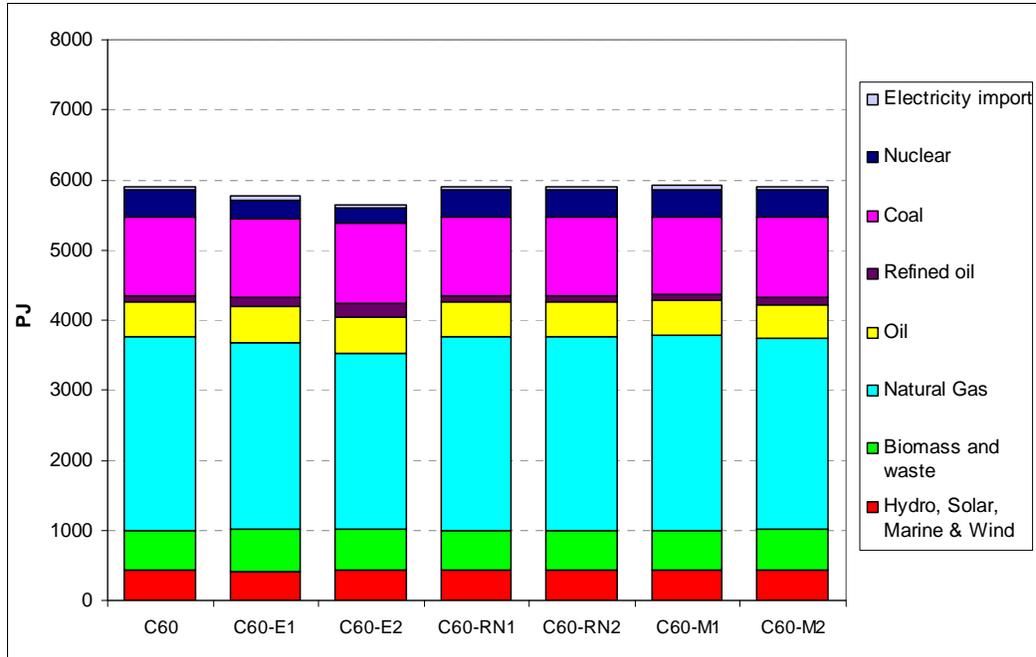
Figure A5: Primary energy in 2050: C60 and efficiency, renewable and micro-generation scenario comparison (2050)

Sectoral CO$_2$ emissions

For the comparison of sectoral CO$_2$ emissions, electricity and hydrogen emissions have not been allocated to end-use sector. Under the base case (BASE) in 2050, the majority of emissions are from the electricity generation sector (due to the significant use of coal). End use and hydrogen production sectors account for the remaining emission in similar quantities (although the service sector has much lower (direct) emissions).

Under the constraints, all sector decarbonise to some extent, although the most significant reductions are seen in the electricity and hydrogen production sectors. Residential sector decarbonises the least – although of course this does not reflect the emission savings from the use of low carbon electricity in this end use sector.

In the restricted innovation runs, the base cases (BASE-R10 / R20) reflect the reduced use of hydrogen, and subsequent higher emission levels attributed to the transport sector. Under the constraint, the transport sector has higher emissions, presumably as there is less take-up of lower emission, higher efficiency vehicles – due to constraint on vehicle performance and costs over time. Increased savings (relative to the constrained base case – C60) are found in the residential sector.
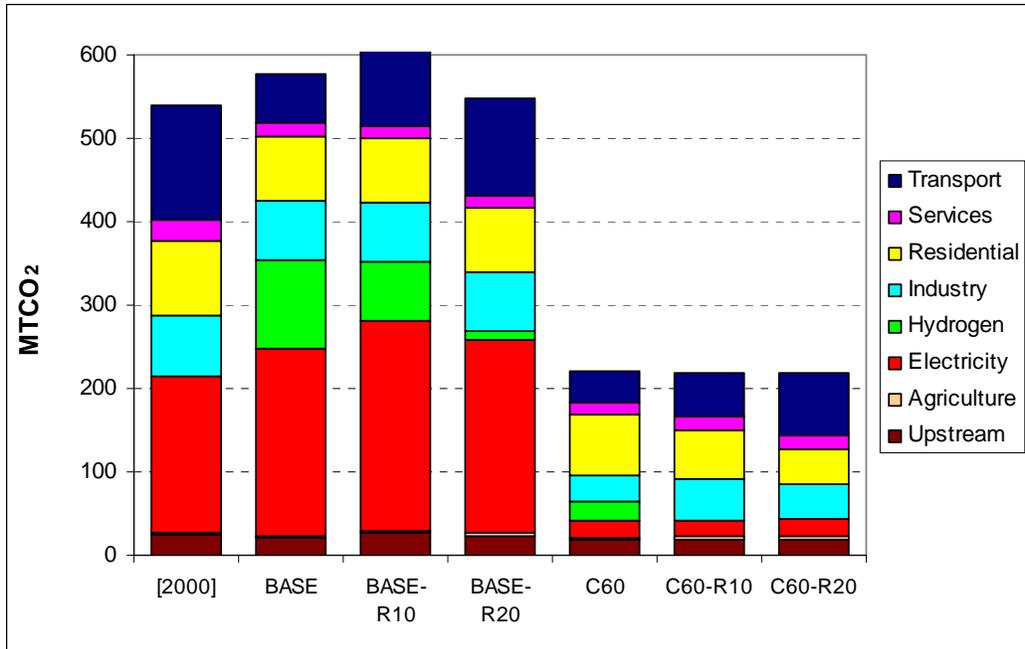
Figure A6: Sectoral CO$_2$ emissions: C60 and restricted innovation scenario comparison (2050)
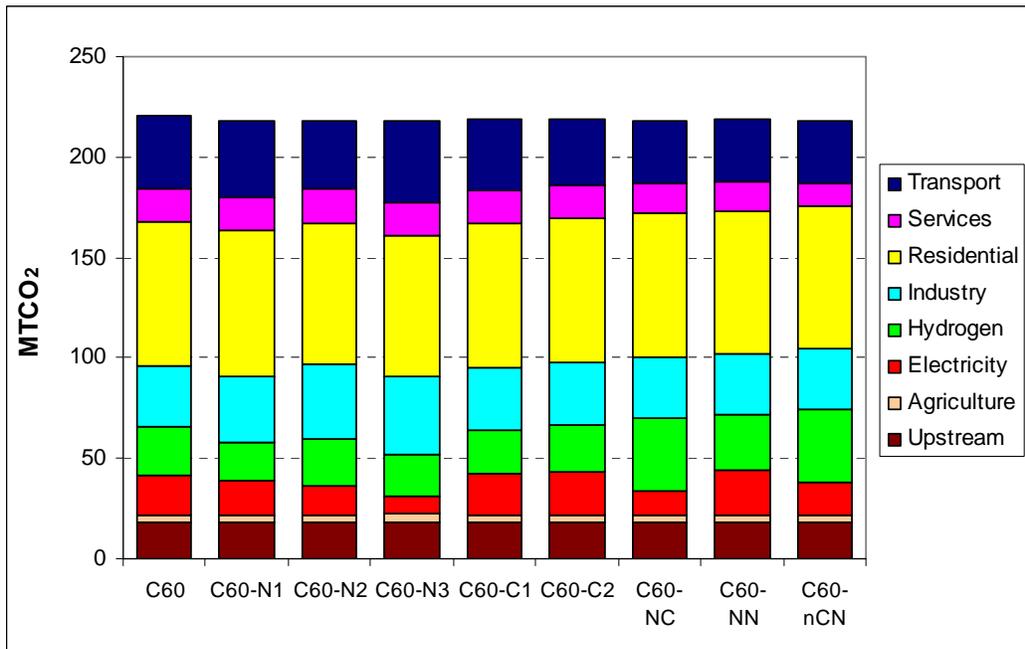
Figure A7: Sectoral CO$_2$ emissions: C60 and nuclear / CCS scenario comparison (2050)

Under the optimistic nuclear cost scenarios, emissions from electricity are lower due to the greater penetration of nuclear generation. This is also the case under the 'no CCS' case (C60-NC) for the same reasons. This appears to afford greater flexibility in the hydrogen production sector to switch to cheaper but higher emission production. Few changes occurs in the more optimistic CCS cases (C60-C1/C2). Few obvious differences in the sectoral CO$_2$

emissions under the micro-generation, renewables and efficiency cases were apparent, and therefore are not presented here.

Electricity generation in 2050

Comparisons have been made between electricity generation profiles in 2050 for the different technology sensitivity cases.
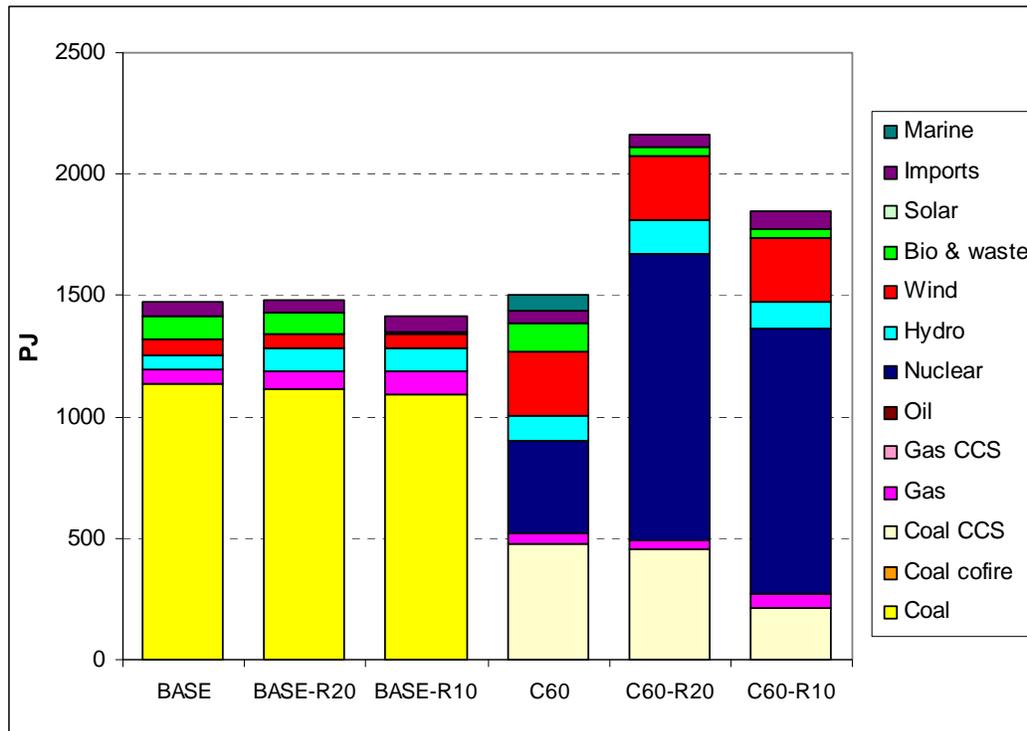
Figure A8: Electricity generation: C60 and restricted innovation scenario comparison (2050)

The restricted innovation base cases are similar to the main base (BASE) case in 2050, the only difference being that there is very limited output from biomass/waste plant (in the 2010 case), presumably due to high costs of these generation technologies. Demand for electricity is much higher in the two restricted innovation cases, driven by what is happening in other end use sectors, and the availability of low carbon electricity technology vintages. The residential sector, for example, uses more electricity for heating than in the constrained base case (BASE).
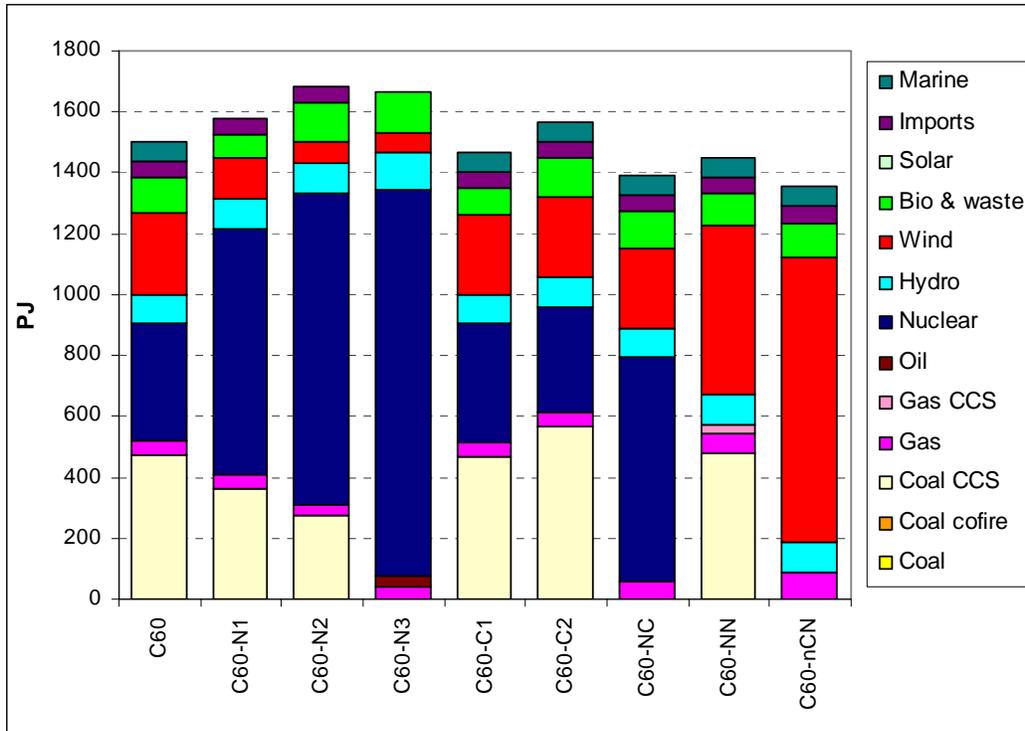
Figure A8: Electricity generation: Nuclear and CCS scenario comparison (2050)

Under the more optimistic nuclear cases, (C60-N1 to C60-N3), as might be expected, the share of nuclear generation increases. Flattening the uranium supply curve (C60-N1) ensures that by 2050 in the constrained carbon world, nuclear electricity generation is larger than that of CCS electricity generation. Under C60-N3, the model chooses no CCS generation at all, due to the very favourable generation costs assumed for nuclear.

Further increasing the cost advantage of CCS (C60-C1) pushes penetration of this technology forward slightly in time but does not significantly increase penetration (due to limits on storage capacity), while increasing the bounds of storage (C60-C2) increases the uptake of CCS relative to nuclear and renewables.

Three sensitivities restricting key low carbon technologies were undertaken. Restricting CCS uptake results in the CCS generation being replaced by nuclear generation. Where new nuclear generation is restricted, it is wind generation that makes up the 'gap'; CCS is at the limits of penetration due to limit on storage capacity. No new nuclear or CCS scenario results in a dominance of wind generation. It is important to stress that the model will build additional capacity to cover intermittency but does not fully reflect the system integration impacts of very large amount of non-dispatchable plant.

Limited differences emerge in the generation profile for the other technology sensitivities concerning micro-generation and renewables.

CO$_2$ Abatement costs

Changes in key assumptions lead to marked differences in the marginal and average costs of CO$_2$ abatement. In the restricted innovation cases (C60-R10 and C60-R20), marginal costs of abatement are much higher relative to the constrained base case. In 2050, costs are between £170-200 /tCO$_2$, relative to the standard results of £135 /tCO$_2$. Under the restriction in innovation post-2010 case, marginal costs are higher in the earlier periods than under the 2020 case as the model has fewer options at lower cost, thereby increasing the marginal costs.
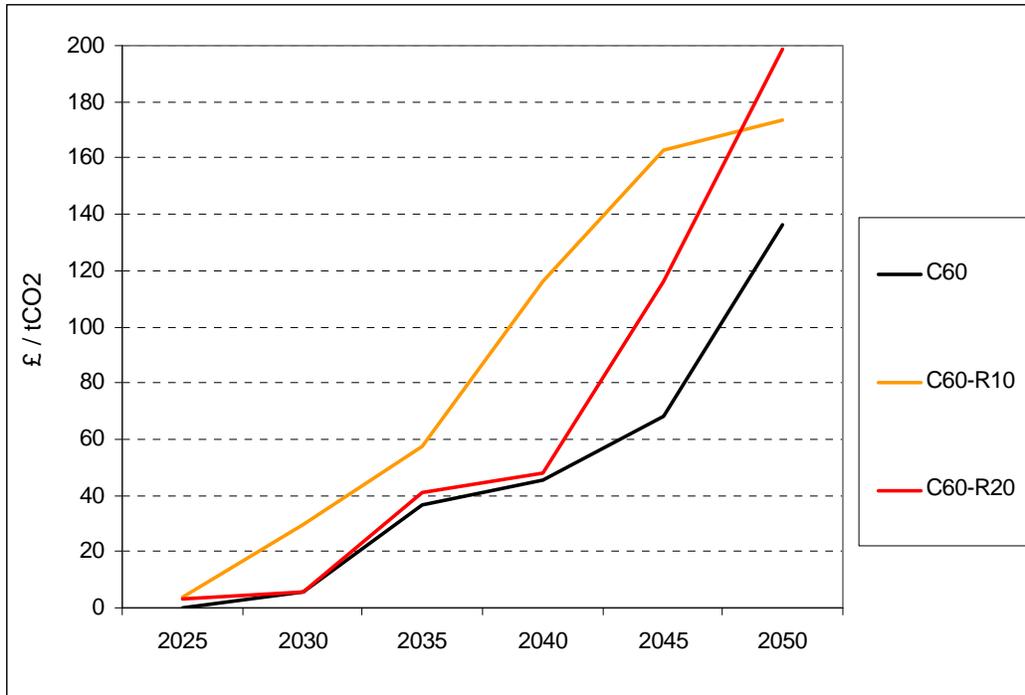
Figure A9: CO$_2$ marginal costs: Restricted innovation scenario comparison
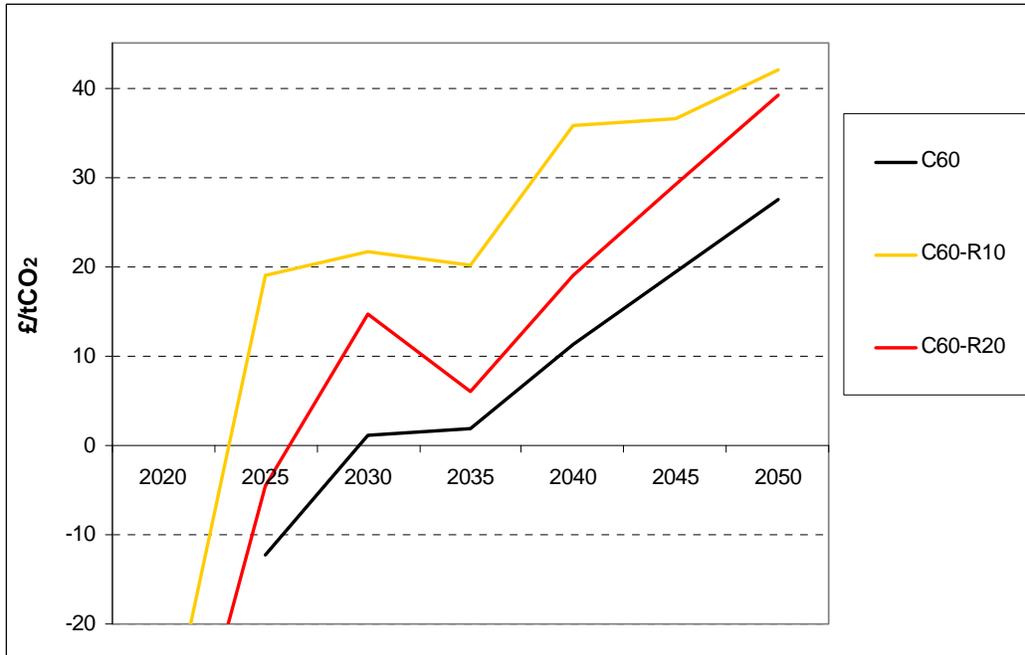
Figure A10: CO_2 average costs: Restricted innovation scenario comparison

As illustrated by Figure A10, average CO_2 costs are also higher (around £40 t/CO_2) due to fewer mitigation options being available to meet the 60% constraint.

Figure A11 below shows how the marginal costs of abatement differ based on the assumptions that are made about nuclear and CCS. When either or both technologies are restricted from the model (as new build options), the marginal costs increase. They are relatively higher in 2050 and also in earlier time periods (after the carbon constraint is introduced); 2030 is when both technologies become important in the electricity generation sector; if one or both technologies are excluded, the marginal abatement costs will also be higher in this period, as the model has to use alternative (and more expensive) low carbon electricity generation types.
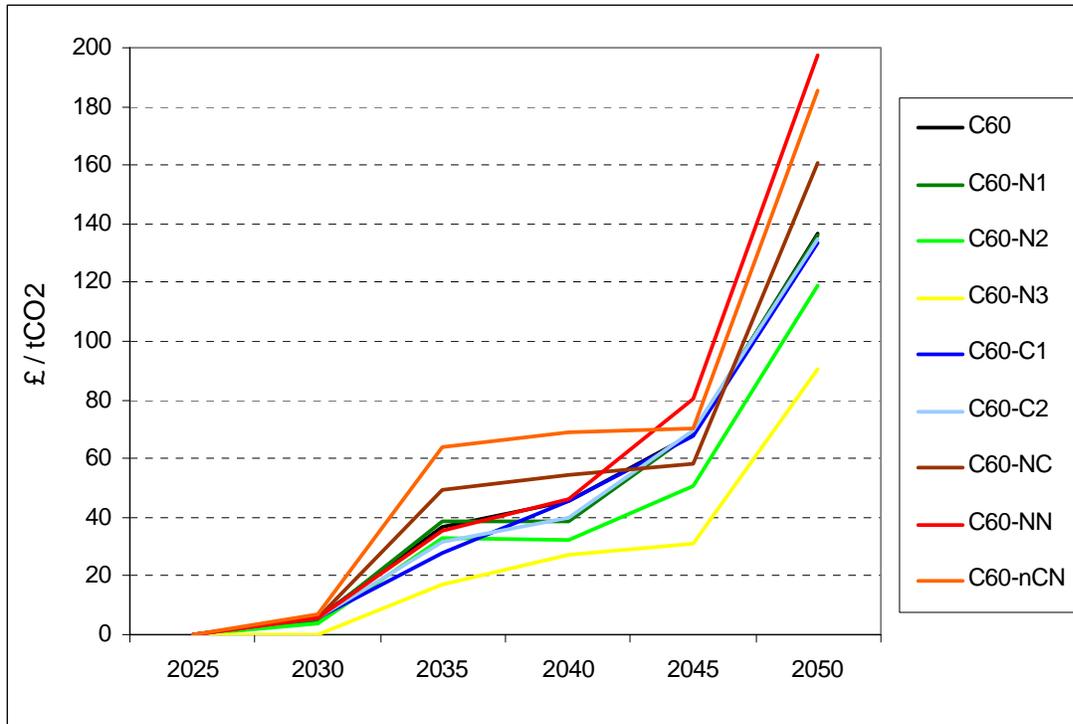
Figure A11: CO_2 marginal costs: Nuclear and CCS scenario comparison

Under the more optimistic nuclear technology scenarios, reducing enrichment costs (C60-N2) and capital costs of technology (C60-N3) has a marked impact on the overall marginal costs of abatement, reducing them significantly. This demonstrates the importance of technology specific assumptions on the costs of abatement. Reducing the costs of the resource (flattening the resource supply curve), in C60-N1, does not have any pronounced effect.

Average costs of abatement are shown in Figure A12 below.
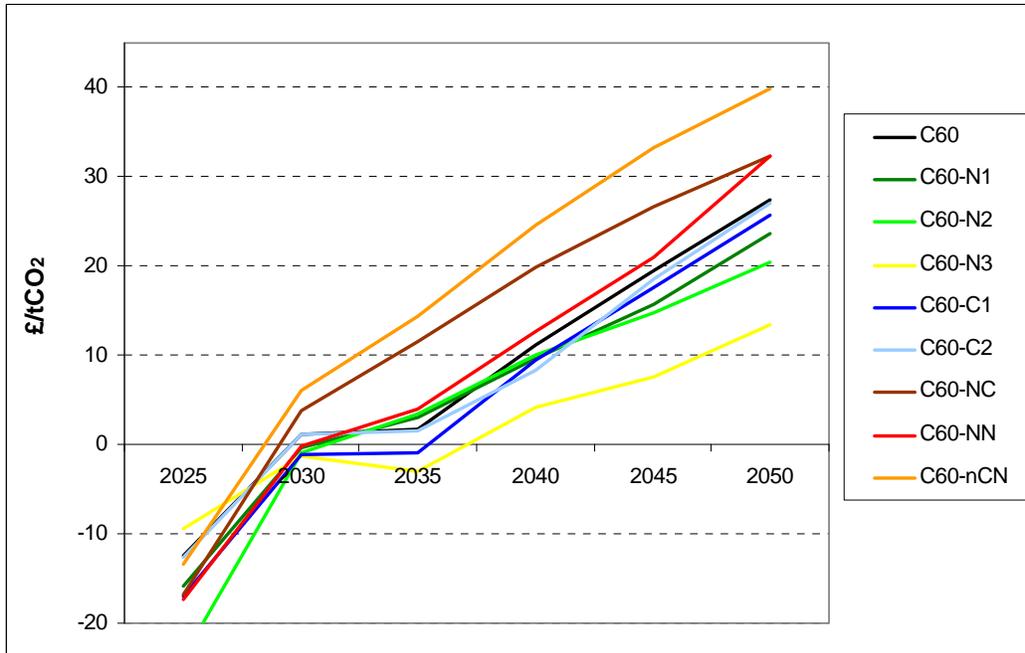
Figure A12: CO_2 average costs: Nuclear and CCS scenario comparison

Improving the cost assumptions of renewables and micro-generation do not have noticeable impact on the costs of CO_2 abatement.

Further Standard MARKAL results (UKERC assumptions): Alternate emission targets

Different emission targets, and the impact on the energy system, have been investigated through model runs using a 20%, 40%, 60% (C60) and 80% cut in emissions.

Figure A13 shows emissions as % of the 2050 base case. Reductions in CO_2 emissions is electricity dominated initially due to coal emissions in power sector (although these reduction are partially explained through fuel switching and end use efficiency). As the model struggles to meet more and more stringent targets, the power sector is almost fully decarbonised as are the buildings and industrial sectors. Transport is the last sector to decarbonise with air transport retaining its emissions share due to lack of technological or behavioural options.
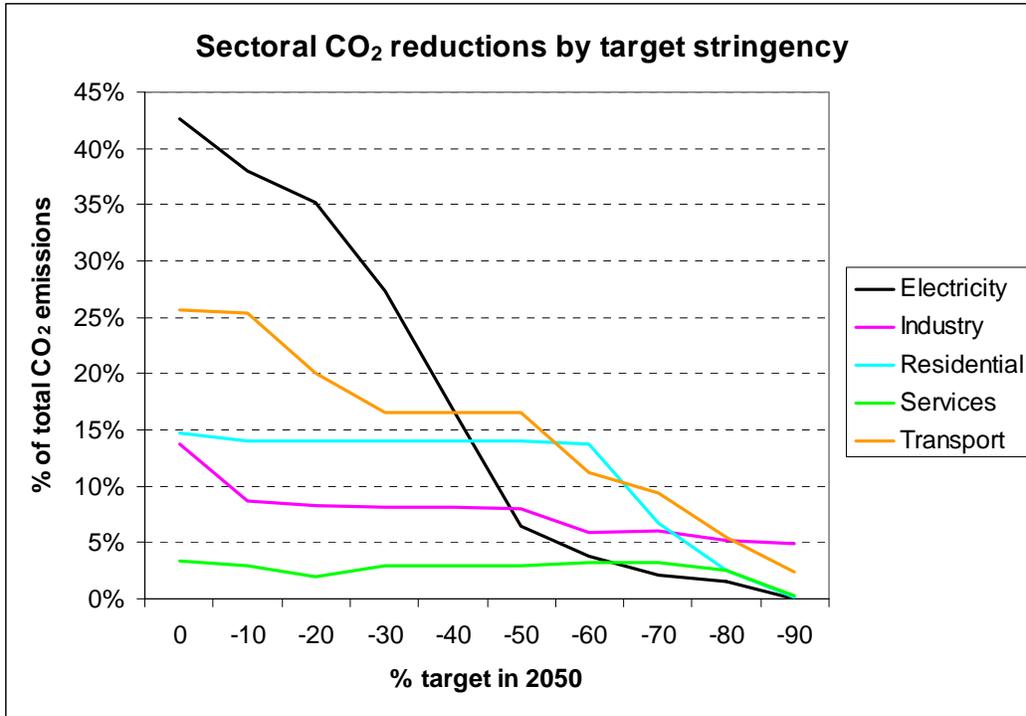
Figure A13: Sectoral CO$_2$ reduction contributions as percentage of 2050 base-case

Figure A14, A15 and A16 illustrate the total abatement costs, marginal CO2 and average co3 prices for alternate emission targets. Modest emissions target entail low or even negative costs – this is a function of the low baseline emissions growth and the availability of efficiency and conservation technologies if non-market barriers are addressed. Conversely, stringent emission targets entail a rapid rise in abatement and CO$_2$ costs, with the abatement curve being markedly convex.
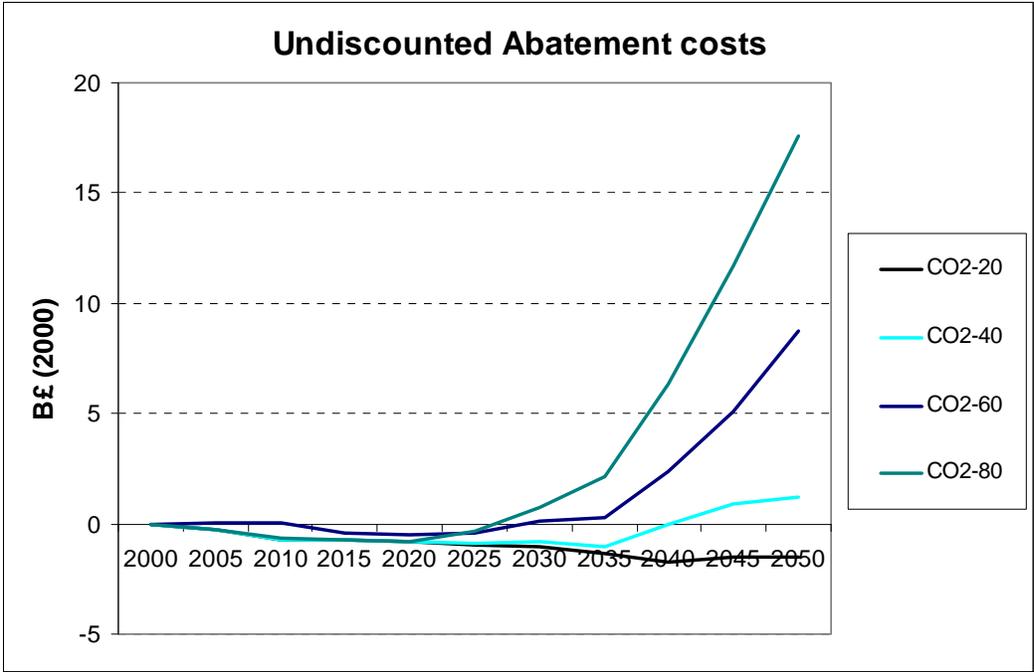
Figure A14: Abatement costs per target stringency
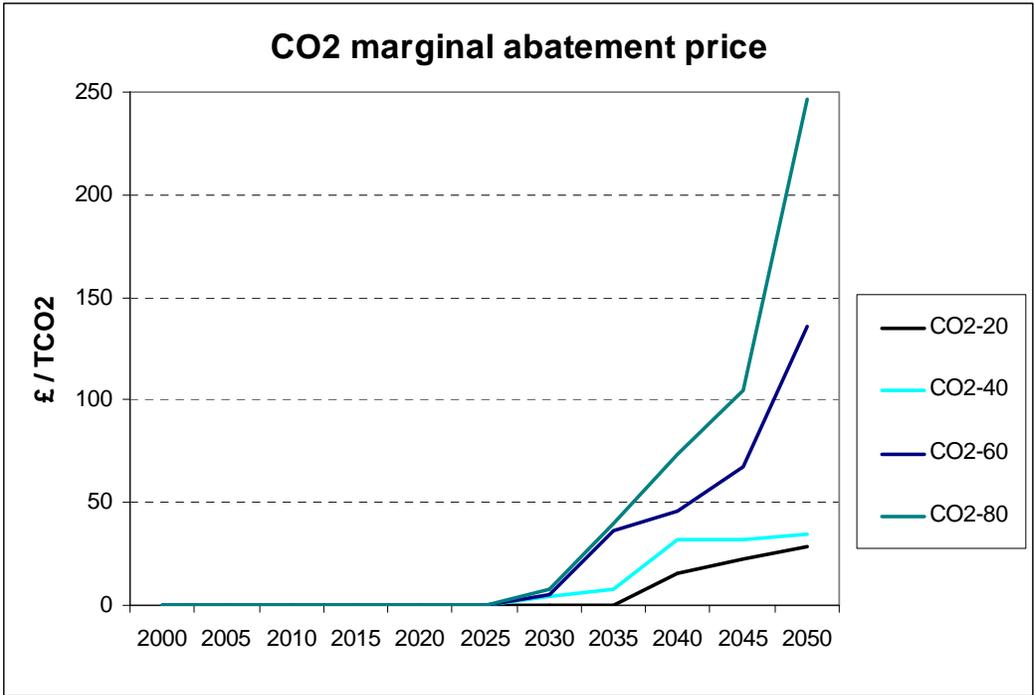
Figure A15: CO_2 marginal costs per target stringency
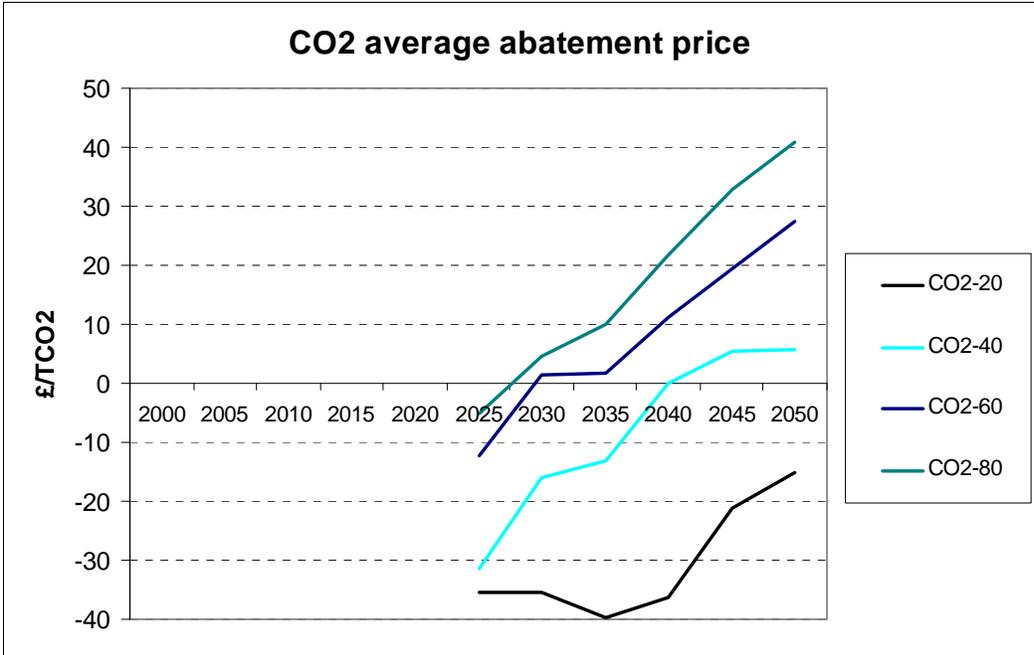
Figure A16: CO_2 average costs per target stringency

Further standard MARKAL results (UKERC assumptions): Additional insights

Figure A17 illustrate hydrogen production under base and CO_2 constrained cases (C60). As noted earlier the overall level of hydrogen is less under CO_2 constraints as it must be sourced from low or zero carbon sources (natural gas SMR or electrolysis). Cheaper coal gasification is not available due to the limit of UK CCS storage potential. In the very long term (2060-2070, waste and biomass gasification begin to become cost effective.
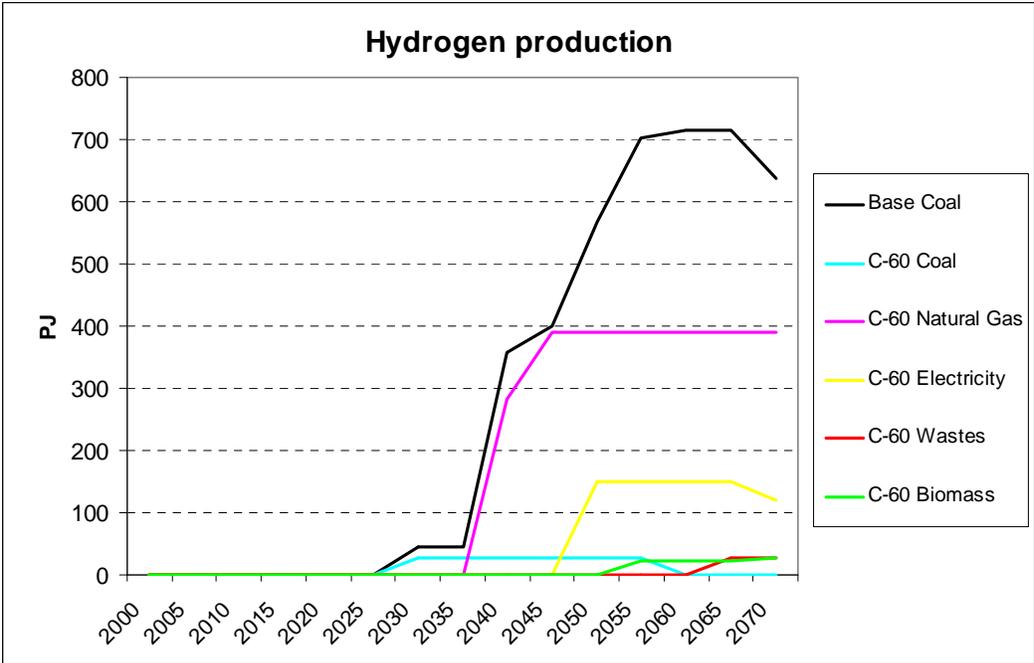
Figure A17: Hydrogen production
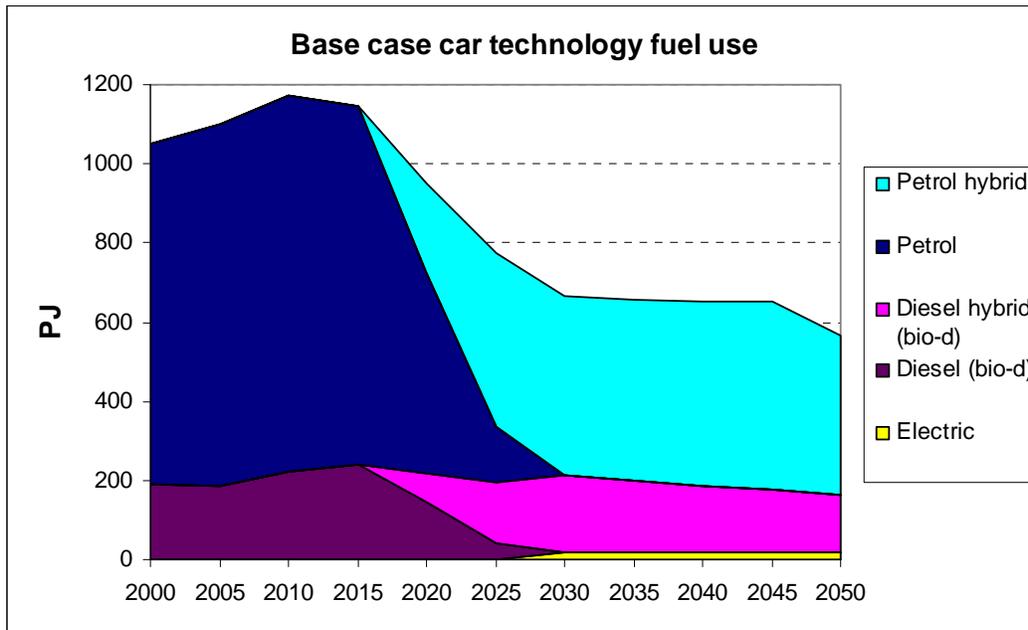
Figure A18a: Base case: Car Technologies

Figures A18 (a, b) and A19 (a, b) show the base and C60 technology shares for cars, and for bus/HGV/LGV respectively. All modes transitions through conventional, hybrid and onto hydrogen technology options, with the order of the hydrogen transition being, buses, LGVs, HGV, and cars. This ordering is driven by the infrastructure requirement to service these modes. Imposing an economy wide CO_2 constraint accelerates these transitions. Note that bio fuels are also a major component of transport fuels in scenarios where hydrogen technologies are restricted, or higher cost.
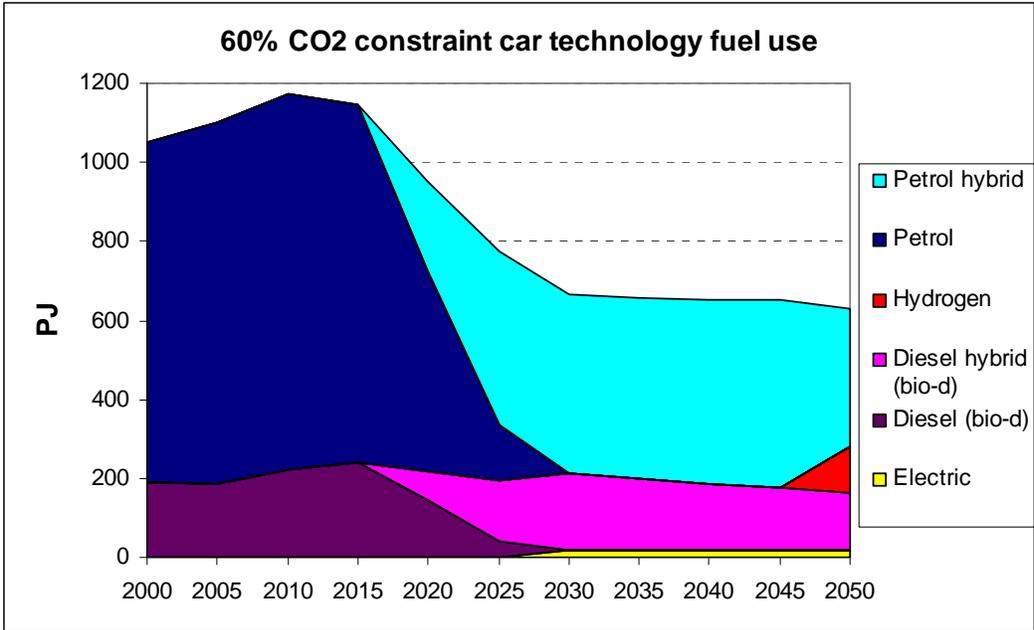
Figure A18b: CO$_2$ constrained case: car technologies
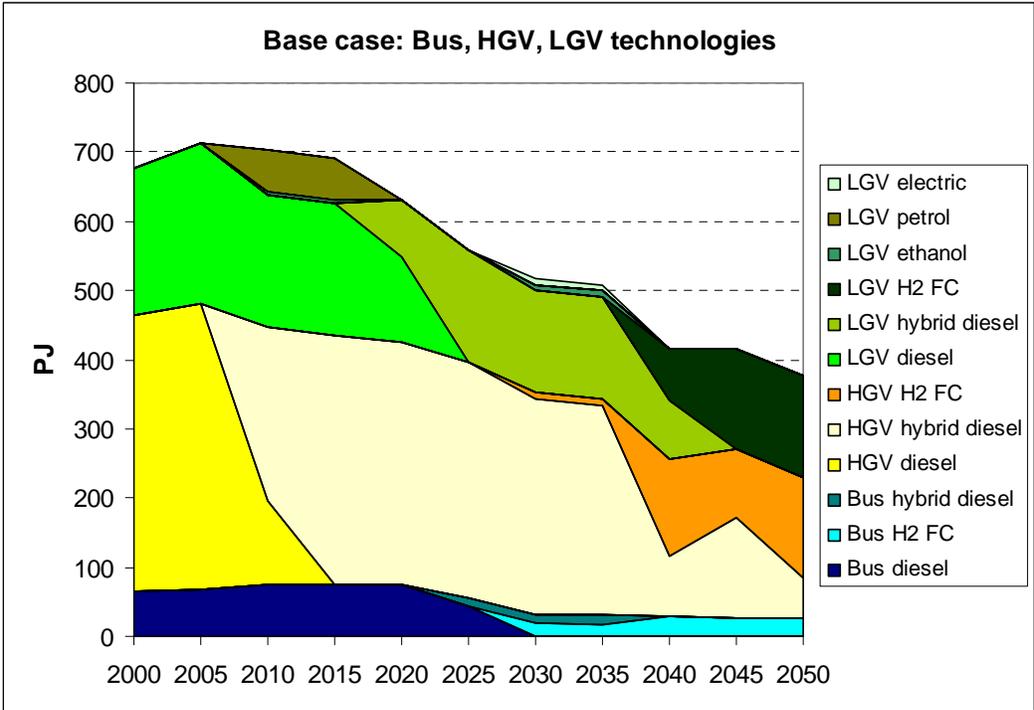
Figure A19a: Base-case: LGV, HGV, Bus transport modes
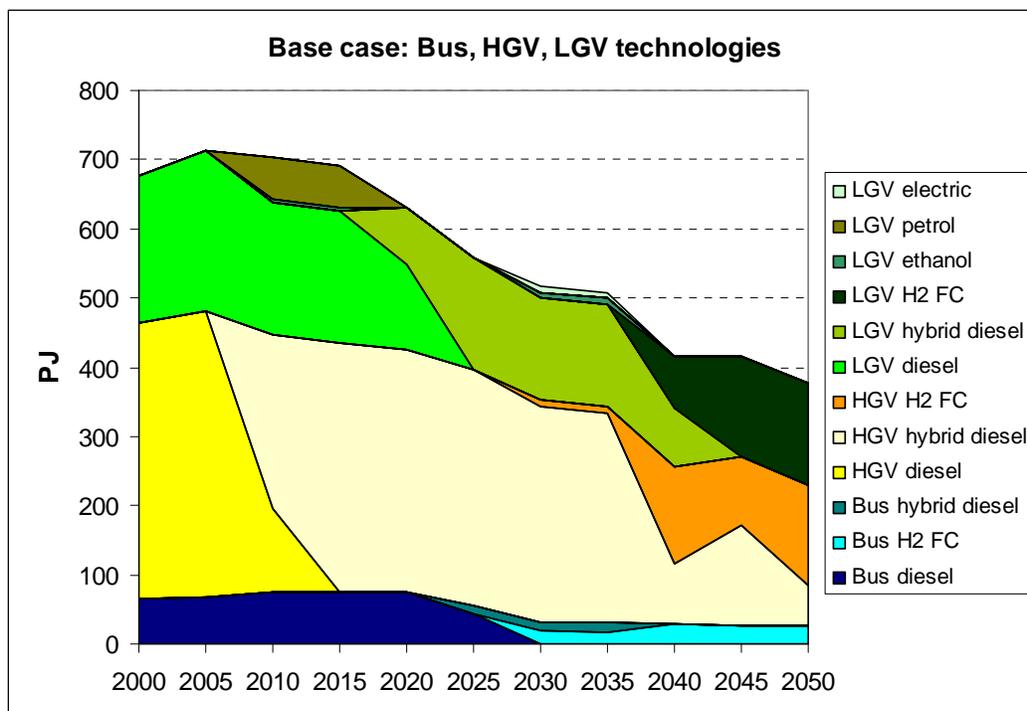
Figure A19b: CO_2 constraint case: LGV, HGV, Bus transport modes

Figures A20 (a, b), A21 (a, b) and A22 (a, b) illustrate UK domestic production, imports and export of marketed fuels (fossil and biomass/waste). Generally the UK moves from being an energy exporter to one dependent on imports, with domestic natural gas and oil falling to a low level by 2020. Hence exports similarly decline. UK coal production continues at its current level unless made cost uncompetitive by a rising carbon price under the constrained runs.

The pattern of production, imports, and export mirror each other. For example in 2030-45, rising global oil prices allow more marginal UK oil reserves to be exploited. Under a CO_2 constraint, overall UK fossil production and imports are lowered, and the UK capacity for biomass production on available land is exploited.

Future work will investigate the interactions between carbon mitigation and energy security policies and energy system pathways.
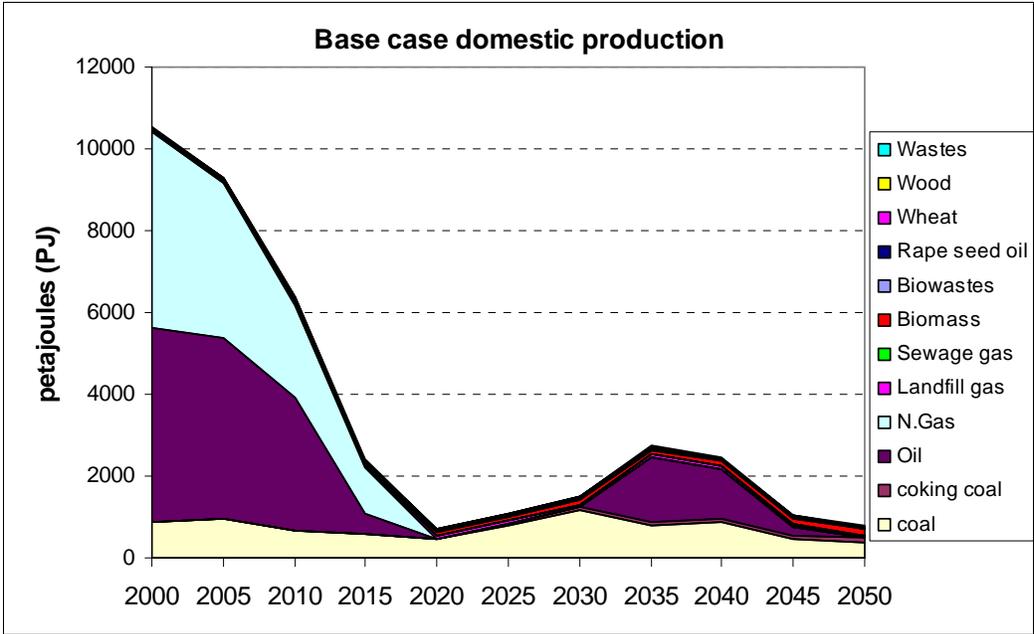
Figure A20a: Base-case: domestic resource production
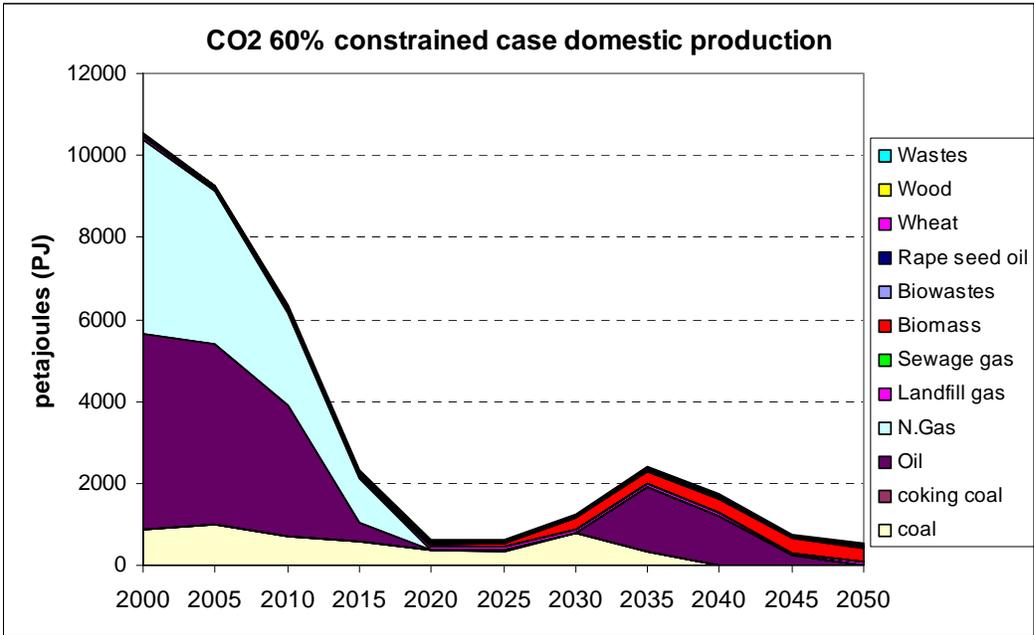
Figure A20b: CO2-60 case: domestic resource production
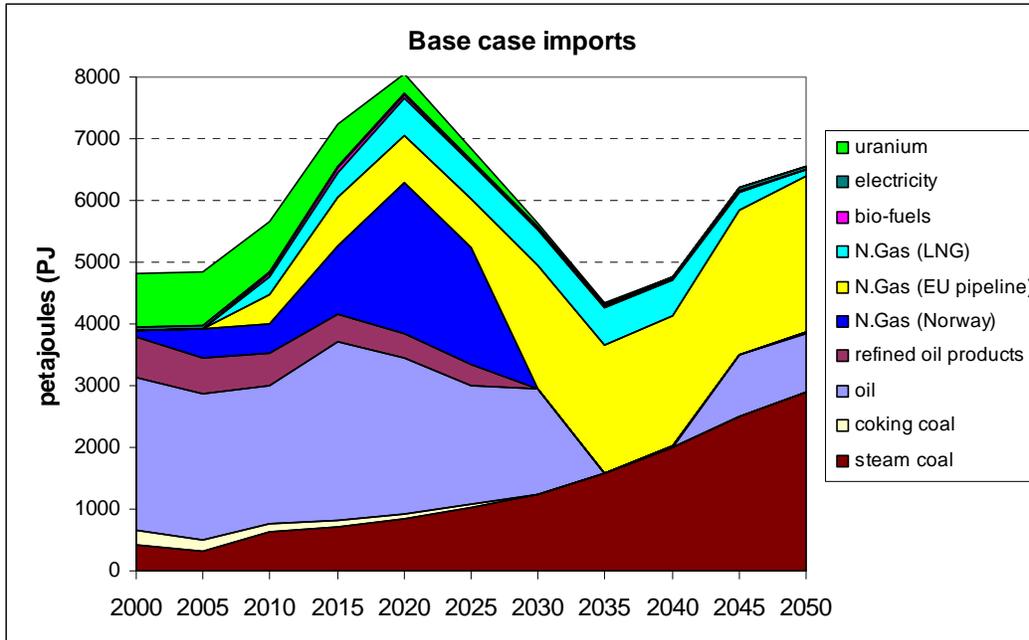
Figure A21a: Base-case resource imports
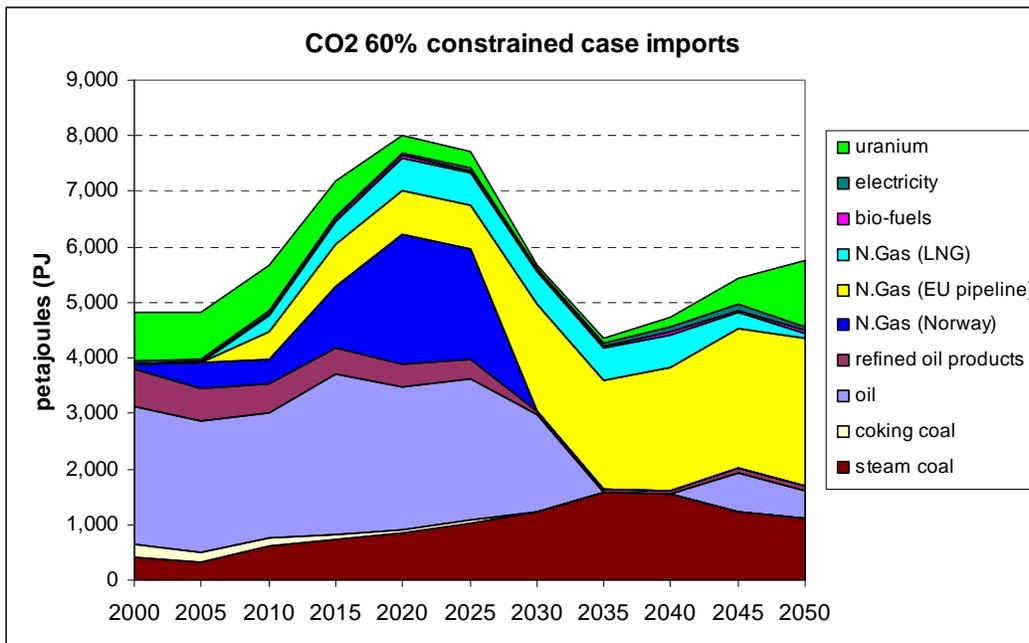
Figure A21b: CO2-60 case resource imports
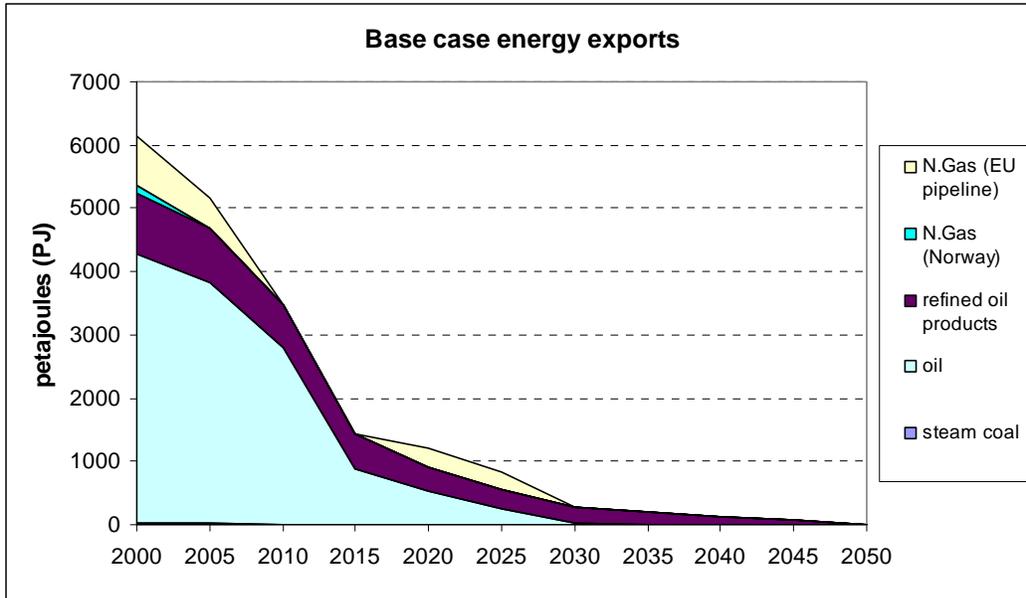
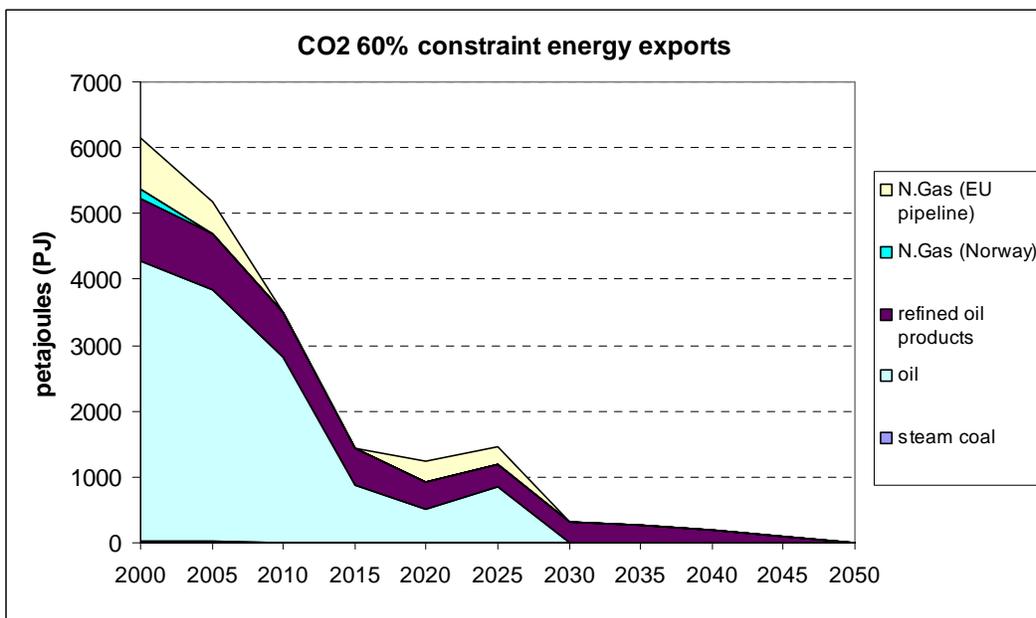**Figure A22a**: Base-case resource exports

Figure A22b: CO2-60 case resource exports

Further M-M results: DTI assumptions - Technology sensitivities

In addition to the above runs, DTI / DEFRA requested a set of model runs with a limited number of changes to the UKERC assumptions. These were separated out into high, central and low cost scenarios.

- Some of the data for electricity technologies was changed, to ensure consistency with the data used in the Energy Review electricity cost analysis (DTI 2006a). This included the use of central, low and high estimates of costs and performance characteristics. This also entailed the simplification of the nuclear fuel cycle with only one resource supply step.
- Assumption concerning conservation were changed, to reflect a more limited uptake of conservation as suggested by DEFRA. Conservation was limited to 25%, 50% and 75% of DEFRA's estimate in high, central and low cost scenarios
- Finally, the role of hybrid vehicles was restricted by adjusting future hybrid technology improvements and hence their fleet penetration

Figures A23 to A30 summarize these runs and further illustrate the uncertainties in projecting technology portfolios, with long-term assessments of alternate data on costs and characteristics.
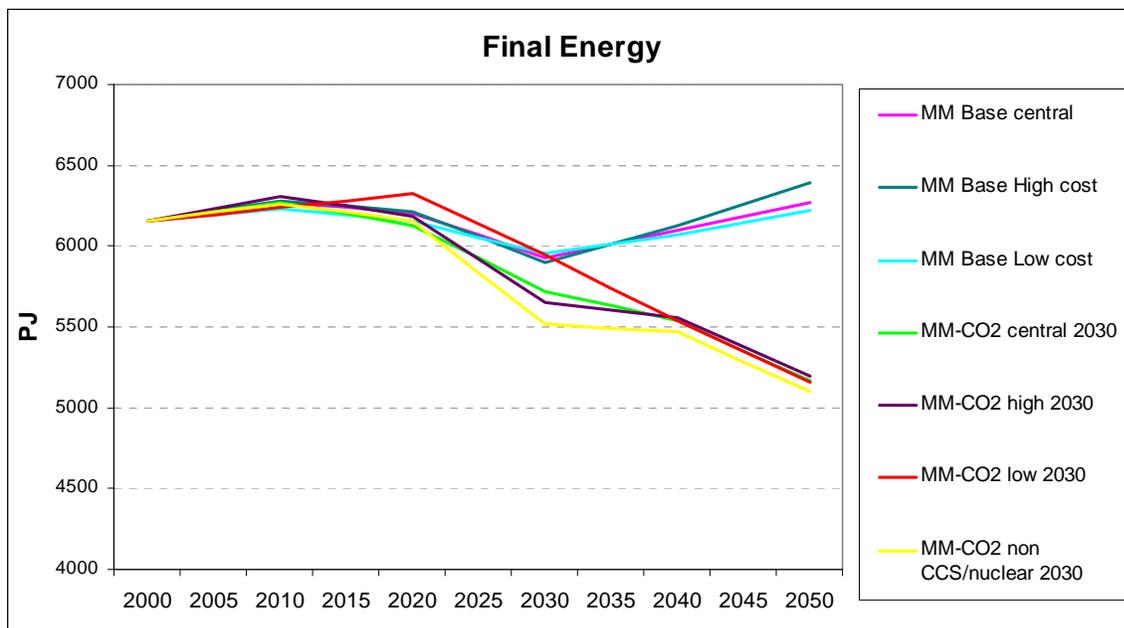
Figure A23: Final Energy: DTI M-M technology sensitivity
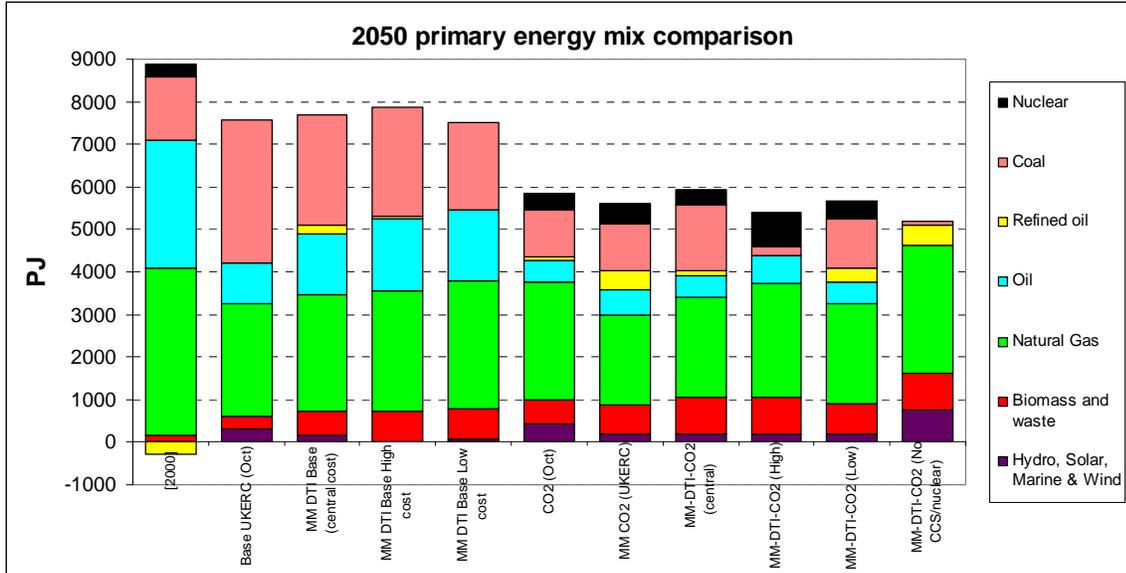
Figure A24: Primary energy 2050 comparison: DTI M-M technology sensitivity
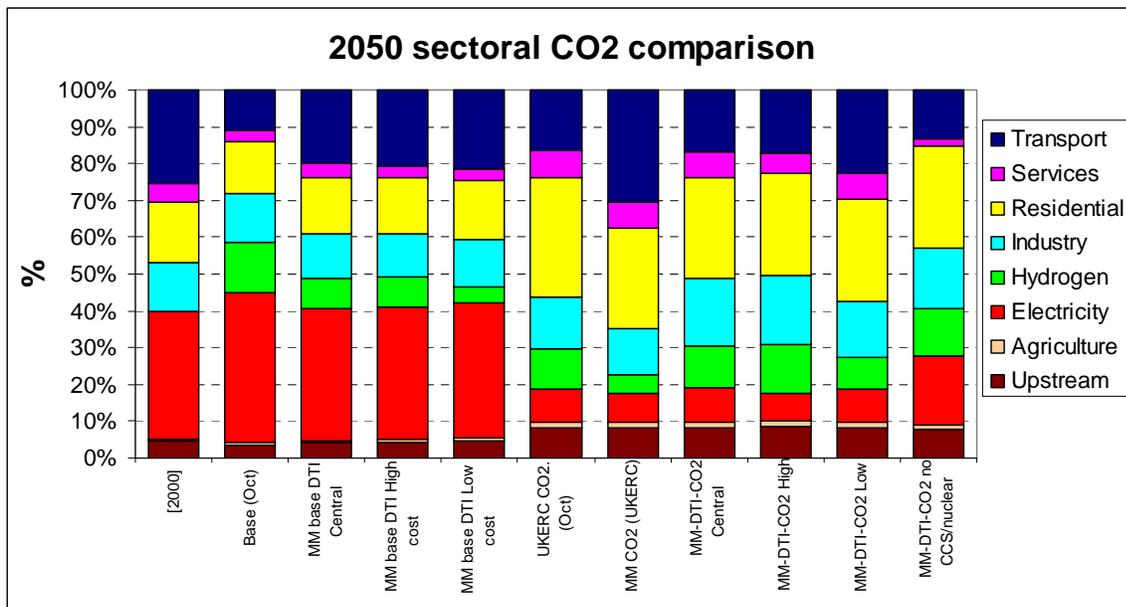

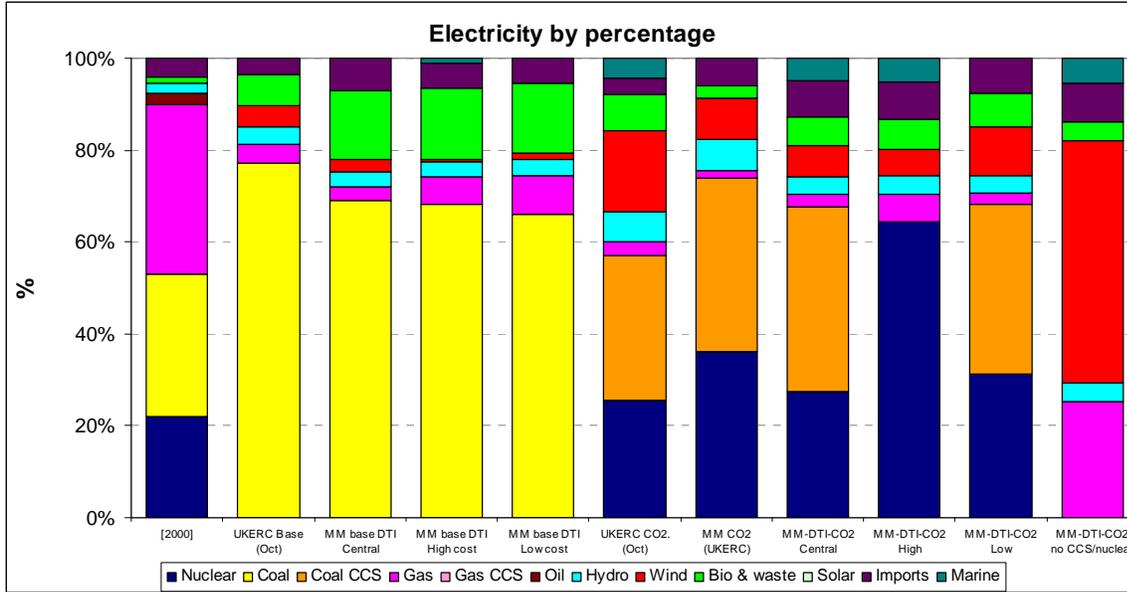**Figure A25**: Sectoral CO₂ emissions 2050 comparison: DTI M-M technology sensitivity

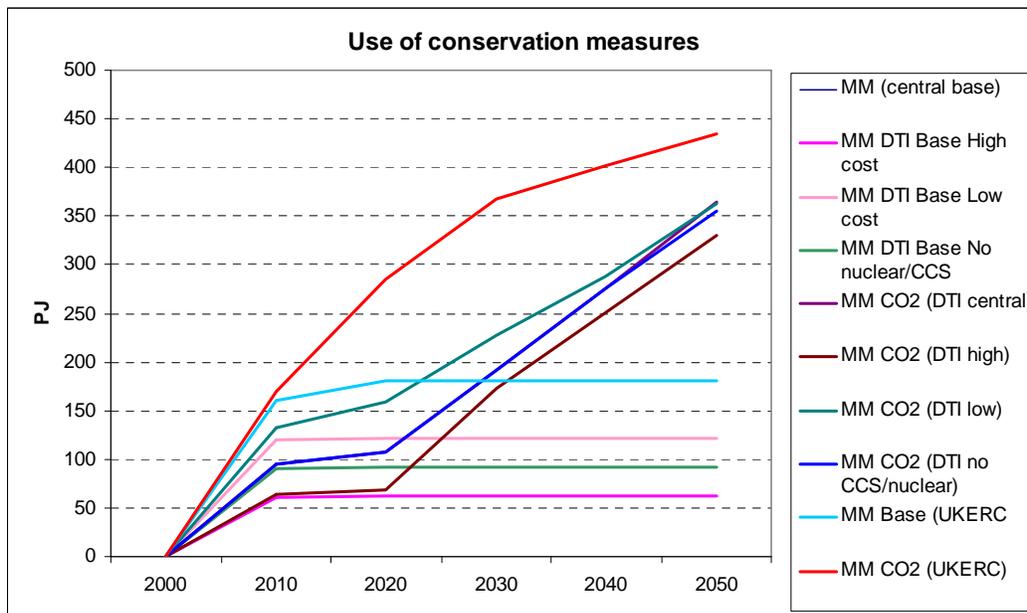**Figure A26**: Electricity generation 2050 comparison: DTI M-M technology sensitivity

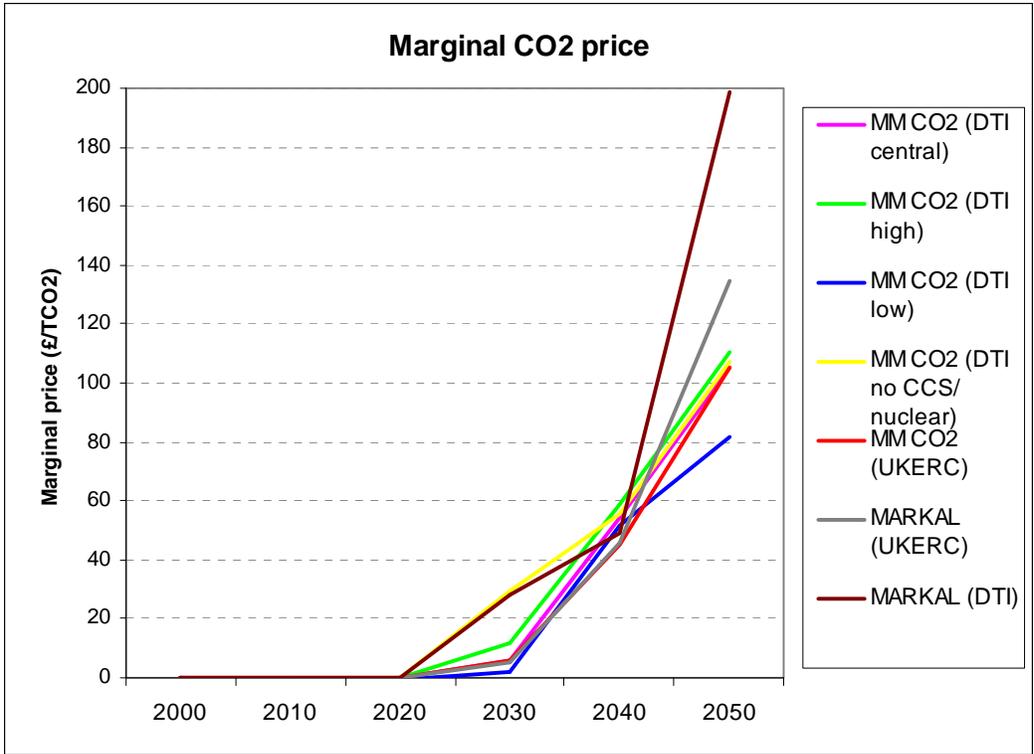**Figure A27**: Conservation measures 2050 comparison: DTI M-M technology sensitivity

Figure A28: Marginal CO2 price: DTI M-M technology sensitivity
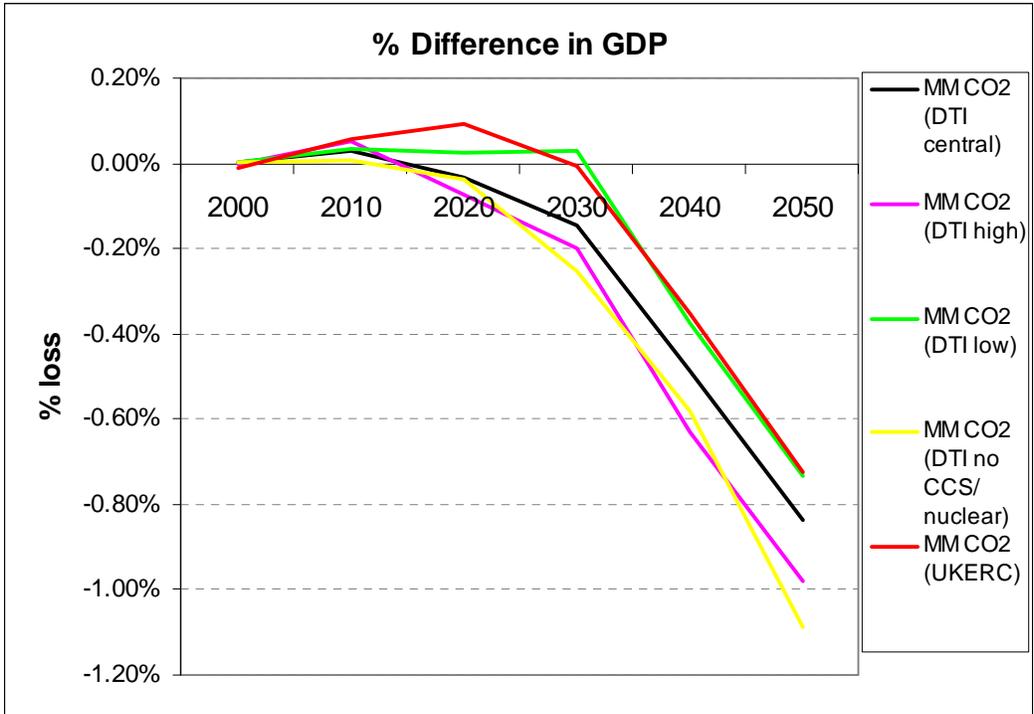

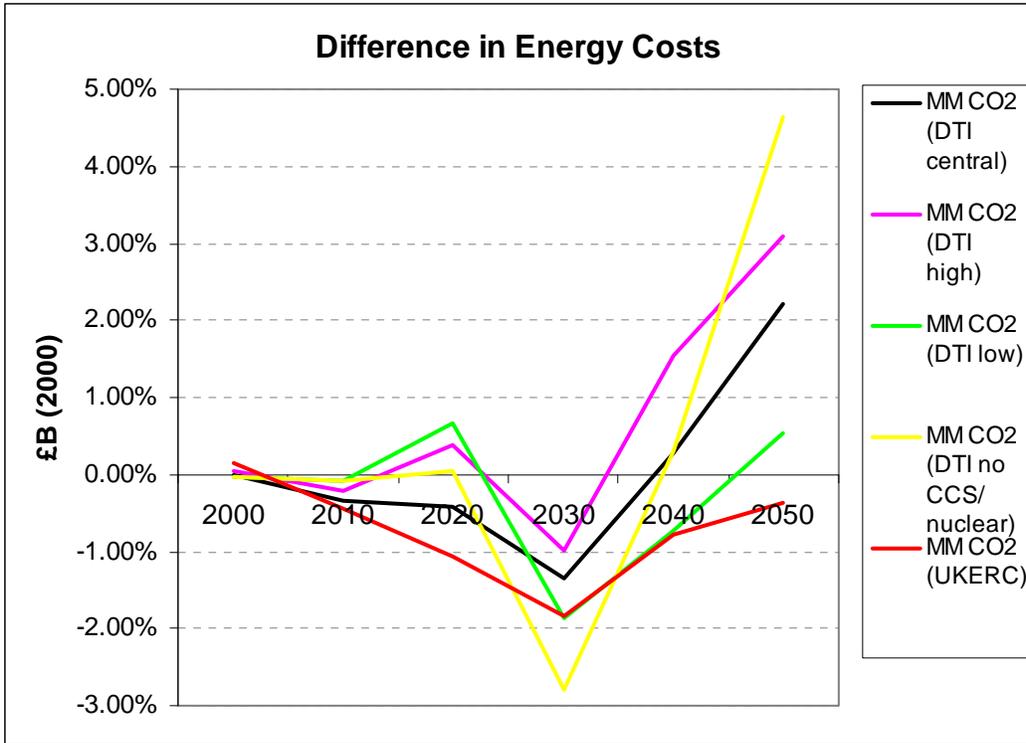**Figure A29**: GDP percentage change: DTI M-M technology sensitivity

Figure A30: Energy system cost percentage change: DTI M-M technology sensitivity