The UK MARKAL Energy Model in the 2007 Energy White Paper

Executive summary

- The DTI has used the UK MARKAL-Macro model (M-M model) to explore the technological and macroeconomic implications of reducing UK domestic carbon emissions by 60% by 2050.
- The M-M model is an integrated energy-macro model, covering the entire energy system in considerable technological detail, including electricity generation, heat and transport. The model explores how, under different assumptions about future fossil fuel prices and the pace of technological innovation, the energy system will evolve under a carbon constraint, and what the macroeconomic implications to the UK economy might be, including the costs to GDP.
- The model produces lower-bound estimates of the long-term costs of carbon abatement. This is, in part, because it is unable to capture the full impact of uncertainty (surrounding, for example, fuel prices or technology costs) which can affect investment in low carbon technologies, and impact on the costs of carbon abatement. It also does not capture the obstacles to the take-up of energy efficiency and conservation measures, which also can increase the cost of abatement.
- The M-M scenarios explored and presented here suggest that the annual costs of reducing UK carbon emissions by 60% could be between 0.3-1.5% of GDP in 2050. These costs are within the range indicated by Stern for global costs, and are significant yet manageable.
- The modelling highlights the importance of fossil fuel prices and technological innovation, as well as the trajectory of emissions reductions, in determining the impact of carbon abatement. The model always chooses a mix of technologies in or to meet the 60% target. It emphasises that a considerable reduction in energy demand is also required, through both increased energy efficiency and conservation; and through a reduction in energy service demands (e.g. a reduction in the number of miles travelled).
- The MARKAL model is useful in exploring the development of the energy system in the long term, i.e. to 2050. The M-M model is a purely domestic model; therefore it cannot consider the implications of carbon trading. As a UK only model, it is also unable to quantify the implications for UK trade and competitiveness; and does not capture potential transition costs that might arise as the economy adjusts to changes in energy policy. We have supplemented the MARKAL work with an analysis of these impacts in the short to medium-term, up to 2020.

1. Introduction – The UK MARKAL and MARKAL-Macro model

The 2007 Energy White Paper: *Meeting the Energy Challenge* is underpinned by a wide range of analytical work, conducted in order to estimate the full impact of our proposals against our long-term goals for energy policy. As part of this, we have explored the economy-wide implications of carbon abatement, both in the short and long-term.

To estimate the long run impact, the DTI commissioned the Policy Studies Institute (under the UK Energy Research Centre (UKERC) Energy Systems and Modelling programme) to update and employ the UK MARKAL model. The focus of this note is to provide an overview of the MARKAL modelling analysis undertaken as part of the 2007 Energy White Paper, and to present the key results. A brief description of model structure of the MARKAL model, and the development of the MARKAL-Macro component, is given in Annex 1 and 2. This note is supplemented by the in-depth technical reports published by the Policy Studies Institute, that include more detail on model data sets and assumptions, model validation and stakeholder processes, and additional scenario results.[1]

The UK MARKAL model has been substantially updated since informing the 2003 Energy White Paper. The model has been developed further by linking a macroeconomic component to the 'standard' MARKAL energy system model – known as the MARKAL-Macro model (M-M model). The new M-M model is thus particularly suited to exploring the long term costs of carbon abatement, and is one of very few models of its kind to retain considerable technical detail of the entire energy system, whilst explicitly calculating macroeconomic impacts out to 2050.

The model is constrained to deliver the Government's goal of achieving a 60% reduction in carbon emissions by 2050. The model then chooses the cheapest combination of technologies to deliver the target reduction in emissions. As with all models, it does have limitations which are important to take into account in interpreting the model results. They include the assumption perfect foresight, which means the model is unable to capture the full impact of uncertainty (surrounding, for example, fuel prices or technology costs) which can affect investment and impact on the costs of carbon abatement. The model is also limited in its ability to capture obstacles (such as information barriers) that, in reality, can slow the uptake of cost-effective abatement; therefore, it also does not capture the costs of implementing policies designed to overcome these obstacles. These mean the modelling may be expected to produce lower-bound estimates of the long-term costs of carbon abatement.

The M-M model describes the economy in equilibrium and therefore is unable to capture transition costs that might occur as the economy adjusts to changes in energy policy or prices. As a UK only model, it also does not

[1] Strachan N., R. Kannan and S. Pye (2007), *Final Report on DTI-DEFRA Scenarios and Sensitivities using the UK MARKAL and MARKAL-Macro Energy System Models,* available at http://www.ukerc.ac.uk/content/view/142/112

capture the implications for UK trade and competitiveness as a result of policies aimed at reducing carbon emissions.

Therefore, in addition to the M-M analysis, we have used the Oxford Energy-Industry Model (OEIM) and global macroeconomic model (GMM) to explore the potential short to medium-term adjustment costs associated with moving to a low carbon economy. [2]

As a purely domestic model, the model cannot explore the implications of international carbon trading. This could lower the cost of reducing emissions by 60%; however, the opportunities available in an international carbon trading market in 2050 are, at the moment, uncertain. It may be that, by 2050, the majority of cheaper abatement options abroad will have been exhausted. We have, however, in the short to medium-term modelling explored the macroeconomic implications of reducing carbon emissions when you allow international carbon trading.

2. Scenarios

The M-M model results are driven by input assumptions. Given the uncertainty over fuel prices and the pace of technological innovation over the forecast period (50 years), we have constructed a number of scenarios to come up with a range of estimates of the costs of achieving a 60% reduction in emissions. The modelling highlights what combination of technologies could deliver reductions in carbon emissions, what the trade-offs between different mitigation pathways are, and what the costs of abatement might be.

Importantly, although the M-M model is a purely domestic model, the scenarios presented here assume an element of international action, insofar as technologies are assumed to be developed globally and to benefit from advances in design, engineering and production. Costs and performance data are set to be representative of commercially deployed technologies enjoying the benefits of volume production, and of good installation and operation practices. For electricity generation, most of the scenarios presented here use those collected and held in the UKERC database.[3] In Section 4.2, sensitivities are presented that use DTI generation cost assumptions published with the Energy Review Report, July 2006.[4]

The scenarios explored and presented in this paper are described in Annex 3.[5] We have explored scenarios under different fuel price assumptions (as

[2] Oxford Economics: *Report on Modelling the Macroeconomic Impacts of Achieving the UK's Carbon Emission Reduction Goal* (May 2007) www.dti.gov.uk/energy/whitepaper
[3] UKERC cost assumptions were collected from a wide array of published sources and peer-reviewed by a panel of experts during April 2006. See Kannan et al (2007) *UK Markal model documentation* UKERC working papers for cost assumptions. www.ukerc.ac.uk).
[4] For details of this see Annex B of the Energy Review Report *The Energy Challenge'* http://www.dti.gov.uk/files/file32014.pdf. DTI assumptions are based on numerous published market studies, reflecting estimates for typical projects being developed in the UK.
[5] Over 50 scenarios were conducted as part of the White Paper analysis. See Strachan et al (2007) for the full set of scenario results. http://www.ukerc.ac.uk/content/view/142/112

published by the DTI and listed in Annex 3), alternative trajectories to 2050, and when innovation is restricted. The restricted innovation scenarios explore the implications for carbon abatement if technologies do not develop beyond 2010 and 2020.

2.1 Base and constrained scenarios

The M-M model creates a baseline or reference case for final energy demand and carbon emissions – the base case.[6] This base-case scenario assumes that there is no further effort to reduce carbon emissions, above what is driven by existing policies and actions which are cost-effective.

Chart 2.1 shows the base case under different fuel prices, and the alternative trajectories to achieving the 2050 goal that we have explored. In the base case by 2050, energy demand is higher than current levels, thus driving the level of emissions up. However, in the short to medium-term (to 2020) the level of emissions are falling due to the current policy measures having an effect in the near term;[7] as well as the take-up of cost-effective conservation measures and investment in more efficient end-use technologies. How much of this cost –effective abatement will occur in reality is unclear, given the evidence of barriers to achieving ‘optimal’ energy use. While the M-M is a cost optimisation model with perfect foresight, in reality, consumers have imperfect knowledge and base their choices on other preferences (colour, brand) rather than on a purely least-cost basis.[8] After 2030, in the absence of a carbon constraint, the abatement options which are not cost-effective are not taken up and emissions begin to rise.

In the constrained case the model is required to achieve a target for carbon emissions – in the following scenarios this is a 60% reduction by 2050.[9] Intermediate carbon constraints can be made in order to replicate a desired path to 2050. The trajectories explored are as follows: in the ‘2030+’ trajectory, the model is constrained to achieve 30% reduction by 2030, thereafter falling linearly to 2050. In addition; under central fuel prices, in the ‘SLT’ the model is constrained to achieve a ‘straight line’ abatement path to 2050. Both trajectories are illustrated in Chart 2.1 below.[10]

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[6] The base case is based on a range of assumptions of drivers of energy service demands, physical constraints on the UK energy system, as well as the complete set of input fuel, infrastructure and technology costs, efficiencies and availabilities. In addition, all existing energy legislation is included (both fiscal and technology measures), with the exception of the EU-ETS.

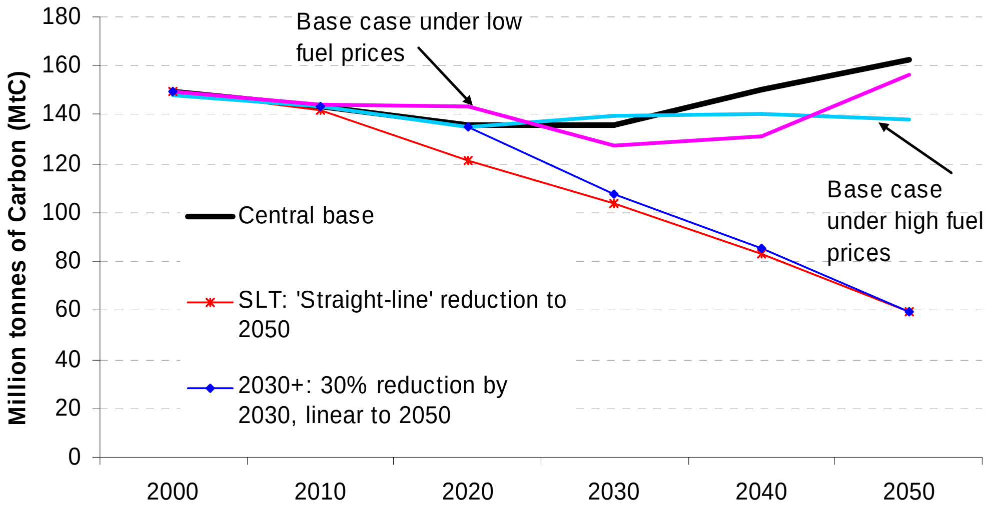
[7] For example the Renewables Obligation: the MARKAL model is fixed to achieve at least 15% renewable generation by 2015 (or by 2020 as M-M model is a ten-year model).

[8] A higher hurdle rate in end-use sectors (25%) has been used to reflect uncertainty in the market.

[9] To maintain consistency with the 2003 MARKAL modelling, in the M-M model the base year for prices and emissions reductions is 2000. The UK’s carbon target (as set out in the draft Climate Change Bill) is to achieve, by 2050, at least a 60% reduction on 1990 levels. However, the target level of emissions in 2050 is similar, i.e. around 65MtC in 2050 from a 1990 base, compared with 60MtC from a 2000 base.

[10] Constraints have been applied in the attempt to replicate realistic options for abatement. Without any intermediate constraints the model might choose a path where all efforts are

Chart 2.1 Base case under different fuel prices, and 2 paths to achieving 60% reduction by 2050*



Source: Strachan et al, 2007.UK MARKAL MACRO. *2 paths to achieving 60% by 2050 under central fuel price assumptions.

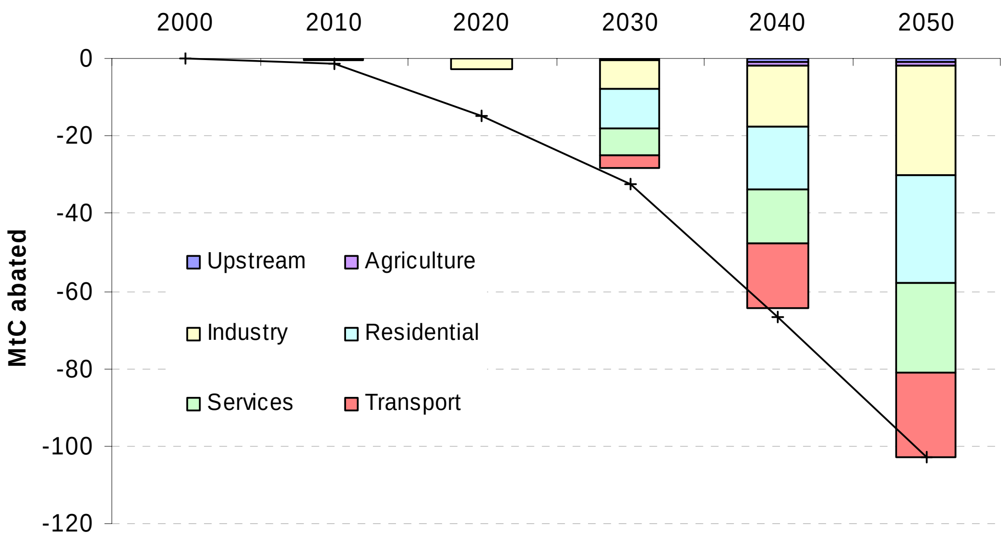
Chart 2.1 shows that under central fuel prices, the energy system is required to abate around 100 million tonnes of carbon (MtC)[11] by 2050, in order to meet a 60% reduction from 2000 levels (i.e. equivalent to aggregate UK carbon emissions of around 60MtC). The level of effort required over the first twenty years is limited (although, as discussed above, this is due to take up of cost-effective abatement opportunities, reducing carbon emissions in the base). Following a straight-line trajectory to 2050 forces the model to abate earlier, implying more effort to reduce emissions on a cumulative measure, but also having implications for both costs and the energy mix (see footnote 16, below).

Chart 2.2 below shows the abatement 'effort' by sector under central fuel prices (2030+ trajectory, the black line illustrates aggregate abatement under straight line trajectory SLT). It illustrates how, by 2050, all the main sectors are contributing to delivering the 60% carbon constraint (although the transport sector comes in at a later stage).

made towards the end of the period, which would, however, imply an unrealistic pattern of asset replacement and might also create some computational problem in the model.

[11] For consistency with the 2007 Energy White Paper, emissions are reported in terms of million tonnes of carbon. In the UKERC reports, emissions are expressed in terms of carbon dioxide (CO_2). To convert carbon (C) into carbon dioxide (CO_2) multiply by 44/12.

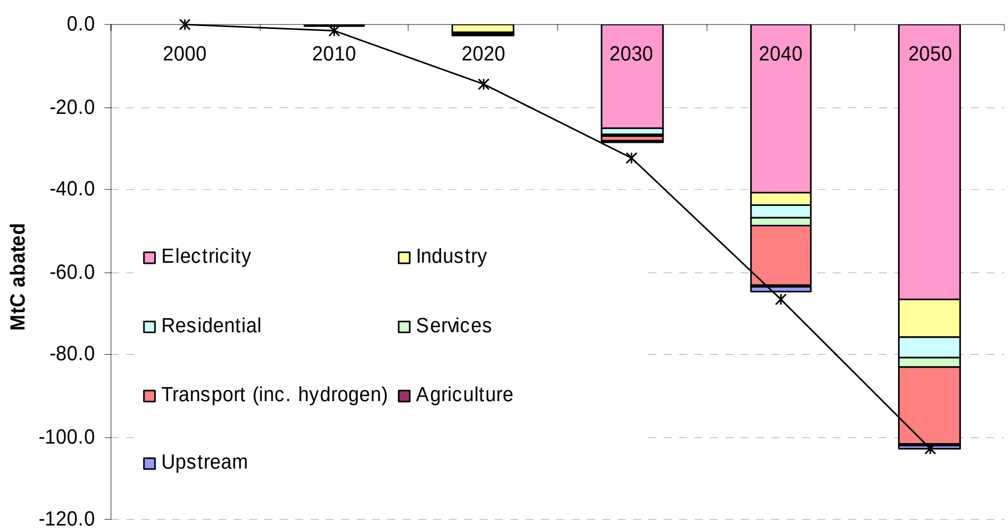
Chart 2.2 Abatement by end use in main sectors, central scenario 2050*



Source: MARKAL MACRO *Abatement is reduction in emissions in constrained scenario over the base case. 2030+ trajectory. Black line denotes all-sector abatement under a straight-line trajectory (SLT).

Within the main sectors in Chart 2.1, there is a considerable reduction in emissions through the de-carbonisation of the electricity generation sector (Section 4.2 below). Chart 2.3 below shows the abatement effort by source.

Chart 2.3 Abatement over time by source, central fuel price scenario*



Source: Strachan et al, 2007. MARKAL MACRO. *Abatement is reduction in emissions in constrained scenario over the base case. 2030+ trajectory. Black line denotes all-sector abatement under a ‘straight-line’ trajectory. (SLT)

The following discussion of the results is organised under the following themes:

- **Energy demand**
  - Discusses how the M-M model reduces carbon emissions through reductions in the energy intensity of the UK economy
- **Decarbonisation**
  - How the model switches to lower carbon fuels over time, and, particularly in electricity generation in 2050 under different cost assumptions
- **Economic implications**
  - The implications for the UK economy as the energy system evolves under a 60% carbon constraint

3. Energy demand

3.1. Primary and final energy demand

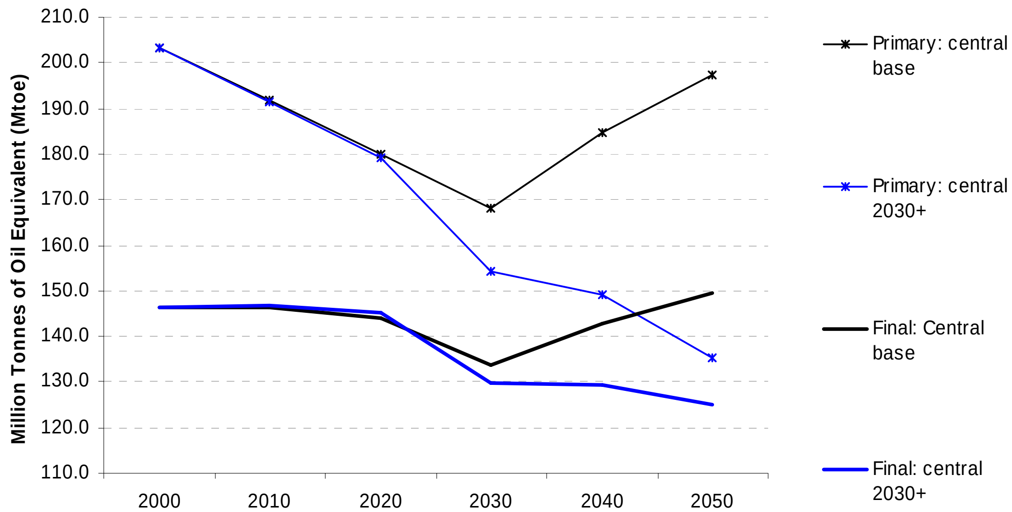
Primary energy is the total input of primary fuel consumed. Final energy excludes energy lost in the distribution of fuel (e.g. in transmission lines) and in conversion processes (e.g. in the production in electricity). The M-M model can reduce the demand for both in 5 ways:

1. Increasing conservation in upstream technologies (namely industrial processes);
2. Improvements in upstream efficiency (power plants, refineries etc);
3. Behavioural response (i.e. the feedback between energy service demands and the price of energy);
4. Conservation of energy (e.g. loft insulation);
5. End-use technical efficiency (e.g. gas fired condensing boilers).

All 5 options are impacting on primary energy demand. The first two options reduce required primary energy by improving the conversion to final consumption, the latter three affect primary demand by reducing the amount of final energy demanded for end-use.

Chart 3.1 below illustrates the economy-wide primary and final energy consumption in the base and constrained scenario under central fuel prices. It shows that, even in base case, energy consumption is falling up to 2030 (due to significant efficiency and conservation occurring, see Section 2.1 above). It illustrates how the ‘gap’ or ratio between primary and final energy consumption is squeezed under a carbon constraint due to improved conservation and efficiency in upstream technologies.

Chart 3.1 Total primary and final energy consumption, central fuel price base and constrained scenarios (2030+ trajectory)



Source: Strachan, et al, 2007. UK MARKAL MACRO.

The constraint on carbon emissions drives, through the efficiency options in the model, further falls in energy demand, beyond 2030. In the central fuel price scenario, final energy demand is around 16% lower in 2050 compared with the base case, rising to 20% under low fuel prices, or 7% under high fuel prices. The feedback between energy service demand and prices means that the reduction in final energy demand in the M-M under central fuel prices (16%) is higher than would be the case in the 'standard' MARKAL (4%).

3.2 Behavioural response

Behavioural response in the M-M model reduces the need for other carbon mitigation efforts. In general, factors that increase the costs of abatement, such as lower levels of technological innovation - induce greater behavioural response through stimulating even higher prices, which incentivises changes in behaviour with respect to energy use.

The responsiveness of energy demand to energy prices is determined by the price elasticity of demand. In the M-M, an economy-wide elasticity of 0.3 is used. From this single price elasticity, the demand response at the sub-sectoral level will vary according to its impact on economic growth, which, in turn, is affected by the technical opportunities available to reduce energy demand.[12] For example, under central fuel prices, the demand for car service demands (i.e. million miles travelled) by 2050 is 3% lower than would otherwise would have been. This is relatively low as the model is able to reduce fuel demand by switching to other technologies (petrol hybrids) that

[12] The potential for behavioural response is, however, restricted to 50% of the base year (2000), as there is likely to be a limit to overall demand response for any given change in prices.

require less fuel. Conversely, for rail passenger transport (where there is less scope for technological substitution) the behavioural demand reduction in 2050 is over 30%. In general, behavioural reductions in energy service demands cluster around 10-15% in 2050 (compared to base).

In general, behavioural response is the favoured mitigation option; which, in the context of around a tripling of GDP, represents a considerable decoupling between energy demand and economic growth over the period. Furthermore, under unchanging preferences, these reductions in energy demand will incur a loss of 'welfare' or ''utility' to the consumers of energy. These are difficult to quantify and ascribe a value, and are not captured in the macroeconomic estimates.

3.3. Residential, services and industry sectors- conservation and energy efficiency

In addition to behavioural response, there are a wide range of conservation measures and more efficient end-use technologies available in the M-M model that reduce the level of energy consumption (for a given level of service demand). The importance of these factors in the M-M model will depend on the assumptions on the costs and abatement potential for each technology.[13]

Energy efficiency in the M-M is modelled through changes to the set of technologies available. These technologies improve over time as they move to a more advanced, more efficient 'vintage', thus simulating the improved efficiency (although, in the restricted innovation scenarios they do not progress beyond their 2010 or 2020 vintage). Less mature technologies (e.g. PV cells), have exogenous learning curves bases on published estimates of learning rates, and IEA forecasts of global technology uptake.

In all cases, the potential savings from conservation measures are consistent with those projected by DEFRA up to 2020. The potential in the base cases is held at this level throughout the entire period, while in the constrained scenario, this restriction is relaxed post 2020 so that the model has freedom to select energy saving technologies, so long as it is cost effective and it is cheaper than other abatement options.[14] By 2050, around 8% of final energy demand is being conserved, although this falls to 3% and 5% in the restricted innovation post 2010 and 2020 scenarios respectively.

[13]Generally a conservation option will just have capital costs but an efficiency technology will generally have higher capital costs and may or may not have increased operation and maintenance (O&M) costs (see Kannan et al (2007) *UK Markal model documentation* UKERC working papers for cost details of end-use technologies by class). www.ukerc.ac.uk

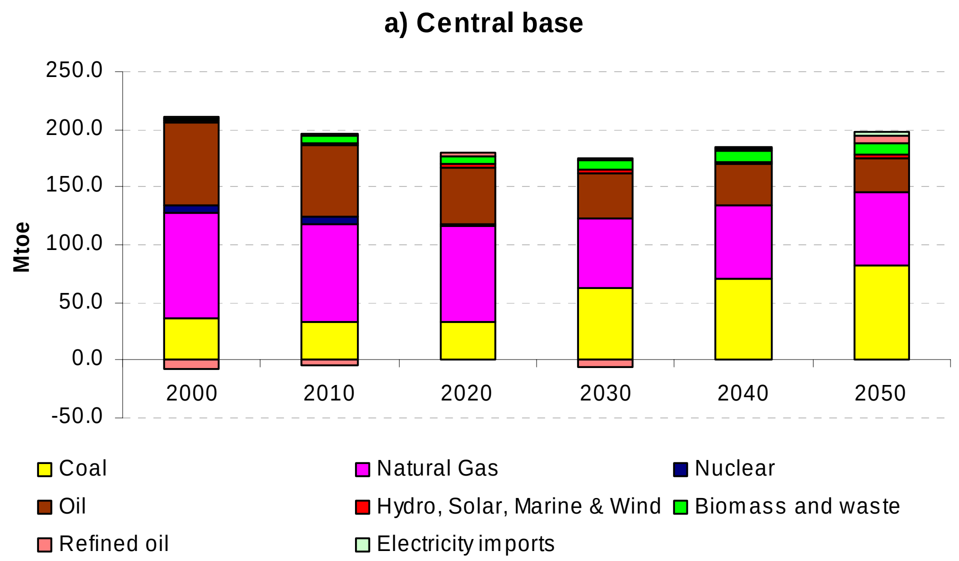
[14] The rationale for this is that, in a world in which there is concerted effort to reduce emissions, there will be greater scope for the conservation of energy.

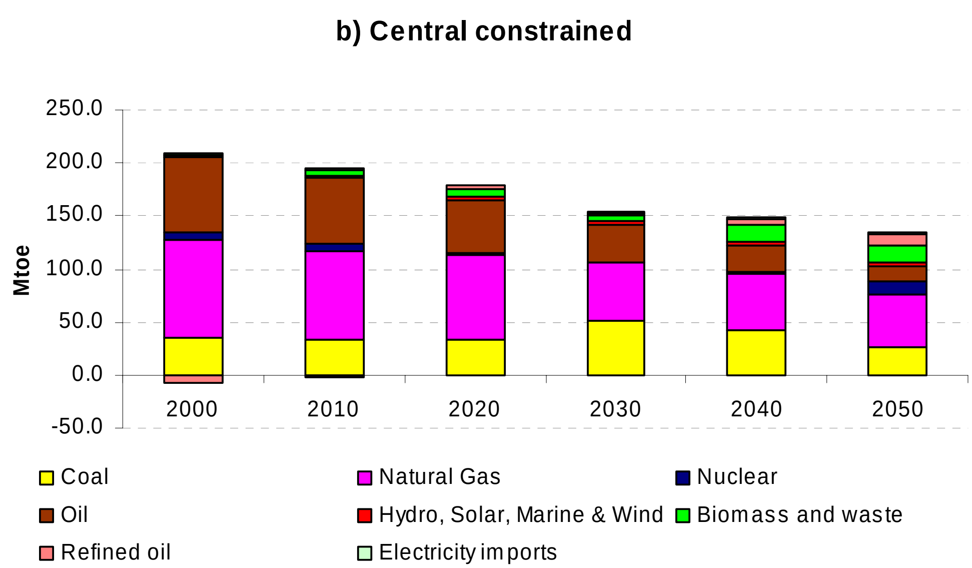
4. Decarbonisation

4.1. Primary energy mix

As well as pursuing options that reduce the energy intensity of the economy, the M-M model will choose technologies that use lower carbon fuels or fuels that are more efficient.[15] This 'fuel switching' under a carbon constraint is illustrated in Chart 4.1 below.

Chart 4.1 Primary energy mix, central (2030+)





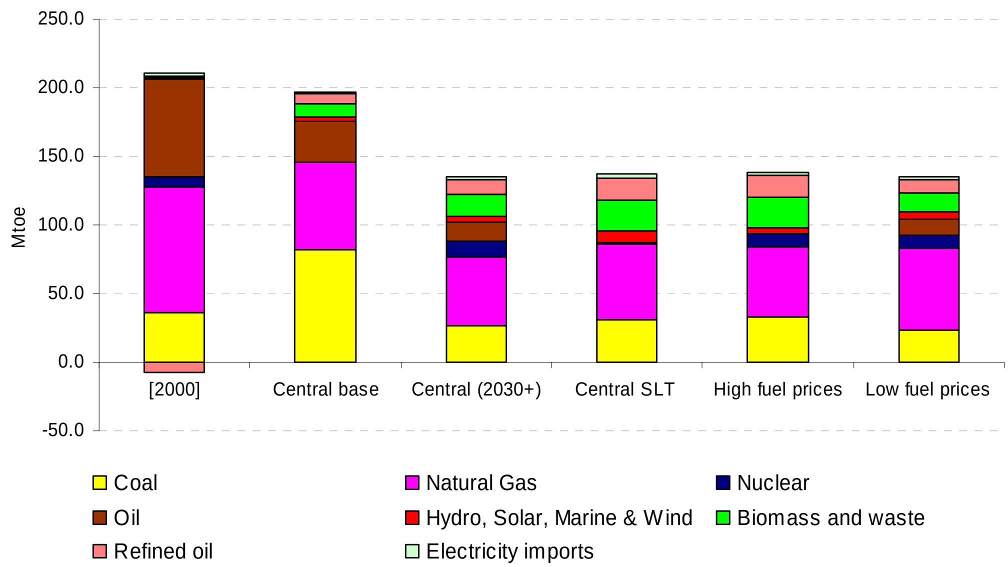
Source: Strachan et al 2007. MARKAL MACRO

[15] Note that lower carbon options may be more or less energy efficient (e.g. coal CCS uses more energy than conventional coal)

Under a carbon constraint, by 2050 the primary use of coal is roughly halved compared with the base case; and is restricted to electricity generation using carbon capture technology (Section 4.2). Due to its relatively low emissions and direct use in heating and industrial processes, the share of natural gas remains fairly constant. Under a carbon constraint, the total share of renewable energy by 2050 rises to around 15% in 2030+ trajectory, and 23% in the SLT run (compared with just 6% in the base case).[16]

Chart 4.2 below compares the fuel mix in 2000, with that in 2050 under different assumptions regarding the trajectory and fuel prices

Chart 4.2. Primary Energy Mix, 2000 and 2050 in main scenarios



Source: Strachan et el, 2007. UK MARKAL MACRO

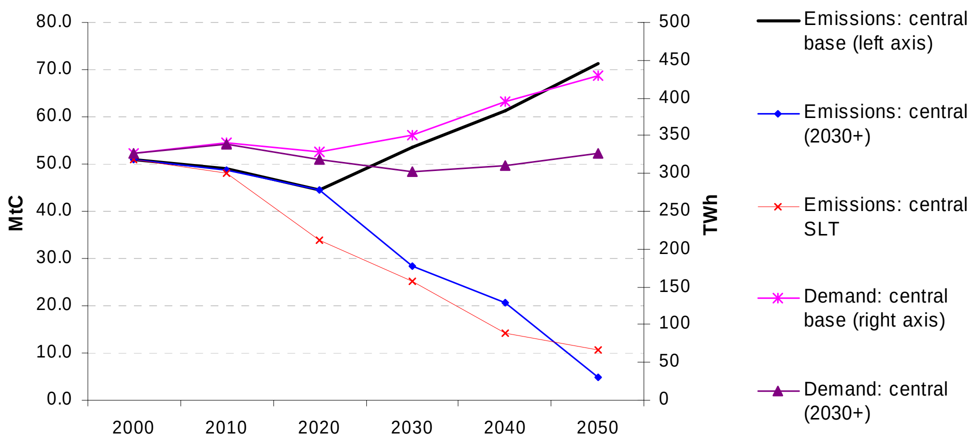
4.2 Electricity Generation

Across all scenarios, there is a considerable reduction in emissions from the electricity sector (up to a 91% reduction on 2000 levels in the central and low fossil fuel price scenarios). This arises through a combination of a fall in electricity demand and changes in the electricity generation mix**.** Chart 4.3 below compares the electricity demand and emissions in the central

[16] In the SLT run there are more renewables in the energy mix than the 2030+ constrained case, despite achieving the same end 'effort' by 2050. The greater interim carbon reductions required in the SLT scenario mean that electricity demand (in addition to the base-load) is met with an expansion of biomass (and wind) fuelled generation, which, because of the interim targets, is a more mature technology than the next generation nuclear plants (which are available in 2020-30), and impose additional costs on the system than under the 2030+ trajectory (marginal cost in 2020 = £10t/C in the SLT runs, compared with £0t/C in 2030+). In 2050, when the overall constraint really bites, significant nuclear expansion is not needed, and the model meets this at the margin in other sectors, i.e. methanol, FT diesel and carbon - free hydrogen in the transport sector. The power sector retains its flexibility (but with higher emissions) and has a portfolio of coal CCS, new gas plants, expansion of wind (as learning effects have taken effect for cost reductions) along with some nuclear.

scenarios. It shows that, in the central constrained case, economy-wide demand for electricity is 24% lower than in the base case in 2050.[17] In the constrained cases, emissions from generation fall to less than 5MtC and 10MtC in the 2030+ and SLT trajectory respectively.

Chart 4.3. Electricity: demand and carbon emissions, central scenarios*

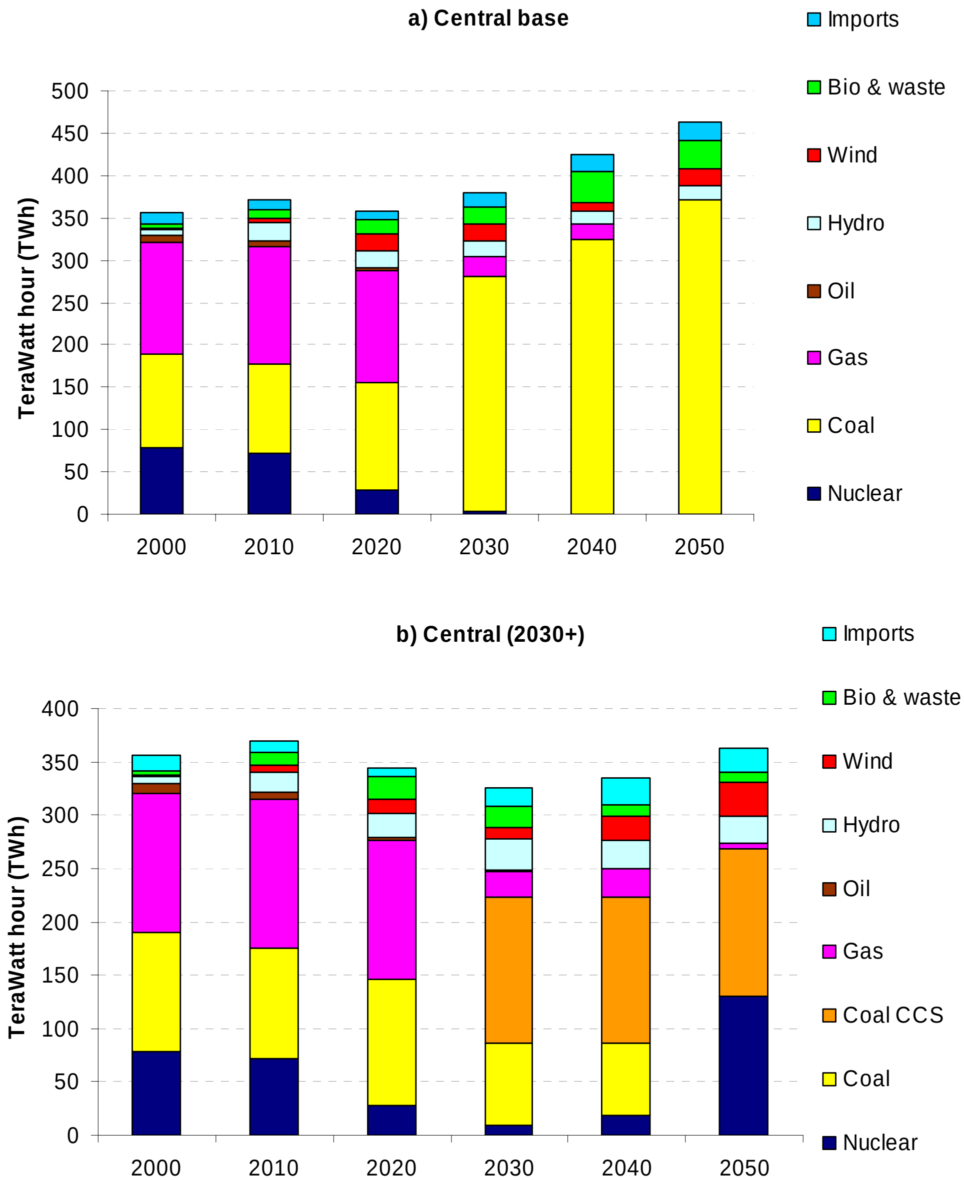


Source: Strachan et el, 2007. UK MARKAL MACRO *Whole economy electricity demand (TWh) and emissions from electricity generation (MtC) under central fuel price assumptions.

Changes in the generation mix are driven by the relative cost of generation technologies, fossil fuel prices and government policy (in terms of carbon constraints or prices). We have conducted a range of sensitivities on generation costs, and Chart 4.4 below shows the mix over the period under the central UKERC generation price assumptions, 2030+ trajectory.[18]

[17] Further sensitivities were conducted excluding new nuclear and nuclear/CCS technology. In these scenarios, the abatement potential of the generation mix is severely constrained. However, a considerable reduction in electricity demand (by 2050 around a 30% reduction on base to 330TWh), contributes to a still significant abatement effort from the sector overall (Over 80% on 2000 levels, depending on trajectory chosen).
[18] See note 3, above.

Chart 4.4. Electricity generation mix, central scenario (2030+)



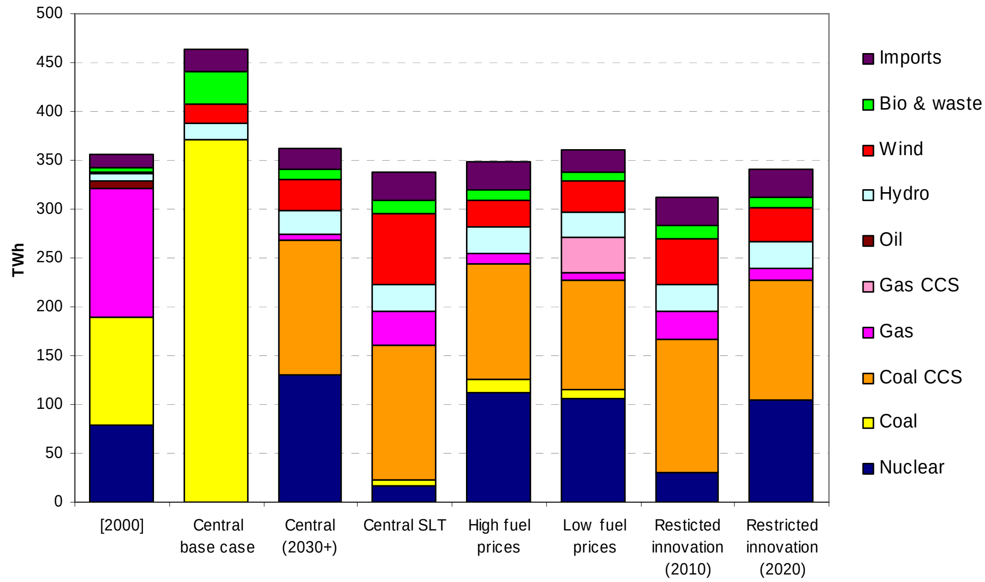
Source: Strachan et el, 2007. UK MARKAL MACRO

Chart 4.5 below shows the mix in 2050 under different fossil fuel price assumptions, alternative trajectories and restricted innovation under the UKERC generation cost assumptions. There are two key elements to highlight: first, the model always chooses a mix off technologies in order to achieve a 60% reduction in overall emissions. [19] Secondly, as the model optimises the electricity mix over the long-term based on the relative costs of the different technologies, any change in the assumptions which leads to one technology becoming marginally cheaper, will imply a switch to that

[19] Policy drivers also have an effect – the M-M model is fixed to achieve at least 15% renewable generation in 2020 to reflect government policy.

technology in the mix. This is particularly important in the context of the contribution of coal-fired CCS and nuclear.

Chart 4.5. Generation mix in 2050, central and sensitivity scenarios*

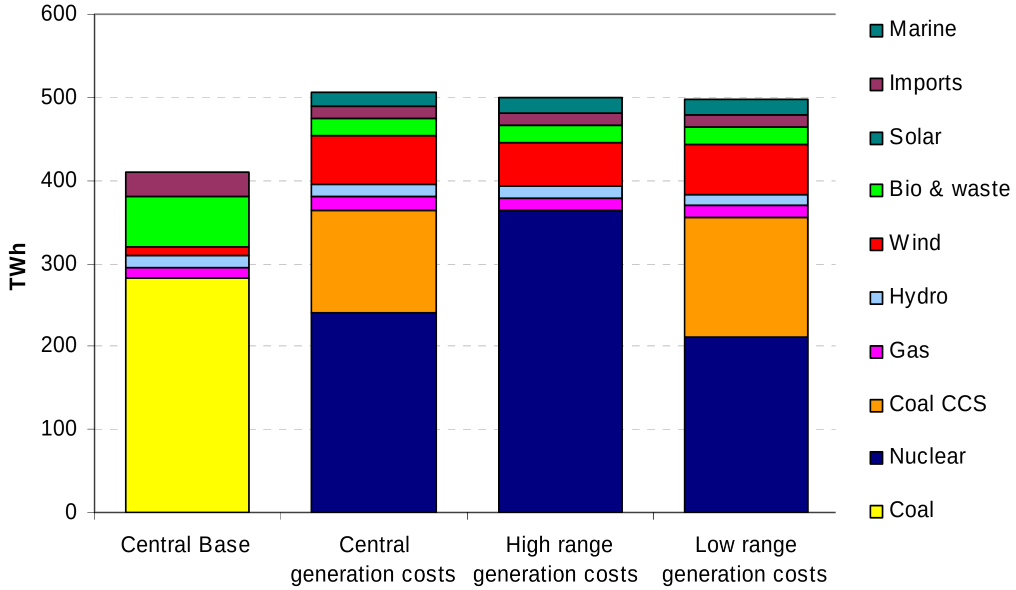


Source: Strachan et el, 2007. UK MARKAL MACRO *Assumptions on generation technology costs from UKERC database. See Kannan et al 2007.

To reflect the uncertainty over the long-term about generation costs we explored further sensitivities. Under alternative cost assumptions produced as part of the Energy Review, nuclear becomes relatively more competitive compared to coal-fired CCS;[20] and comparing Charts 4.4 and 4.5 illustrates how, depending on the costs assumptions, nuclear contribution to the mix in 2050 could range from 5% to more than 60%; and coal-fired CCS can also range from 30% to 40% of the mix by 2050.[21]

[20] For details of this see Annex B of the Energy Review Report 'The Energy Challenge' http://www.dti.gov.uk/files/file32014.pdf. DTI assumptions are based on numerous published market studies, reflecting estimates for typical projects being developed in the UK. This therefore underlines the fact that while CCS has the potential to play a significant role in tackling climate change, is still an unproven technology subject to considerable uncertainty around costs.
[21] The implications for generation mix are presented here, for the full set of model outputs in these scenarios see Strachan et al, 2007.

Chart 4.5. Generation mix in 2050, central and sensitivity scenarios under alternative cost assumptions*



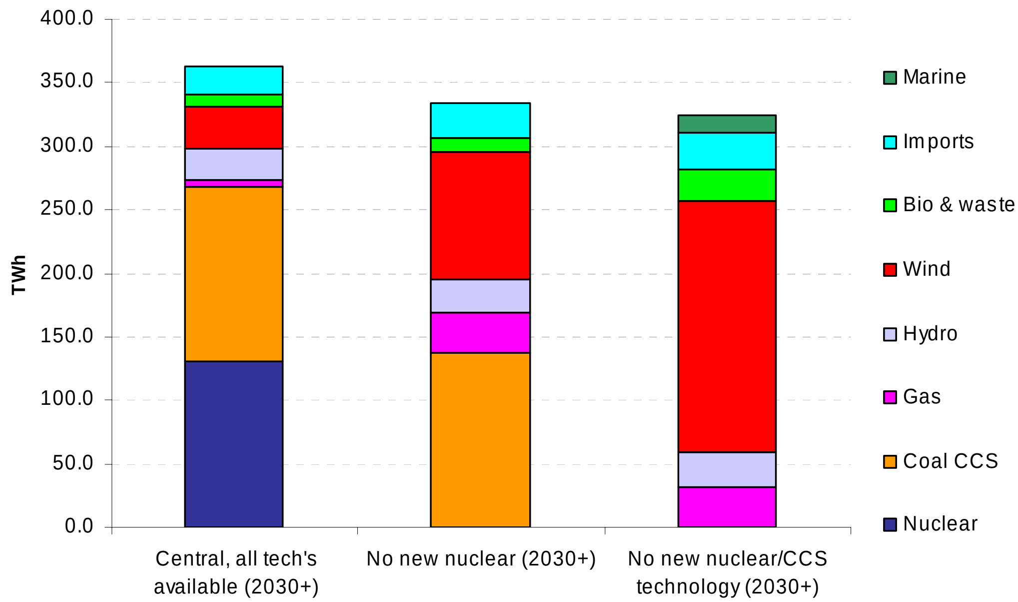
Source: Strachan et el, 2007. UK MARKAL MACRO *Assumptions on generation technology costs from financial modelling conducted for the Energy Review Report 2006. High, central and low ranges.

We also conducted further sensitivities on the implications on the mix where specific technologies were excluded. Chart 4.6 below show the mix in 2050 where new nuclear,[22] or *both* new nuclear and CCS technology are excluded from the model. The model shows that electricity supply is further reduced (to just over 300TWh in 2050) and the model has to invest in significant amounts of renewable technology, namely wind.[23]

[22] In all scenarios unless otherwise stated, the model has the option to invest in new nuclear power stations so long as it is economic to do so. The Government is publishing a consultation on the option for investment in new nuclear power stations by the private sector alongside the 2007 Energy White Paper.

[23] The required wind capacity in this scenario is considerable (nearly 200TWh, compared with around 4TWh today) and the M-M model does not capture the explicit spatial constraints or planning issues that might be associated high levels of wind capacity. The model does, to an extent, account for increased investment required to cover intermittency, however its treatment is simplistic compared with models that focus solely on the generation sector.

Chart 4.6. Generation mix in 2050, technologies excluded* (nuclear and CCS)



Source: Strachan et el, 2007. UK MARKAL MACRO *Assumptions on generation technology costs from UKERC database. Kannan et al 2007.

4.3 Transport – emerging technologies and fuels.

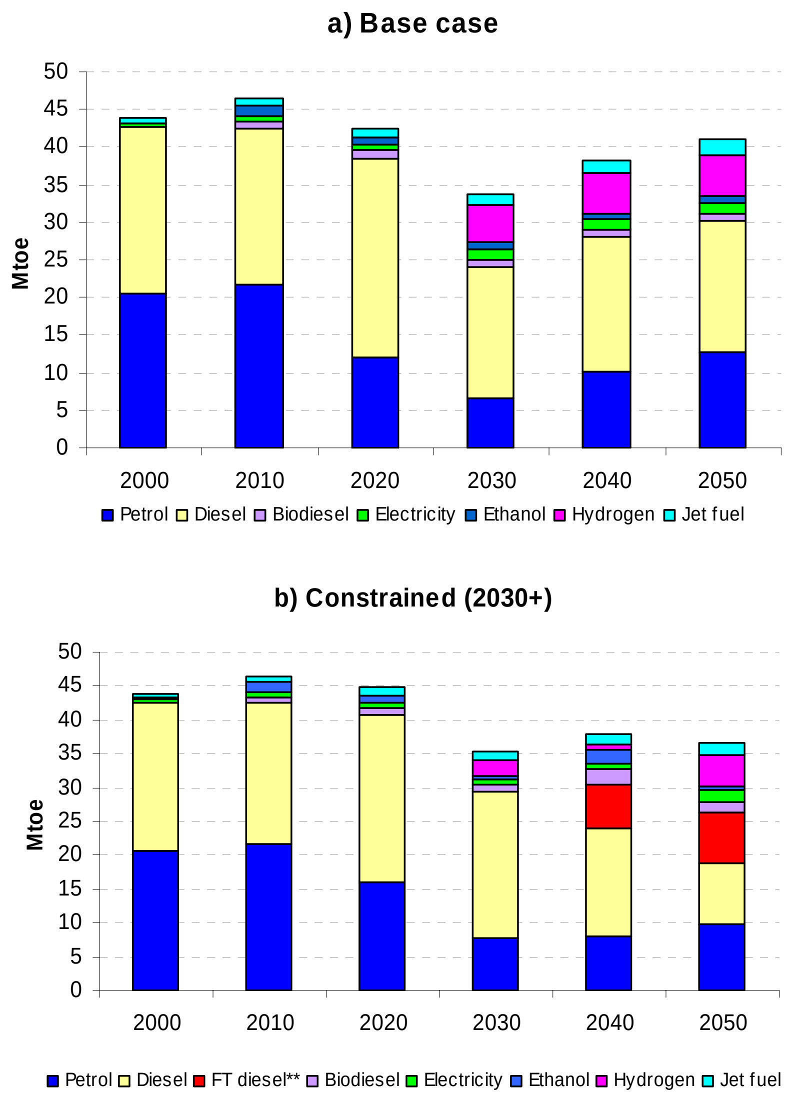
In the central 2030+ scenario the transport sector reduces emissions by around 45% on 2000 levels by 2050, but on a somewhat later trajectory than the economy as a whole. Carbon abatement in the transport sector occurs through a combination of a reduction in service demands and a switch to lower carbon technologies.

In the base case there is already some uptake of new car technologies with better fuel efficiency (chiefly greater penetration of hybrid vehicles as these are cost-effective on the basis of fuel saved alone), leading to energy demand falling even in the absence of a carbon constraint.[24] A carbon constraint induces an even greater take up of lower carbon technologies in the car sector (as well as further reductions in final energy demand). New technologies in other sectors (i.e. larger vehicles such as buses and Heavy Goods Vehicles (HGVs), contribute to a change in the overall fuel mix in

[24] For example, in the central fuel price base case, hybrid technology constitutes around 33% of car vehicles in 2030 (from 0% in 2000), before falling off to just 5% in 2040 and 0% in 2050. In the 2030+ case, however, hybrids remain cost-effective into 2040 (when they constitute 40% of the vehicles). Due to increased pressure on the electricity generation sector under this trajectory (and therefore less of a need for transport to meet the carbon constraint) hybrids fall back to 6% in 2050. As described in footnote 16 above, in the SLT scenario, vehicles running on more expensive fuel (ethanol) become cost effective, constituting 21% of car vehicles by 2050. For more detail on car technologies across the scenarios, see Strachan et al 2007.

transport sector, illustrated in Chart 4.7 below. Note that some low carbon fuels, such as hydrogen and electricity, are present in the base case.[25]

Chart 4.7 Transport fuel 2000-2050, central scenario (2030+)



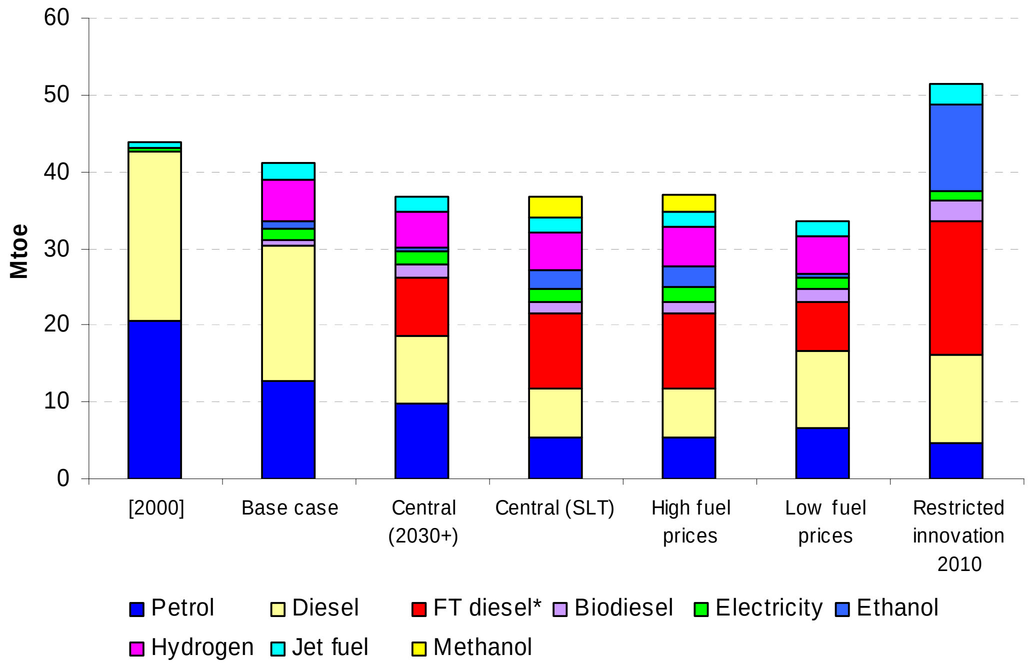
Source: Strachan et el, 2007. UK MARKAL MACRO. **Fisher-Tropsch diesel. Central fossil fuel prices.

Under a carbon constraint, the model switches conventional fuels for lower carbon substitutes so that by 2050, the fuel mix is more diverse. Chart 4.8 compares the transport fuel mix (in 2050) under alternative fuel and technology assumptions. Carbon fuel intensity is further constrained under

25 Hydrogen *per se* is not a low carbon fuel; it depends on the methods used to produce it. In the base cases hydrogen production comes from carbon intensive processes, namely coal gasification and gas steam methane reforming (SMR). In constrained cases, the production of hydrogen fuel is lower, as the carbon implications of (less efficiently) producing this carbon intensive hydrogen is too high. Hence the model diverts to higher efficiency SMR (more expensive) and bio and waste to produce hydrogen; which is resource limited. For more details, see Strachan at al 2007.

high fossil fuel prices, and the more expensive low carbon fuels become economic (i.e. ethanol and methanol).[26] The tough abatement profile in the straight line (SLT) scenario has a similar effect (see footnote 16, above). The level of innovation has important implications for the mix, as car technologies are restricted to 2010 vintage, and more fuel is needed as there are fewer efficient technologies available.

Chart 4.8 Transport fuel 2050, main scenarios



Source: Strachan et el, 2007. UK MARKAL MACRO. * Fisher-Tropsch diesel.

As in the generation sector, Chart 4.8 illustrates that no single fuel (and associated technology) in the transport sector will provide what is required to deliver lower emissions; rather, the solution depends on the cost assumptions and trajectory that are made in each scenario.

[26]The model does replicate the constraints on the supply of transport fuel; specifically, in the case of biofuels - the raw bio-products from within the UK are constrained by resource supply curves based on the opportunity costs of using limited agricultural lands. For imports of raw bio-products and refined bio-fuels, the global potential is restricted to a proportion for export, and with the UK having access to 10% of this export market (based on the UK share of global GDP, and increased based on first mover potential into new fuels' markets).

5. Economic Implications

5.1 Key macroeconomic results

The M-M model calculates the change in GDP as the energy system meets the carbon constraint, and is expected to produce lower-bound estimates of the long-term cost (in terms of overall reduction in GDP) of achieving a reduction in carbon emissions. In the scenarios explored as part of the 2007 Energy White Paper, the annual cost to GDP (from a relatively smaller energy system)[27] of reducing domestic UK emissions by 60% by 2050 range from a 0.3% to 1.5% in 2050.[28] This represents the long-term cost (in terms of a permanent reduction of GDP) of achieving a lower level of emissions by 2050. Table 5.1 below shows that investment and consumption in the economy as a whole is lower in 2050 as a result of carbon abatement.

Table 5.1. Change over base case in 2050, key macro parameters*

	GDP	Consumption	Investment
High fuel prices	-0.3%	-0.2%	-0.8%
Central (2030+)	-0.7%	-0.3%	-2.6%
Central (SLT)**	-0.8%	-0.3%	-3.1%
Low fuel prices	-0.7%	-0.3%	-2.8%
Restricted innovation (2020)	-1.2%	-0.6%	-3.8%
Restricted innovation (2010)	-1.5%	-0.9%	-4.3%

Source: UK MARKAL-MACRO. *Reduction in GDP (consisting of consumption and investment) over the base case, in 2050. Base cases vary according to scenario. **The 'straight-line' trajectory scenario under central fuel prices

The analysis highlights the importance of a number of factors in the determination of the costs of abatement**.**

- **High fossil fuel prices** can reduce overall costs - as low carbon technologies under high fuel prices become more competitive on a cost basis – energy demand and therefore carbon emissions are lower in the base case therefore requiring less 'effort' (Chart 2.1 above, abatement effort under high fuel prices is around 78MtC in 2050 compared with 102MtC under central fuel prices).
- **Low fossil fuel prices** will increase abatement costs as low carbon alternatives become relatively more expensive, and as demand for energy increases in response to low prices.[29]

[27] Improvements in energy intensity make the energy sector relatively less important as a percentage of UK GDP. As the economy grows faster than the energy sector, the GDP contribution of the energy system falls from 8% in 2000 to around 5-6% by 2050 in the constrained scenarios. If the relative value of the energy system is lower, the abatement costs (as a proportion of GDP), are also lower.

[28] The GDP cost in 2050 is a common metric in this type of modelling, and is consistent with that used in the Stern Review and the 2003 Energy White Paper. The 0.3-1.5% range is equivalent to an undiscounted annual cost in 2050 of between £8bn-£42bn (£2000 prices).

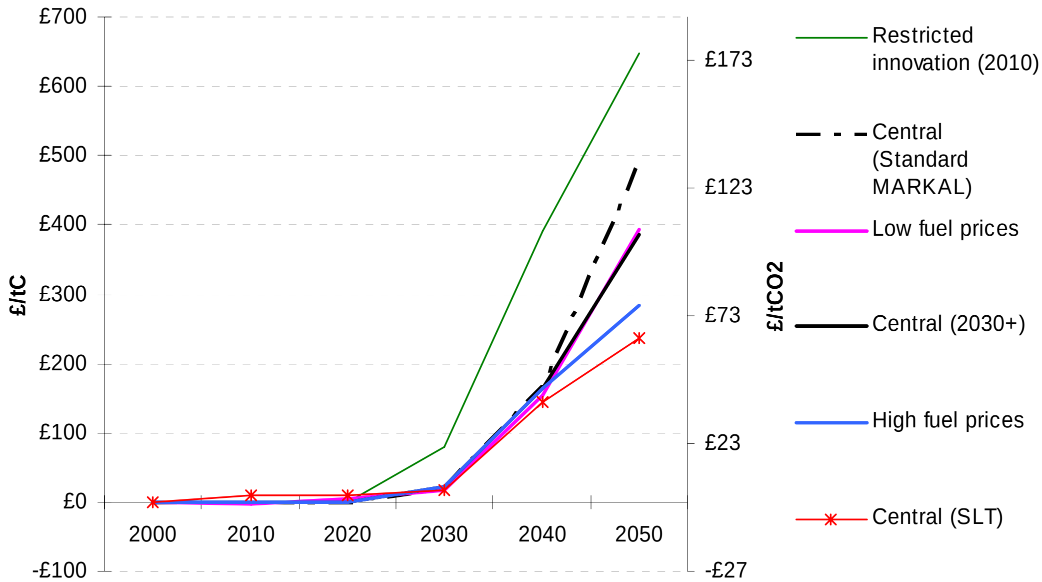
[29] In the low fuel price scenario it is important to note that not only are all fossil fuels cheaper, but the relative price of fuels change; which has an additional effect. Here, the relative price of

- **Improvements in the efficiency and availability of low carbon technologies** are also important in containing costs**.** The long-term impact on GDP rises to 1.5 % reduction in 2050 if innovation is restricted beyond 2010.[30]

5.2 Marginal costs

The marginal abatement cost is the cost of abating the final unit of carbon. Marginal costs are expected to increase over time as the carbon constraint tightens and as cheaper abatement options are used in the early years and more expensive options need to be taken. [31] However, at the same time, when demand for energy is lower, the marginal costs of abating carbon will also be lower, as less effort to abate emissions is needed therefore reducing the requirement to adopt more expensive technologies/options. Marginal costs will be lower in the M-M model compared with the 'standard' MARKAL (other things being equal), due to behavioural response. As Chart 5.1 shows, in the central scenario in the standard MARKAL, marginal costs in 2050 are around £495/tC compared with £385/tC in the M-M model.

Chart 5.1. Marginal costs (£/tC left axis, £/tCO2 right axis)



Source: Strachan et el, 2007. UK MARKAL MACRO.

Across all scenarios in the M-M, costs are low (in some cases, negative) and close to zero up to 2030, reflecting the significant amount of conservation and

gas becomes more favourable, to an extent reducing emissions in the base case, requiring less effort to abate and limiting abatement costs.

[30] In both restricted innovation scenarios, early vintages of CCS technology are still available. Costs are likely to be higher if these are also excluded, and innovation is restricted in other technologies (for example in end-use technologies).

[31] Since the M-M model does not quantify welfare losses arising through a reduction in energy demand, we use marginal costs here to reflect the value of carbon required to achieve this level of abatement.

efficiency occurring in the base case, due to low cost efficiency options, fuel switching and conservation being taken up. The modelling therefore implies that the carbon constraint is relatively easy to meet in the early years. However, how much of this cost-effective abatement will occur in reality (and given the limitations of the model to capture the barriers to this activity and the costs of overcoming them) these reflect the lower-bound marginal costs of abatement.

6. Conclusions

We have employed the MARKAL-Macro model (M-M model) - one of very few models that combine a very rich technological representation of the entire UK energy system with the explicit calculation of macroeconomic variables - to inform estimates of the abatement costs of reducing UK domestic carbon emissions by some 60% by 2050.

The scenarios explored in this paper provide new and valuable insights into the long-term implications of carbon abatement; with the costs of reducing carbon emissions by 60% by 2050 ranging between a 0.3-1.5% reduction in GDP in 2050.

Both the trajectory to 2050, as well the relative price of fossil fuels and the level of technological innovation, have significant implications for the costs of carbon abatement. The model chooses a mix of technologies and uses a range of mitigation responses order to deliver a significant cut in domestic UK emissions. The shift to less carbon-intensive fuels and the development of low-carbon technologies, particularly in the electricity generation sector, does contribute significantly to the overall abatement effort and also to the diversification of the energy mix.

The model also highlights how the implications of carbon abatement on the way we use energy could be quite significant, if we are to be able to reduce carbon emissions without excessive costs for the economy. To meet the carbon target, the M-M model invests in a combination of more efficient end-use technologies and conservation measures, which improve the efficiency of the energy system (and hence do not necessarily carry large costs). These investments are combined with a concerted reduction in the demand for energy services, which, under unchanging consumer preferences will also have implications for consumer 'satisfaction' and well-being which are not quantified and captured in the modelling.

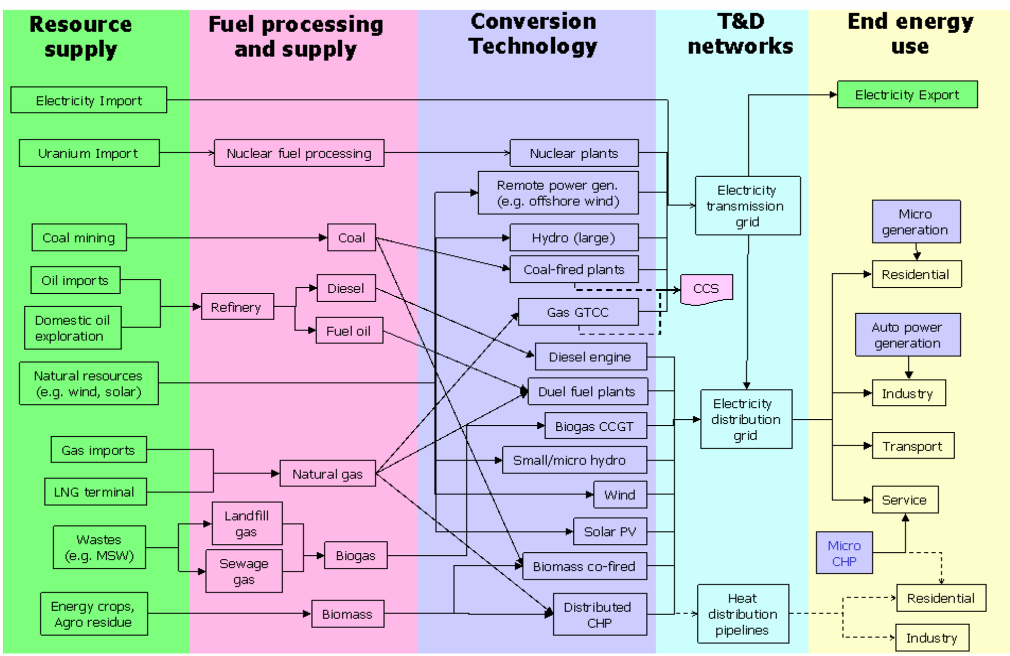
Given the difficulties associated in forecasting important aspects of the energy system such as fuel prices and technology costs, there remains considerable uncertainty about the long-term costs of carbon abatement. Although the long-term costs estimated in the M-M analysis are significant, they remain within the range calculated by Stern to be the global cost of stabilising carbon dioxide emissions. However, as a UK only model, the M-M model is unable to quantify the implications for UK trade and competitiveness; and does not capture potential transition costs that might arise as the economy adjusts to changes in energy policy. Therefore, in addition the long-term impacts, there may be higher adjustment costs for the UK, which will depend on the speed and flexibility with which the economy adjusts to changes in relative factor prices, and the extent to which cost-effective abatement options are taken up in the market.

Annex 1: The 'standard' UK MARKAL model

The UK MARKAL model (acronym for MARKet ALlocation) is a dynamic energy optimisation model that minimises the total cost of the energy system over a 50 year horizon. The first 'step' of the model development was the substantial update of the MARKAL model from that which was used to inform the 2003 Energy White Paper (see Box A1).

The latest UK MARKAL model is centred on the construction of the 'Reference Energy System' (RES). This is intended to capture the UK energy system in its entirety; from the first stage of identifying an energy resource supply, through the conversion process and to consumption as an end-use within a sector. The UK MARKAL model disaggregates into sectors – the larger sectors (in terms of consumption of energy) consisting of the Residential, Industry, Services, and Transport sectors; and the smaller sectors Upstream (i.e. Energy supply sector including power stations and oil refineries) and Agriculture. Each sector has a RES specific to it. Figure 2.1 illustrates a highly simplified RES, consistent with that in the latest 'standard' UK MARKAL model.[32]

Figure A1.1 Example of Reference Energy System in UK MARKAL model



Source: Strachan et al, 2007.

The latest 'standard' UK MARKAL model has benefited (from the 2003 iteration) from updated technology data;[33] supply curves for both domestic

[32] Note the actual UK MARKAL RES is perhaps 100 similarly complex diagrams embedded in the summary boxes of Fig 2.1.

[33] MARKAL has thousands of 'technologies' - by the term 'technology' in MARKAL, we refer to a range of variables present at either resource through to end-use stage; including; resource supply steps, pipelines, refineries; electricity generation technologies such as nuclear or Coal

and input resources; detailed fuel infrastructure representation on a sectoral basis; depiction of key energy processes including hydrogen processes and biomass chains; and an update of the electricity sector including micro and remote grid representation. End use sectors have been substantially enhanced to capture efficiency, fuel switching and conservation options. In addition, the new UK MARKAL model has explicit treatment of mitigation options including the nuclear fuel cycle, carbon capture and storage (CCS) options and combined heat and power (CHP).[34]

Box A1: The UK MARKAL in the EWP 2003

An earlier version of the UK MARKAL model was used for the 2003 Energy White Paper. It helped to inform the Government on the technical options and costs of moving to a low carbon energy system, in response to the Royal Commission on Environmental Pollution recommendation for a target of a 60% reduction in carbon dioxide emissions by 2050. The work explored a number of base cases and the implications of reductions in carbon emissions of 45%, 60% and 70%. Sensitivities were conducted on the trajectory to 2050, the level of energy efficiency and innovation, the availability of fossil fuel and exclusion of certain low carbon technologies.

The analysis suggested that the average cost of reducing emissions by 60% by 2050 was in the range of £200-£300 per tonne of carbon (£/tC). Marginal costs in 2050 were in the range of £300-£1000/tC. Based on an economic growth rate of 2.25 per annum, abatement costs were equivalent to between 0.5-2% of GDP in 2050. But this was an 'off model' estimate, due to the 2003 model having no explicit GDP calculation. High range costs occurred if innovation and low carbon technologies were limited; if efficiency improved only in line with past trends; and if both nuclear and CCS were completely excluded in the longer term.

The model is driven by data assumptions and inputs. In developing the latest version of the MARKAL model, UKERC/PSI undertook an extensive process of model validation through a combination of literature review and stakeholder workshops. The model development has also been peer reviewed by ECN Netherlands. [35]

CCS plants; and end use conservation technologies such as A+ rated electronic appliances, i.e. refrigerators in new and existing dwellings.

[34] See full technical model documentation published by UKERC: Kannan R., N. Strachan and S. Pye (2007), *UK MARKAL model documentation*, UKERC working papers, available at www.ukerc.ac.uk

[35] Martinus G, (2006) a report to the DTI, May 2006

Annex 2: UK MARKAL-MACRO model

The MARKAL MACRO model (M-M) links the detailed characterisation of the 'standard' UK MARKAL with a 'top down' macroeconomic component. The M-M model is one of few models that link a macro component to a detailed energy system model. It captures the interplay between the energy system and the wider economy as it faces a carbon constraint. In doing this, it allows energy demand to respond to changes in the price of energy, as payments for energy services are 'traded off' against the need for investment in capital and labour in other areas of the economy.[36] It also facilitates the explicit calculation of the macroeconomic variables, whilst retaining the detail of energy system dynamics consistent with 'bottom up' models.

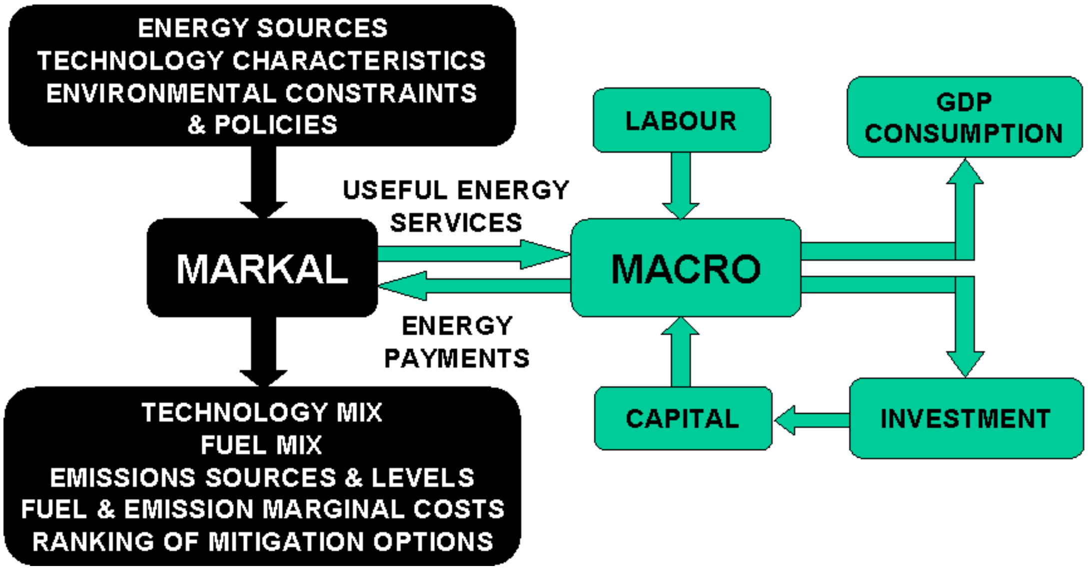
The macroeconomic component in the M-M model is a simple, neo-classical growth module consisting of consumption and investment. As with the 'standard' MARKAL, the M-M model is a single economy model, and does not model trade or other countries' economies. Therefore, the MM model cannot capture shifts in sectoral competitiveness and trade implications arising from changes in relative factor prices in the UK and abroad. The M-M model covers UK domestic carbon emissions only, and therefore does not allow for any effect of carbon trading. There is no Government sector therefore any revenue raised from taxes or permits does not re-enter the economy.[37]

Figure A2.2 is a schematic representation of the M-M model. The M-M model maximises overall consumption over the solution period, whilst optimising aggregate investment in the economy and minimising the cost of the energy system. The MACRO component calculates changes in GDP, consumption and investment, at the level of energy prices given by the MARKAL component; at the same time MARKAL responds by configuring the optimal energy system to meet adjusted demand. The model solves in 10 year time steps and uses non linear optimization (in contrast to the 'standard' UK MARKAL model, which solves in 5 year steps and gives a somewhat smoother transition path).

[36] Full details on the system parameters, structure and assumptions in the M-M model are available in Strachan N., R. Kannan and S. Pye (2007), *Final Report on DTI-DEFRA Scenarios and Sensitivities using the UK MARKAL and MARKAL-Macro Energy System Models*, available at http://www.ukerc.ac.uk/content/view/142/112

[37] We have not looked at the implications of taxes or permits in this paper.

Figure A2.2 UK MARKAL-Macro model



Source: Strachan et al, 2007.

The feedback between energy demand and energy prices provides an additional mitigation option to the standard MARKAL model. As agents respond to relative factor price changes, there is less pressure on other mitigation options to meet the constraint. All other things being equal, this additional response should produce lower policy costs.

The MARKAL and the MARKAL-Macro models are particularly useful in exploring the energy system in the long-term, to 2050. They can show the least cost technology mix to meet a given carbon constraint, and may be expected to produce lower-bound estimates of the long-term costs of carbon abatement. This is, in part, because they describe the economy in equilibrium, and therefore are unable to capture transition costs that might occur as the economy adjusts to changes in energy policy or prices. As UK only models, they do not capture implications for UK trade and competitiveness as a result of reducing carbon emissions. As perfect foresight models, they too are somewhat limited in their ability to capture the obstacles that, in reality, can slow the uptake of cost effective abatement, such as information barriers and transaction costs.

Annex 3: Description of main scenarios

Table A3.1 sets out the main scenarios described in this paper. Over 50 scenarios were explored as part of the analysis, for the full list of scenarios and model outputs, see Strachan et al, 2007.

Table A3.1 Scenario list and description

Scenario	Scenario description
Central base	Base, central fuel prices
Central (2030+)	60% carbon constraint applied as a 30% reduction in 2030 – straight line interpolation to 60% reduction in 2050. Central fuel prices.
Central (SLT)	60% carbon constraint applied as a straight line trajectory from 2010
High base	Base, high fuel prices
Low base	Base, low fuel prices
High fuel prices	As central (2030+) with high fuel prices
Low fuel prices	As central (2030+) with low fuel prices
Base, 2010	Central base with innovation limited to no technologies beyond a 2010 vintage
Base, 2020	Central base with innovation limited to no technologies beyond a 2020 vintage
Restricted innovation (2010)	As central (2030+) with innovation limited to no technologies beyond a 2010 vintage
Restricted innovation (2020)	As central (2030+) with innovation limited to no technologies beyond a 2020 vintage

In the updated version of UK MARKAL, domestic fossil and renewable resources, and fossil imports are depicted via supply curves rather than discrete values. Table A3.2 lists representative base case, high case and low case fossil import prices in £2005. These were published by the DTI with the Energy Review Report.[38] From these, multipliers calibrated 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.

Table A3.2 Fossil fuel price assumptions

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

[38] DTI: *Updated Energy Projections* (2006) http://www.dti.gov.uk/energy/environment/projections/index.html