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[1] **The authors gratefully acknowledge the advice and guidance provided by Gary Goldstein (IRG Ltd) and Neil Strachan (PSI).**

Executive summary

This report is the final report under the Defra contract EP0202 *MARKAL Macro analysis of long run costs of mitigation targets*. The objective of this study was to consider the additional impacts (economic and technological) of moving to an increasingly carbon constrained energy system, with reductions in CO_2 of 70% and 80% by 2050. In addition, another objective was to assess the impact of including emissions from international aviation, and the implications for abatement in other sectors under a 60% constraint in 2050. This analysis builds on work led by Policy Studies Institute (further referred to as the *EWP 07 MARKAL analysis*),[2] to inform the Government's Energy White paper, published in May 2007. In that analysis, up to 60% reductions in emissions of CO_2 by 2050 were considered, with many associated sensitivity runs undertaken to examine different assumptions.

A key part of the strategy outlined in the Energy White Paper *Meeting the Energy Challenge* included the provision of legally binding carbon targets for the whole UK economy, to progressively reduce emissions. A Climate Change Bill is being proposed that would implement such targets, and has recently been consulted on.[3] As part of further discussions around longer-term targets, Defra commissioned this additional MARKAL analysis, to explore the impacts of more stringent targets than those considered in the Energy White Paper.

Although probably clear to the reader, it is important to highlight the comment in *EWP 07 MARKAL report* that *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*. Hence it should be stressed that this analysis provides some useful and informative insights based on the many assumptions in the model, not necessarily the definitive answers to challenging and complex energy issues.

There are a number of headline messages emerging from this analysis:

- Increasingly stringent constraints on the energy system force even more radical change on the energy system, in terms of energy mix and technology take-up, than seen in the previous 60% constraint runs. The choice of energy and technologies reflects the very many trade-offs in the system in moving to a lower carbon economy.

- Importantly, the energy system still has the necessary abatement options to be able to ensure that significant additional reductions in CO_2 can be met, even when the system is further constrained in terms of technological innovation and other cost-effective options.

- As concluded in the previous EWP 07 MARKAL analysis, all sectors contribute (fairly equally) to emission reductions (based on allocation of end-use emissions from electricity and hydrogen production) although relative timings of contribution differs. The electricity sector is a key sector for realising emission reduction targets, almost fully decarbonising by 2050.

- Additional reductions in CO_2 emissions lead to higher marginal abatement costs, as abatement measures chosen by the model become increasingly more expensive (less cost-effective). This indicates that as constraints become more stringent, the energy system requires a higher CO_2 price signal to respond accordingly.

- The impacts on GDP are also more significant, as consumption and investment levels decrease further due to increasing energy payments. Under a 70% constraint, GDP decreases by 1.1% (£B29.8) in 2050 while under an 80% constraint it decreases by 1.6% (£B44.9). This compare to 0.8% reduction in 2050 under a 60% constraint (or £B22.2 loss).

- Inclusion of international aviation in the model results in significant additional burden on the other parts of the transport sector and on the wider energy system to provide additional CO_2

[2] "Final Report on DTI-DEFRA Scenarios and Sensitivities using the UK MARKAL and MARKAL-Macro Energy System Models", Final Report prepared by the Policy Studies Institute for the Department of Trade and Industry (DTI) and the Department of Environment, Food and Rural Affairs (DEFRA). Dr Neil Strachan and Ramachandran Kannan, Policy Studies Institute; Steve Pye, AEA Energy and Environment. May 2007.
[3] Consultation can be found at http://www.defra.gov.uk/corporate/consult/climatechange-bill/

reductions, due to the inability of aviation to make significant emission reductions other than by reducing demand. This impacts on the marginal CO_2 abatement costs and GDP losses for the 60% STL runs with international aviation, which are similar to those in the (non-aviation) 70% SLT runs.

The three sections that follow do not reflect the findings of the analysis to assess the impact of the inclusion of international aviation. This is included in the fourth section, titled *International aviation.*

System evolution

System evolution considers changes in the primary and final energy demand across the time period, and the impact on CO_2 emissions.

Total **primary energy** use in the UK energy system under the base case first decreases to 2030, then rises to comparable levels in 2050 to those observed in 2000. This reduction to 2030 is due to the energy system, without any additional constraints, moving towards more cost-effective technologies (hybrid and hydrogen fuel cell vehicles cars in the transport sector) and conservation measures (in the base case). The introduction of carbon constraints leads to significant reductions in primary energy use, as the energy system moves to using energy more efficiently and using less energy (through increasing levels of conservation / endogenous demand response). Reductions are greater the more the system is carbon constrained; under an 80% constraint, primary energy has reduced by up to 37% by 2050. Under the 60% constraint, the reduction is approximately 31%. Final energy consumption follows a similar trend.

The evolution in the type of energy provides a picture in 2050 of significantly lower coal and gas use, and limited use of transport based fossils fuels. Renewables and nuclear (for electricity generation) are much more significant, while biomass provides much of the energy needs of the road transport sector. Compared to the system under a 60% reduction, differences in 2050 under a 70% reduction constraint include use of nuclear in the electricity generation sector and less use of fossil fuels in the transport sector.

The 80% constraint has much higher levels of renewable use, driven by increasing electricity generation from wind. Natural gas use is noticeably lower, with end use sectors (particularly residential sector) shifting from natural gas use to low carbon electricity. Constraining levels of biomass inevitably leads to increased use of refined oil products, whilst limits on wind generation leads to the take-up of gas CCS (Carbon Capture and Storage) and increased levels of nuclear generation. Limits to key carbon abatement technologies in the electricity generation sector (nuclear and CCS) result in increasing reliance on wind generation. Additional constraints to ensure more realistic wind penetration mean that end-use sectors have to rely more heavily on conservation and endogenous demand response rather than low carbon electricity as before.

By 2050, all end-use sectors are contributing to the significant reductions required to meet **CO_2 emission** targets. Relative to the 60% constrained case, under more stringent constraints, all sectors make additional contributions to mitigation, with the transport and residential sectors tending to contribute to a more significant proportion of total abatement in 2050. The transport sector is an interesting case as emission reductions are ‘hidden’ in the base case as the vehicle fleet moves to hybrid and hydrogen vehicles even in the absence of constraints. Therefore emission reductions are less obvious. Significant additional abatement above the baseline from this sector occurs post-2030 due to the increase in hydrogen use and then again in 2050 as oil-based fuels are increasingly replaced by biofuels.

The electricity generation sector, with the technological options to decarbonise fully, is critical to achieving the reductions in 2050 (and in other target years along the emission reduction trajectory) under both 70% and 80% constraints as was observed in the *EWP 07 MARKAL analysis*. Under an 80% constraint, it accounts for over 50% of the required emission reductions in 2050. However, it is worth noting that this is enabled by large amounts of wind generation (with little account for grid stability or constraint issues, planning etc) and a prominent role for CCS, a technological option still at the demonstration stage).

Technology pathways

The focus of the assessment of technological change was the electricity generation and transport sectors. These are key sectors to ensure the UK can move to a low carbon energy system. However, it is also important to recognise the role of other end use sectors all of which play a role in carbon reductions even though the technology pathways for those sectors have not been presented in detail.

In the previous analysis for the EWP 2007 where the impacts of a 60% reductions by 2050 were analysed, the **electricity generation sector** moved from a coal dominated base case to one that featured a diverse generation profile, with coal CCS and renewables the key technologies. The main changes observed from moving to a 70% reduction by 2050 is an overall higher level of generation delivered by nuclear generation. Coal CCS levels are the same because capacity bounds had already been reached while gas is no longer part of the mix. Under an 80% constraint, generation levels are even higher, made possible by large amounts of new offshore wind capacity. Marine technologies also feature but at low capacity levels. The additional electricity generation appears to be largely driven by end use sectors shifting away from gas to low carbon electricity.

Sensitivity analysis around key assumptions on wind, CCS and nuclear provide additional insights. Limits on new nuclear build result in wind generation filling the gap. However, if the role of wind generation is constrained, gas CCS becomes the significant generation technology, accounting for up to 50% of overall output. Gas CCS is chosen instead of coal CCS because higher levels of gas CCS generation can be achieved under a given CCS storage bound because the carbon intensity of this generation type is lower.

No nuclear or CCS build again leads to domination by wind generation due to limited constraints. Introducing constraints on the role of wind results in electricity generation output falling to the levels observed under the 70% constraint case. End use sectors invest significantly in additional conservation, and reduce their demand (through the endogenous demand response) in the absence of high levels of low carbon electricity previously available under the standard 80% constraint.

As previously mentioned, under the base case (in the absence of constraints), the **transport sector** is already moving towards more efficient technologies e.g. hybrids. Large reduction targets for CO_2 lead to overall energy demand decreases as vehicles become more efficient but also as a result of demand reduction in response to price increases. A more important role for biomass emerges in later periods, particularly biomass-to-liquid fuels (BtL), than seen in the EWP analysis. In the 80% reduction cases, by 2050 biofuels account for over 60% of total transport fuels leading to limited or no further use of conventional road transport fuels (petrol and diesel). Constraints on biofuels in transport result in a greater role for petrol and diesel

In periods preceding 2050, hydrogen use is highest in the base case. Lower levels in the constrained cases reflect the fact that the hydrogen production in the base case is through carbon intensive fossil fuels. Much of the hydrogen that is used in the last period under the 80% constrained case is from hydrogen production from electrolysis, using low carbon electricity.

Considering technologies used in the road transport sector, it is interesting to observe that with the exception of the restricted innovation case, the use of diesel and hybrid vehicles in 2050 is at the same level to that observed in the base case(s) due to constraints on fleet profile. The high level of conventional diesel vehicles is enabled due to the use of BtL (Biomass-to-liquid fuels or second generation biodiesel), replacing diesel. A 70% reduction in 2050 leads to some changes from the previous 60% analysis, with no flex-ethanol, methanol fuel cell or conventional petrol vehicles in the mix. A reduced demand and petrol hybrids ensure levels of demand are still met. In the 80% reduction cases, methanol fuel cell vehicles are taken up with less use of petrol hybrids. The uptake of different technologies suggests that differences in relative unit costs of these technologies in 2050 are small.

Demand response is an important feature of the MARKAL Macro model, enabling the model to reduce costs through reductions in consumer demand for energy rather than have to invest in higher cost, low carbon technologies. As emission constraints get more stringent, demand response becomes an increasingly important mechanism to help minimise the marginal costs of abatement; under the 60% constraint, demand reductions of around 9-13% in 2050 can be observed (excluding transport). In 2030 – when constraints are lower, demand responses are below 5%. Transport also reflects these demand response trends but at lower reduction levels. Under an 80% constraint, the reductions are between 15-20% in 2050. This suggests that where low carbon options are more expensive, demand reductions are even greater as the system tries to minimise costs. Interestingly, the demand response trend follows the marginal abatement cost trends, indicating that the level of marginal costs is a significant driver of the demand response.

The relative response between sectors differs, with the largest reductions seen in the residential, industry and agriculture sectors. The transport sector is the least responsive sector.

The system can also reduce demand through the uptake of conservation measures. Relative to the analysis of a 60% reduction, the use of conservation does increase when emission constraints are tightened but only by limited levels. Under the 60% case, most cost effective conservation has been taken, with potential remaining for more expensive conservation measures. Expensive conservation measures are taken up, particularly in the residential sector, in the most constrained cases e.g. no nuclear or no nuclear / CCS, with additional bounds on wind generation and biomass resources.

Economic impacts

Marginal abatement costs increase significantly as emission reduction targets are increased. For the 60% reduction case (under the EWP analysis), costs were approximately £65/tCO_2 (£240/tC). These increase to £145/tCO_2 (£530/tC) under a 70% constraint and £215/tCO_2 (£790/tC) under an 80% constraint. Where additional constraints are put on the system, these costs are pushed up further, with £395/tCO_2 (£1450/tC) under the 80% reduction case, where CCS / nuclear technologies are not available, and additional wind generation and biomass resource constraints are introduced. The marginal costs also differ across the time horizon; under the alternative emission reduction trajectory (where emission reduction targets are markedly higher in earlier years), costs are unsurprisingly higher than seen under the core SLT cases. In many of the runs, a reduction in costs in 2030 relative to 2020 indicates the emergence of more cost-effective low carbon technologies.

The Macro model also makes a direct calculation of **GDP**, based on the interactions between the energy sector and the rest of the economy, and how this impacts on levels of consumption and investment. In the EWP 2007 model runs, a 0.8% (£B22.2) loss in GDP was estimated based on the SLT 60% reduction run. The most significant GDP losses in the *EWP 07 MARKAL analysis* were observed under the 60% restricted innovation post-2010 case at 1.5% (or £B42.0).

In this analysis, all 70% reduction cases lead to estimated GDP losses of around 1.1% in 2050. Cumulative losses are of course greater for the MM-C70A case (alternative trajectory) where higher constraints are imposed across the emissions reduction trajectory. For the 80% reduction cases, losses are between 1.6 and 1.8% except for the high resource cost and restricted innovation cases, where losses are 1.1% (£B31.6) and 2.6% (£B73.0) respectively. Again, the 80% alternative trajectory leads to greater cumulative GDP losses.

International aviation

The inclusion of international aviation emissions in the energy system results in the need for significant additional reductions in CO_2 across the system. This is due to the apparent inability of the aviation sector to achieve reductions though technological or fuel switching means – relying on demand reduction to contribute to emissions reductions required under the 60% reduction case.

Under 60% CO_2 constraints, the wider system changes resulting from the inclusion of international aviation include a substantial increase in nuclear electricity generation and increased use of BtL diesel and hybrid petrol car technologies in the transport sector.

The resulting 2050 marginal CO_2 abatement costs (97 £/tCO_2) and GDP losses (1.24%, 34.8 £Billion) of 60% constrained runs are mid-way in between those reached by the 60% and 70% constrained runs without international aviation.

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1 Introduction

This is the final report under Department for Environment, Food and Rural Affairs (Defra) contract EP0202 *MARKAL Macro analysis of long run costs of mitigation targets*. The objective of this contract was to undertake an analysis using the UK MARKAL model to assess the additional impacts (economic and technological) of moving to an increasingly carbon constrained energy system, with reductions in CO_2 emissions of 70% and 80% by 2050. This analysis builds on work led by Policy Studies Institute (further referred to as the *EWP 07 MARKAL analysis*),[4] to inform the Government's Energy White paper, published in May 2007. In that analysis, up to 60% reductions in emissions of CO_2 by 2050 were considered, with many associated sensitivity runs undertaken to examine different assumptions.

A key part of the strategy outlined in the Energy White Paper *Meeting the Energy Challenge* included the provision of legally binding carbon targets for the whole UK economy, progressively reducing emissions. A Climate Change Bill is being proposed that would implement such targets, and has recently been consulted on.[5] As part of further discussions around longer-term targets, Defra commissioned this additional MARKAL analysis, to explore the impacts of more stringent targets than those considered in the Energy White Paper. Key issues for assessment included the additional impacts on GDP, costs of abatement, technological change (particularly in the electricity generation and transport sectors, and sectoral contribution to emission reductions.

The analysis presented in this report has used the same MARKAL Macro model used for the Energy White Paper (2007) analysis, and retained the same assumptions to ensure consistency. The model runs that have been undertaken explore 70% and 80% CO_2 reductions by 2050 based on two different emission reduction trajectories. Additionally, four key sensitivities have been assessed to explore changes in assumptions:

- Less optimistic view of technological innovation
- Higher energy prices
- Restriction in electricity generation technologies – nuclear and carbon capture and storage (CCS)
- Restrictions on biomass use in the transport sector and electricity generation from wind technologies

In addition, model runs have also been undertaken to explore the impact of accounting for CO_2 emissions from international aviation in the UK, and the impact this has on meeting a 60% reduction target in 2050.

A comprehensive overview of the structure and data inputs of the UK MARKAL model can be found at the UKERC website, and therefore is not covered in this report.[6] Information on the MARKAL model and how it works can be found in the *EWP 07 MARKAL analysis* report.

[4] "Final Report on DTI-DEFRA Scenarios and Sensitivities using the UK MARKAL and MARKAL-Macro Energy System Models", Final Report prepared by the Policy Studies Institute for the Department of Trade and Industry (DTI) and the Department of Environment, Food and Rural Affairs (DEFRA). Dr Neil Strachan and Ramachandran Kannan, Policy Studies Institute; Steve Pye, AEA Energy and Environment. May 2007.
[5] Consultation can be found at http://www.defra.gov.uk/corporate/consult/climatechange-bill/
[6] UK MARKAL model documentation can be found on the UKERC website at http://www.ukerc.ac.uk/ResearchProgrammes/EnergySystemsandModelling/ESMMARKALModelDocs.aspx

2 Model runs

A range of different model runs were determined to assess the impact of even more stringent CO_2 cuts across the economy. These were discussed and agreed in consultation with Defra, BERR and DfT analysts. The 10 runs are listed below in Table 2.1.

Table 2.1 Model runs to assess costs of long-term mitigation targets

Run No.	Run Name	Description
1	MM-C70S	70% CO_2 reduction by 2050 assuming straight line trajectory (SLT) between 2010 and 2050
2	MM-C80S	80% CO_2 reduction by 2050 assuming straight line trajectory (SLT) between 2010 and 2050
3	MM-C80S1	As for MM-C80S, except technology innovation is restricted post-2010
4	MM-C80SH	As for MM-C80S, except higher resource prices have been assumed
5	MM-C70A	Straight line from 2010 to 35% CO_2 reduction (on 1990) at 2020; another straight line from 2020 reaching 70% reduction (on 2000) by 2050.
6	MM-C80A	Straight line from 2010 to 40% CO_2 reduction (on 1990) at 2020; another straight line from 2020 reaching 80% reduction (on 2000) by 2050.
7	MM-C70BW	As for MM-C70S, except restrictions on the take-up of biomass in transport sector and contribution of wind to electricity generation mix
8	MM-C80BW	As for MM-C80S, except restrictions on the take-up of biomass in transport sector and contribution of wind to electricity generation mix
9	MM-C70SN	As for MM-C70S, except no new nuclear build assumed
10	MM-C80SN	As for MM-C80S, except no new nuclear build assumed
11	MM-C80NC	As for MM-C80S, except no new nuclear build assumed and restrictions on the take-up of biomass in transport sector and contribution of wind to electricity generation mix
12	MM-C70CC	As for MM-C70S, except no new nuclear build assumed, and no CCS build assumed
13	MM-C80CC	As for MM-C80S, except no new nuclear build assumed, and no CCS build assumed
14	MM-C80XC	As for MM-C80S, except no new nuclear build assumed, and no CCS build assumed, and restrictions on the take-up of biomass in transport sector and contribution of wind to electricity generation mix
15	MM-BASAA	Baseline recalibrated model run including international aviation
16	MM-C60SA	60% CO_2 reduction by 2050 assuming straight line trajectory (SLT) between 2010 and 2050, including international aviation

NB. Technical data on model version and model run dates / timings are provided in Annex 2.

Base cases were re-run for the standard, high resource price and restricted innovation cases. This was done as part of the process to ensure consistency with EWP 07 base cases. These are labelled as follows in the report:

- Standard base – MM-BASA
- High resource price base – MM-BAS-H
- Restricted innovation base - MM_B_10

2.1 Model run trajectories

Most of the model runs were undertaken using a straight-line trajectory (SLT), reflecting the fact that carbon constraints on the economy are likely to be implemented at frequent intervals rather than in a single year e.g. 2050. Two runs were also undertaken with an alternative trajectory (ALT), to consider the costs and other implications of a more stringent target in 2020 than imposed using the straight-line trajectory.

A further two model runs were undertaken to assess the impact of including the international aviation sector in the energy system emissions accounting.

2.1.1 SLT trajectory

The Straight Line Trajectory (SLT) is consistent with the implementation of SLT trajectory in the EWP runs (see *EWP 07 MARKAL analysis* report and associated documentation). The trajectory is drawn from 2005 emission levels to the 70% or 80% reduction levels in 2050 (relative to 2000 emissions). The SLT CO_2 emission constraint values tested are provided in Table 2.2 below.

The 70% and 80% SLT leads to CO_2 emission reductions of 29% and 32% in 2020, relative to 1990 levels. This is within the range for 2020 being discussed in the context of the draft Climate Change Bill of 26% and 32% reductions relative to 1990.

Table 2.2 Straight Line Trajectory (SLT) emission constraints

Trajectory		**2000**	**2005**	**2010**	**2020**	**2030**	**2040**	**2050**
PSI-SLT (-60)	**Carbon**	148,600	150,538	140,425	120,200	99,975	79,751	59,526
	CO_2	544,867	551,972	514,893	440,735	366,577	292,419	218,261
	Reduction on 2000			*6%*	*19%*	*33%*	*46%*	***60%***
	Reduction on 1990			*13%*	*26%*	*38%*	*51%*	*63%*
SLT (-70)	**Carbon**	148,600	150,538	138,765	115,218	91,672	68,126	44,600
	CO_2			508,804	422,468	336,132	249,796	163,533
	Reduction on 2000			*7%*	*22%*	*38%*	*54%*	***70%***
	Reduction on 1990			*14%*	*29%*	*43%*	*58%*	*72%*
SLT (-80)	**Carbon**	148,600	150,538	137,122	110,292	83,461	56,631	29,800
	CO_2			502,782	404,403	306,024	207,646	109,267
	Reduction on 2000			*8%*	*26%*	*44%*	*62%*	***80%***
	Reduction on 1990			*15%*	*32%*	*48%*	*65%*	*82%*

* Constraints imposed in the model from 2010 onwards. 2000 and 2005 values provided for information only.

2.1.2 Alternative trajectory

The alternative trajectory is a variation on the SLT, with more stringent targets in 2020. Under the 70% reduction in the 2050 case, the 2020 emission reduction level is 35% (relative to 1990 levels) while under the 80% reduction case, the 2020 emission reduction level is 40%.

Such a trajectory was proposed in consultation with the Climate Change Bill team, to provide insights into the implications of a more stringent target in the shorter term.

Table 2.3 Alternative Trajectory (ALT) definition

Trajectory		**2000**	**2005**	**2010**	**2020**	**2030**	**2040**	**2050**
AT (-70)	**Carbon**	148,600	150,538	135,350	104,975	84,850	64,725	44,600
	CO_2			496,284	384,908	311,117	237,325	163,533
	Reduction on 2000			*9%*	*29%*	*43%*	*56%*	***70%***
	Reduction on 1990			*16%*	***35%***	*47%*	*60%*	*72%*
AT (-80)	**Carbon**	148,600	150,538	132,658	96,900	74,533	52,167	29,800
	CO_2			486,414	355,300	273,289	191,278	109,267
	Reduction on 2000			*11%*	*35%*	*50%*	*65%*	***80%***
	Reduction on 1990			*18%*	***40%***	*54%*	*65%*	*82%*

* Constraints imposed in the model from 2010 onwards. 2000 and 2005 values provided for information only.

All four trajectories are shown in Figure 2.1 below. The divergence between the SLT and comparable ALT trends is most pronounced in 2020, converging by 2050.

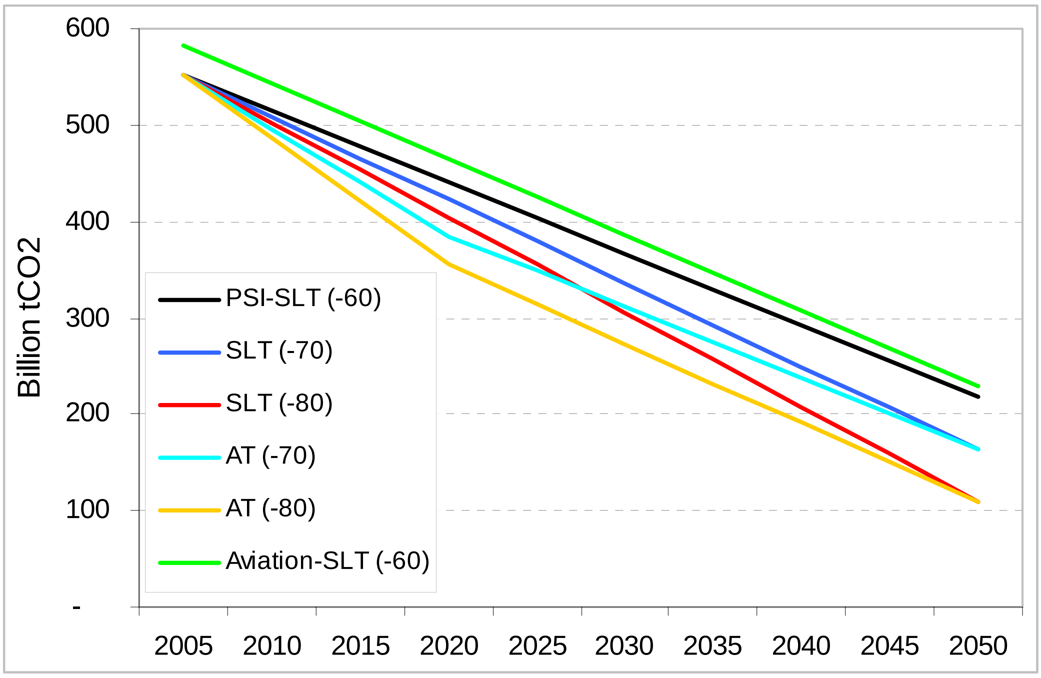


Figure 2.1 **Model trajectories – Straight line (SLT), Alternative (ALT) and International Aviation trajectories**

2.1.3 International aviation

For the international aviation runs a revised 60% SLT run was agreed with Department for Transport (DfT) and Defra, to be based upon reductions on the year 2000 emissions plus those resulting from international aviation bunkers (30,249 ktCO_2 / 8,250 ktC in 2000). This trajectory, presented in Table 2.4 and Figure 2.1, is consistent with what DfT judges the most likely of the possible methodologies for international aviation CO_2 allocation currently being developed.

Table 2.4 **International Aviation SLT (-60%) Trajectory definition**

Trajectory		2000	2005	2010	2020	2030	2040	2050
Aviation SLT (-60)	**Carbon**	156,850	160,085	149,269	127,637	106,004	84,372	62,740
	CO_2			547,320	468,002	388,683	309,365	230,046
	Reduction on 2000			*0%*	*19%*	*32%*	*46%*	***60%***
	Reduction on 1990			*10%*	*23%*	*36%*	*49%*	*62%*

* Constraints imposed in the model from 2010 onwards. 2000 and 2005 values provided for information only.

International aviation demand projections provided by DfT were also added to the baseline MARKAL model. These projections are consistent with the national aviation bunker fuel consumption and CO_2 emissions, i.e. they only account for the first legs of departing (outward) flights from the UK. These projections are presented alongside the existing domestic aviation demand projections in Table 2.5 and Figure 2.2.

Table 2.5 **Domestic and international demand projections, billion vkm**

	2000	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
Air (international)	1.219	1.456	1.849	2.200	2.488	2.730	2.990	3.433	3.799	3.966	4.078
Air (domestic)	0.147	0.177	0.212	0.247	0.313	0.355	0.451	0.511	0.657	0.745	0.974

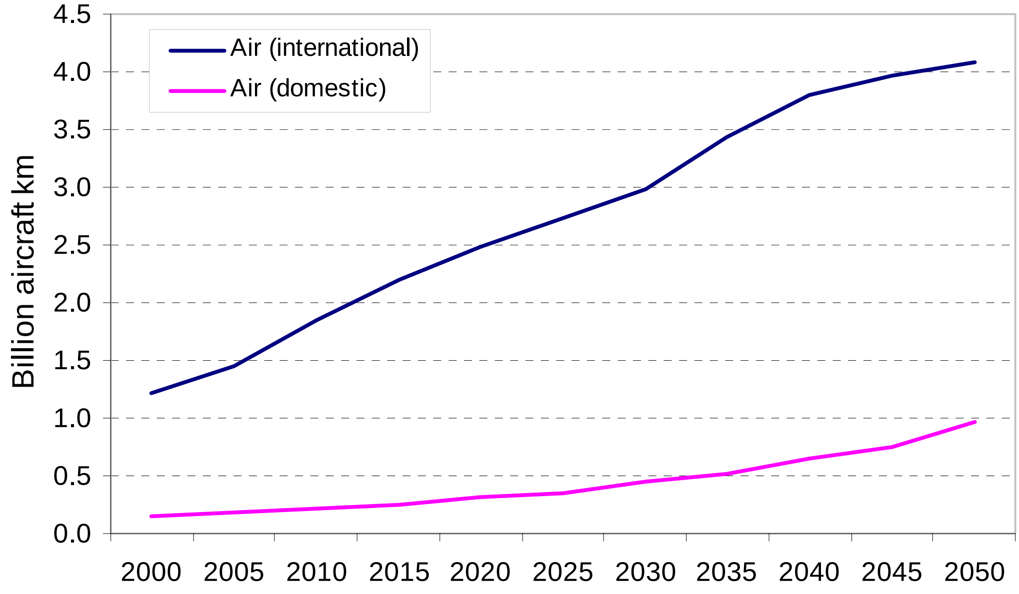


Figure 2.2 Baseline MARKAL domestic and international aviation demand curves

2.2 Model run assumptions

Four runs using the SLT and ALT trajectories were undertaken. Apart from the trajectories and 2050 emission reduction targets, these runs were consistent with the UKERC set of assumptions as outlined in *EWP 07 MARKAL analysis* report.

A further ten runs were undertaken using the SLT but with some changes to key assumptions. Changes to assumptions included:

- Restricted innovation post-2010 (for 80% reduction case)
- Higher resource prices (for 80% reduction case)
- No new nuclear build (for 70% and 80% reduction cases)
- No new nuclear build or introduction of CCS technologies (for 70% and 80% reduction cases)
- Restricted wind generation / biomass use in transport (for 70% and 80% reduction cases plus 80% reduction cases with no nuclear and no nuclear / CCS)

Finally, a further two runs were undertaken to investigate the impacts of international aviation.

Restricted innovation post-2010

A model run was undertaken to assess the impacts of restricting innovation of technologies (post 2010) through reducing improvements in technical performance and reductions in costs. This has been implemented as follows:

- Future technology vintages beyond 2010 are not permitted. This results in costs and performance of technologies restricted to 2010 levels
- Conservation in the base cases is limited to Defra's 2010 estimated potential and held at that level throughout the model horizon
- Conservation in the CO_2 constraint cases post 2010 are limited to approximately 25% of BRE's maximum estimated potentials.

Higher resource prices

As described in Section 2.2.2 of the *EWP 07 MARKAL analysis* report, a set of energy prices provided by DTI was used in the EWP 07 model runs. [7] This model run was undertaken to assess the impact of the high energy price assumptions. Given that energy prices are not input into the model as discrete values, 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.

Restricted wind generation / biomass use in transport

Two striking results of the initial set of model runs under the 80% reduction cases were that: 1) high levels of electricity generation were coming from wind technologies e.g. over 60% in the restricted innovation case in 2050; and 2) the transport sector was using very high levels of biofuel to meet demand e.g. over 85% in the restricted innovation case in 2050.

Further consideration of the results indicated significant uptake of offshore wind in the final period, allowed due to relaxed constraints on new offshore wind build. Biomass was being used exclusively in the transport sector, with the majority of fuel being imported. The most significant contribution to biofuel use in the transport sector was biomass-to-liquid (BtL, 2nd generation biodiesel) fuel. The majority of this was being produced domestically, using imported biomass. The capacity on imports of BtL and production of BtL using domestic biomass had been reached, so imported biomass was the remaining option.

It was decided to undertake a set of model runs where the levels of biomass in the transport sector and generation from wind were constrained. These constraints were implemented as:

- Limit transport biofuel to the maximum levels under the 60% CO_2 reduction SLT case (679PJ, 44% of transport fuel). It would have been better to put this constraint on the resource sector itself but this was deemed too complex in the time available – due to the many different biomass resource streams that would need to be considered. The problem with the actual approach taken is that biomass constraints on transport could result in significant uptake in other sectors.

- A limit of 505 PJ on wind generation was implemented, substantially below the levels used in the 80% CO_2 reduction SLT runs (ranging from 820PJ to 1320PJ). The 505 PJ value is based on information from the DTI Renewables Innovation Review[8] on the low end potential for onshore and offshore wind (high end potential was about 645PJ).

No new nuclear or CCS build

In a carbon-constrained system, nuclear and CCS often play an important role in the electricity generation sector, particularly in the post-2030 period. Two sensitivity runs have been undertaken to explore how the modelled system responds when no new nuclear build is permitted in future years, and a situation where no new nuclear build is permitted and CCS technologies are not deployed.

The role of nuclear in future years has been subject to an ongoing Government consultation (now closed), making these sensitivities important for exploring alternative options to nuclear power in the electricity generation sector. CCS is an emerging technology that will be subject to a demonstration programme over the next 10 years. Following successful demonstration, it is hoped there will be full-scale commercial deployment. Given the uncertainties around this emerging technology, i.e. it has not been demonstrated as an integrated process, this sensitivity run is an important one to undertake.

Both sensitivity cases have been run under 70% and 80% constraints. In addition, the 80% no nuclear constrained run has also been run with wind and biomass constraints. This version of the model has limited or relaxed constraints on offshore wind and imported biomass, and therefore an 80% emission reduction target in 2050 result in significant take-up of wind generation, and biomass in the transport sector. These constraints force the model to use other types of energy.

[7] *Updated Energy Projections* (updated from EP-68), Department of Trade and Industry, July 2006
[8] Renewables Innovation Review website - http://www.dti.gov.uk/energy/sources/renewables/policy/government-renewable-energy-policy/renewables-innovation-review/page15308.html

International aviation

Model runs to include the international aviation sector within 60% emission reduction targets in 2050 (baseline and aviation 60% SLT) have been undertaken to investigate the following questions:

- What happens in the aviation sector when constraints are applied compared to the baseline? What are the effects in terms of technology change, demand response and CO_2 emissions?
- How does the inclusion of international aviation affect the effort required from the rest of the transport sector?
- How does the inclusion of international aviation affect the rest of the energy system and wider economy?

Adding international aviation demand in the model has required re-calibration to develop a new baseline consistent with the projected international aviation (and other sector) demands. There are three technological choices (vintaged at each 10 year period) available to meet the international aviation demand:

1. Standard kerosene fuelled jet aircraft
2. Advanced airframe design (e.g. Blended Wing-Body concept) kerosene fuelled jet aircraft (only available after 2020)
3. Hydrogen fuelled jet aircraft (only available after 2020)

High efficiency Blended Wing-Body (BWB) aircraft design is mainly appropriate for long-haul aircraft categories and is likely not to be suitable for smaller airports. Therefore their take-up was constrained to a maximum share of 50% of capacity of the international aviation technology mix.

The technical and costs assumptions on the technologies used in the international aviation sector can be found in Annex 5.

3 Model results and analysis

The results of the model runs, described in the previous section, are presented and discussed in this section under the following three headings:

- **System evolution** –focuses on changes over time on energy use (primary and final) and resulting CO_2 emissions.
- **Technology pathways** –provides an overview of how the technology mix in two key sectors – electricity and transport – develops over the time horizon plus the role of demand responses in the model.
- **Economic impacts** –assesses the changes in costs of the energy system, marginal costs of abatement and impacts on GDP.

This section provides a summary of the results outputs. Additional results are presented in the annexes and accompanying results spreadsheets. **Results and analysis for the aviation runs are presented separately in section 3.4.**

3.1 System evolution

Primary energy

The trends in total primary energy use for the different levels of 2050 constraints, for both types of trajectory (SLT and alternative) are presented in Figure 3.1. The base case shows primary energy falling in the period to 2030 and rising significantly thereafter. This reduction to 2030 reflects the fact that the base case is also cost-optimising despite the lack of emission constraints. This is primarily due to the availability of cost-effective transport technologies to meet demand, and the cost-effective potential of energy conservation across end-use sectors (excluding transport).

As constraints are imposed from 2010 onwards, the energy system responds by using more efficient technologies (and therefore less energy), more conservation measures. Energy consumption also decreases due to a demand response in end-use sectors, reflecting increasing energy prices. Figure 3.1 illustrates the reduction in primary energy requirements, increasing as constraints get tighter. The alternative trajectory cases have lower primary energy demands in earlier years, due to the more stringent constraints in earlier years. An interesting anomaly is the slightly higher primary energy use under the 70% reduction case than under the 60% reduction case in 2030; it is not clear why this trend occurs but will be due to the technology choices and demand response in that given period, within the emission constraints imposed.

Figure 3.2 shows total primary energy for restricted innovation and higher resource cost cases. Under the restricted innovation base case, the total primary energy requirements are much higher than in other cases (as more efficient cost-effective technologies are less available). An 80% constraint does lead to reductions but not to the same extent as seen in the standard SLT 80% reduction case. The opposite is true of the higher resource price case, where primary energy demand is lower due to the higher resource costs.

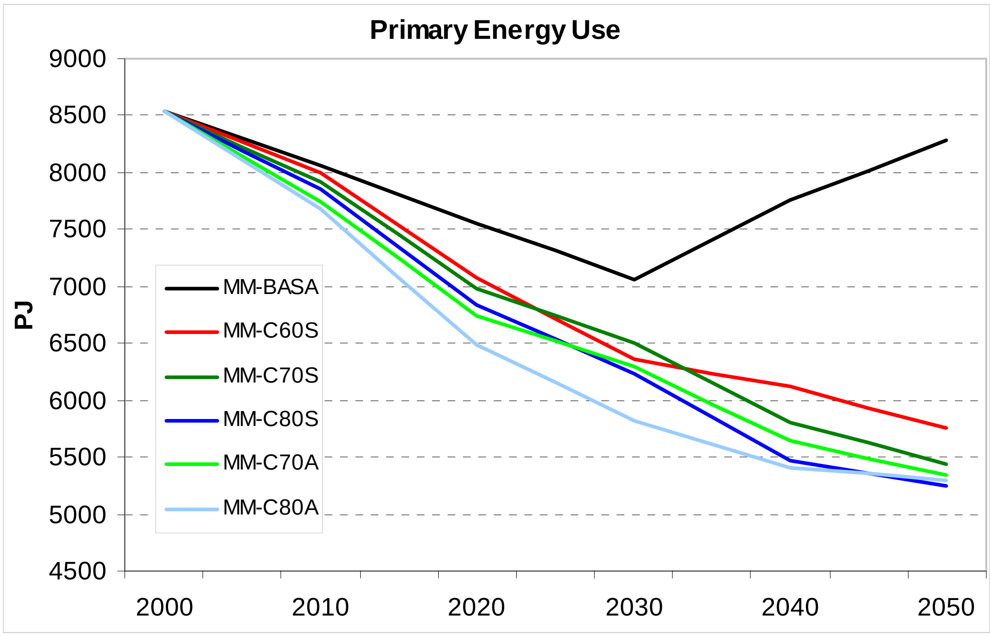


Figure 3.1 Comparison of the trend in total primary energy use for baseline and constrained (SLT / ALT) CO_2 runs

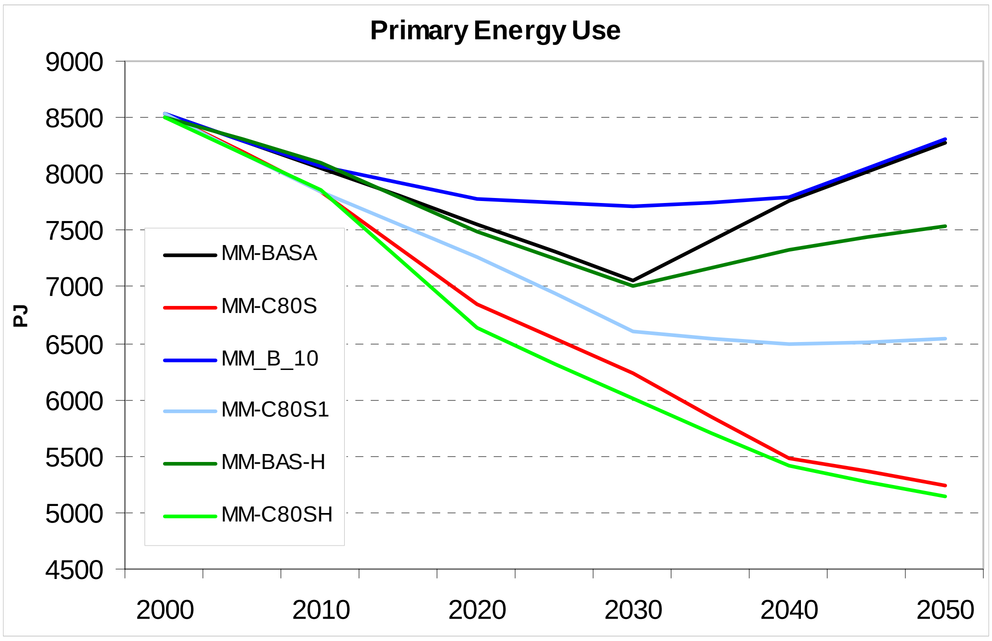
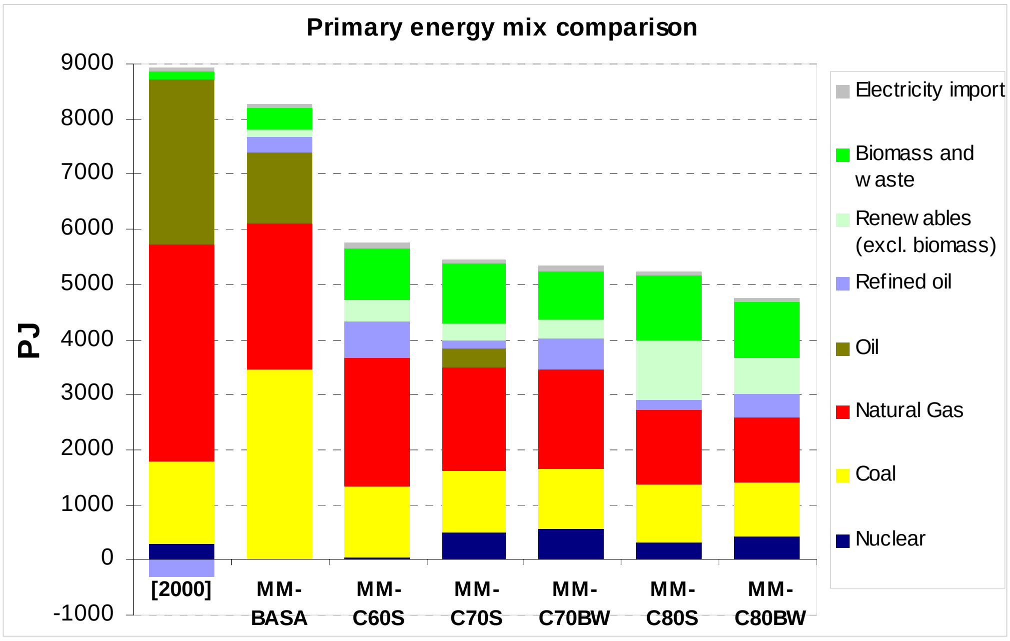


Figure 3.2 Comparison of the trend in total primary energy use for high resource costs and restricted innovation baseline and constrained (SLT) CO_2 runs

Differences in the type of energy being used in the system help provide a more detailed understanding of the impacts of very stringent constraints on CO_2 emissions. Compared to the 60% SLT constraint, shown in Figure 3.3, differences in 2050 under a 70% reduction include use of nuclear in the electricity generation sector and lower levels of oil due to less use of fossil fuel in the transport sector. The shift to crude rather than refined suggests that it may be more cost-effective to refine oil products in the UK rather than import. In the 70% case where biomass / wind restrictions are imposed (MM-C70BW), levels of refined oil are comparable with the 60% reduction case but no crude oil is now in the mix, suggesting only imports of refined oil products. An 80% constraint leads to much higher levels of renewable use, driven by electricity generation from wind. Natural gas use is noticeably lower, with end use sectors shifting from natural gas to the use of low carbon electricity, primarily in the residential sector (gas boilers to electric boilers).

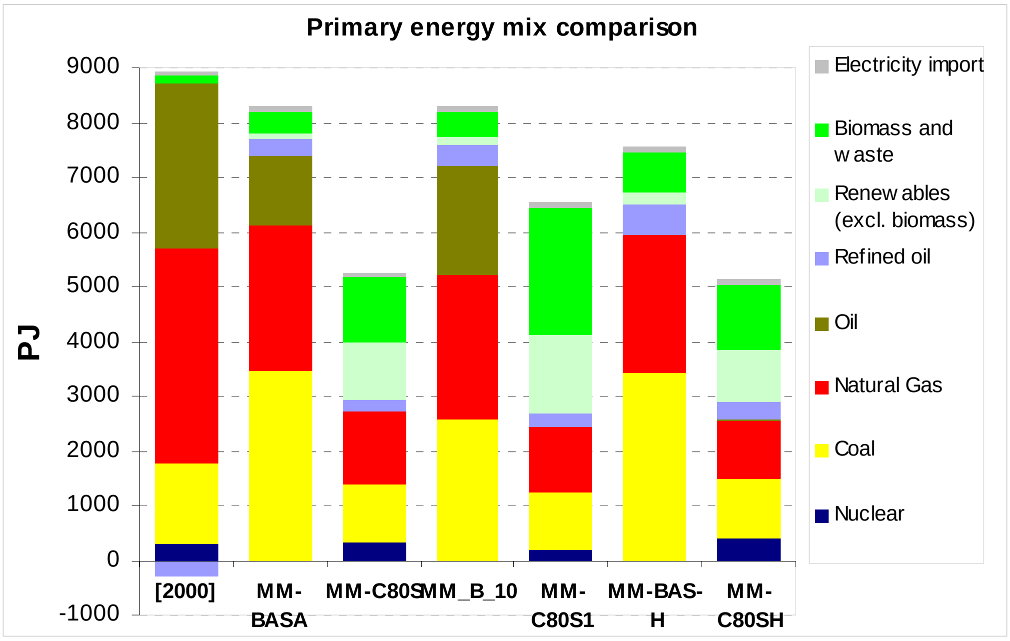
Given the constraints on biomass and wind generation in MM-C80BW, the energy use profile that emerges is one that would be expected. Petrol and diesel use (refined oil) increases while biomass decreases as less is used in the transport sector. Due to the constraints on wind generation, the level of renewables is significantly lower.



NB. Negative value in 2000 reflects net exports of refined oils. Note that CO_2 emissions from electricity imports are not accounted for in the UK inventory.
The alternative trajectory fuel mixes have not been included in the graph below as they are virtually the same as the SLT cases.

Figure 3.3 Comparison of the 2050 primary energy use by fuel for baseline and constrained (SLT / ALT) CO_2 runs

Type and level of primary energy use in 2050 is shown in Figure 3.4 for the restricted innovation and high resource price cases (against their relevant base cases). The restricted innovation base case (M_B_10) shows higher levels of oil and lower levels of coal than seen in the standard base case (MM-BASA). Under a constraint, overall energy use decreases while the use of renewables energy and biomass increases significantly, to levels much higher than observed under the 80% constraint case (MM-C80S). The higher levels of primary energy reflect the lower levels of system efficiency due to the restrictions on innovation. Under the high resource price case, a similar energy mix to the 80% constraint case is observed.



NB. Negative value in 2000 reflects net exports of refined oils. Note that CO_2 emissions from electricity imports are not accounted for in the UK inventory.

Figure 3.4 Comparison of the 2050 primary energy use by fuel for high resource costs and restricted innovation baseline and constrained (SLT) CO_2 runs

A number of sensitivities were also run under 70% and 80% SLT constraints to explore the impact of new nuclear build and CCS **not** being available options for future electricity generation. In 2050, under the 70% case, with no nuclear permitted overall primary energy levels fall and levels of renewable generation increase. Removing CCS technologies leads to further reductions in overall primary energy levels further, and increasing contribution from renewables. A similar pattern is observed under the 80% reduction cases.

An additional sensitivity on the 80% cases was to explore the impact of removing these key technologies but with additional constraints on wind and biomass resources (see section 2.2 for assumptions). In the no nuclear case (MM-C80NC), a reduction in overall energy use and significant increase (of 100%) in gas use is observed (primarily due to the uptake of gas CCS in the generation sector). In the no nuclear / CCS case, overall primary energy use is significantly lower (less than 4000 PJ compared to 5000 PJ in MM-C80S). This significant reduction in primary energy is enabled by a significant demand response in end use sector, high levels of conservation, and the increased uptake of more efficient technologies.

Final energy

This section explores changes in final energy use, moving from an energy system with no constraints to one with required reductions of 80% by 2050. The final energy consumptions provides an indication of how the system is responding to such constraints – types of fuels used in end use sectors due to technological change or fuel switching, and the quantity of fuel reflecting efficiencies of chosen technologies and changes in the endogenous demand response.

Figure 3.5 shows final energy use under the base case, and for SLT and ALT 70% and 80% constrained cases. Under the base case, total energy use rises by about 2% by 2050 relative to 2000 levels. Reductions of around 9% are initially seen in 2030 (relative to 2000 levels) as the model looks for cost-effective energy provision even in the absence of constraints. As discussed in the previous section, much of this reduction is due to technological change in the transport sector, with a large increase in the numbers of hybrid vehicles.

As CO_2 constraints on the system increase, final energy use significantly decreases due to uptake of more efficient technologies and increase demand reductions in end use sectors. In cumulative terms, under the ALT cases, final energy use is even lower due to the imposition of tighter constraints across the emission reduction trajectory.

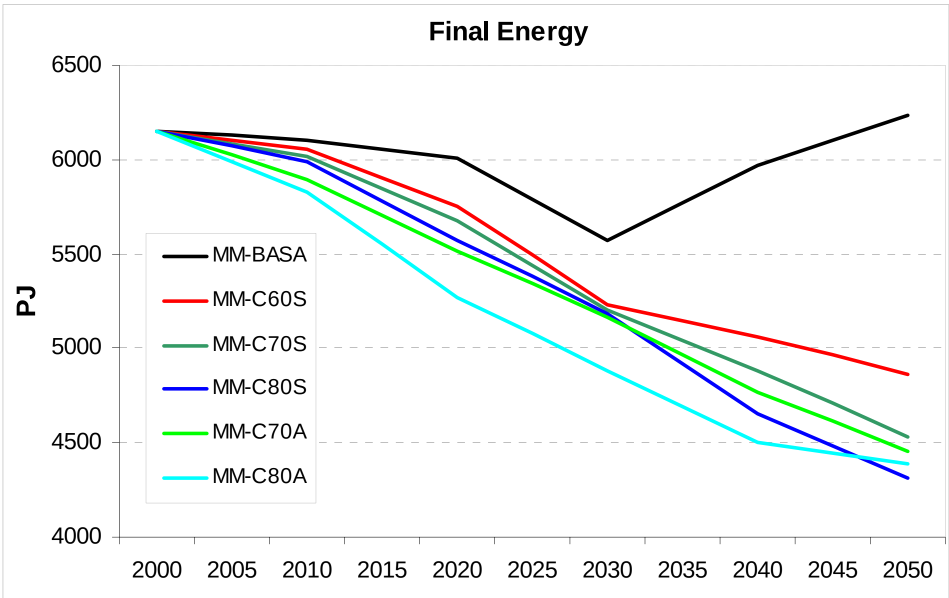
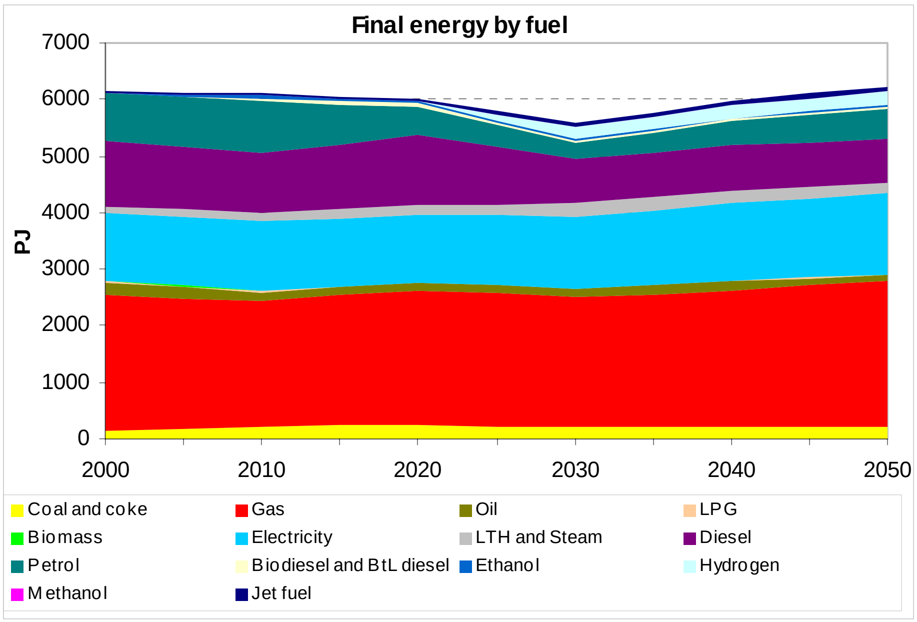


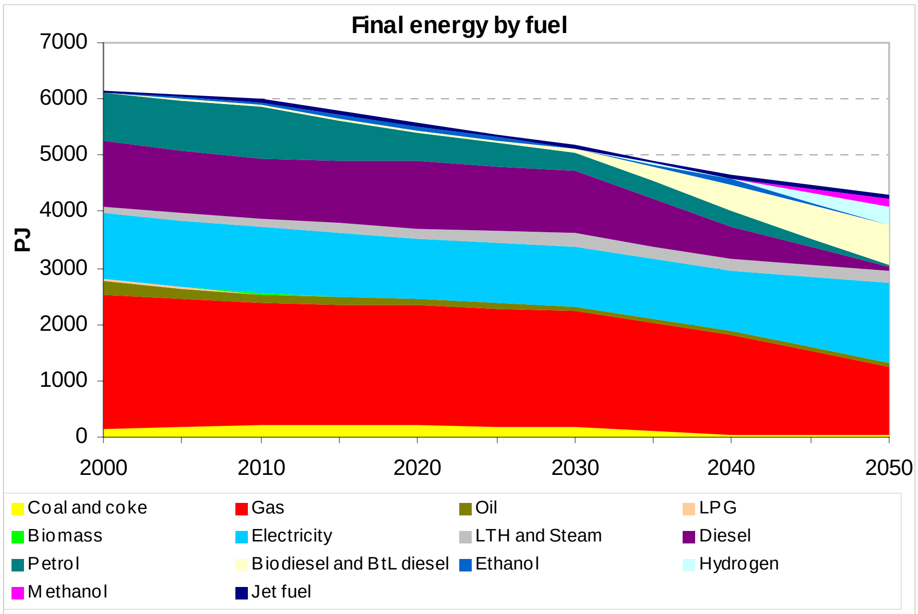
Figure 3.5 Comparison of the trend in total final energy use for baseline and constrained (SLT / ALT) CO_2 runs

Changes in final energy use by fuel for the 80% constrained (SLT) case are shown in Figure 3.6. In the base case, it is primarily the reduced levels of diesel and petrol consumption due to the uptake of hybrid vehicles and hydrogen vehicles that causes the overall reductions in 2030 observed in previous figures. Other types of fuel use remain relatively stable over the time period, growing at relatively slow rates.

Under the 80% constrained case (MM-C80S), changes in the transport sector lead to a much increased use of biomass and the complete reduction in the use of petrol / diesel. Coal and coke use declines by 2040 / 2050, as such carbon intensive fuels are no longer used (except in CCS (Carbon Capture and Storage) technologies). Natural gas use in the residential sector also declines in use due to the significant increases in the price of this resource in later time periods. Electricity becomes a much more important source of energy for the residential sector, with electric boilers replacing gas boilers. In 2050, residential natural gas use is at 580 PJ, dropping from a level above 1000 PJ (in 2040). Electricity use increases from 430 PJ (in 2040) to 860 PJ in 2050.



MM-BASA



MM-C80S

Figure 3.6 Final energy consumption by fuel for base case and SLT 80% constrained case

Under the biomass / wind constrained runs, energy use in the 70% case closely matches that observed in the standard SLT 70% constrained case. However, under an 80% constraint, final energy drops significantly relative to the standard 80% case. In 2050, total energy use is approximately 10% lower, primarily due to a reduction in the use of gas in the residential sector.

The higher resource price base case (MM-BAS-H) is intuitively lower than the standard base (MM-BASA) – although follows a similar trend over time - as the higher price of energy has an impact on consumption in end use sectors. From this lower base case, under an 80% constraint, final energy use is significantly lower as the energy system moves towards a lower carbon economy. The restricted innovation case shows much higher final energy consumption than under the standard base case due to the lack of available high efficiency technologies and opportunities for energy conservation. The lack of innovation is reflected with no reduction in consumption to 2030, as seen across all other model runs. As with the other cases, reductions in demand result from CO_2 constraints.

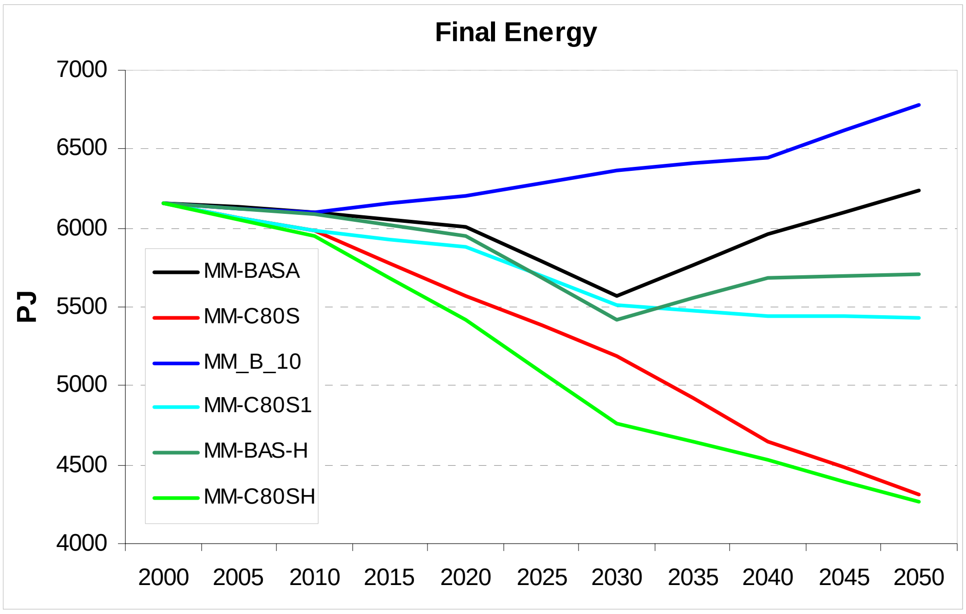


Figure 3.7 Comparison of the trend in total final energy use for baseline and constrained (SLT) CO_2 runs with restricted innovation and high resource costs

Under the sensitivities run to explore the impact of new nuclear build and CCS **not** being options for future electricity generation, limited differences can be seen relative to the standard SLT 70% and 80% cases. When wind generation and biomass resource constraints are imposed, reductions in demand in 2050 relative to the SLT 80% case are 11% under no nuclear case and 19% under the no nuclear / CCS case. Such reductions are due to end use sector demand response, conservation (see *Demand response* in section 3.2) and the uptake of more efficient technologies.

CO_2 emissions

The objective of this work is to understand how the energy system meets even more stringent constraints than those considered in the *EWP 07 MARKAL analysis*. What is therefore most interesting is to compare differences between abatement levels across different sectors and any differences concerning timing in abatement over the model horizon.

Figure 3.8 shows a comparison of CO_2 reductions in 2020 based on the different level of 2050 constraint (70% or 80%) and type of trajectory (SLT or ALT). Under the alternative (ALT) trajectories in 2020, CO_2 reduction requirements are greater than under the SLT case, and therefore more abatement is required. For both the ALT cases, greater reductions are seen in the electricity generation sector, primarily due to the earlier investment in coal CCS. In the ALT 70% reduction case, the transport sector has lower emissions relative to the baseline – as opposed to higher emissions in the SLT case,[9] whilst in the ALT 80% reduction case, transport plays an even more significant role, both in absolute terms and in terms of contribution to abatement. This is due mainly to the uptake of diesel hybrid cars, which account for around 60% of the car fleet in 2020. A small amount of BtL biodiesel is also introduced, which contributes to reducing the emissions although to a lesser extent. The residential sector also becomes an increasingly important sector for CO_2 reduction opportunities as constraints tighten, whilst services and industry remain at similar levels.

It is important to recognise that Figure 3.8 has not allocated 2020 savings from electricity production to end-use sectors. If allocated, it is clear that all sectors play a significant role in reducing emissions.

[9] Small increases in emissions relative to the baseline in the transport sector reflect the trade-offs between choice of technologies and required emission reductions in different sectors.

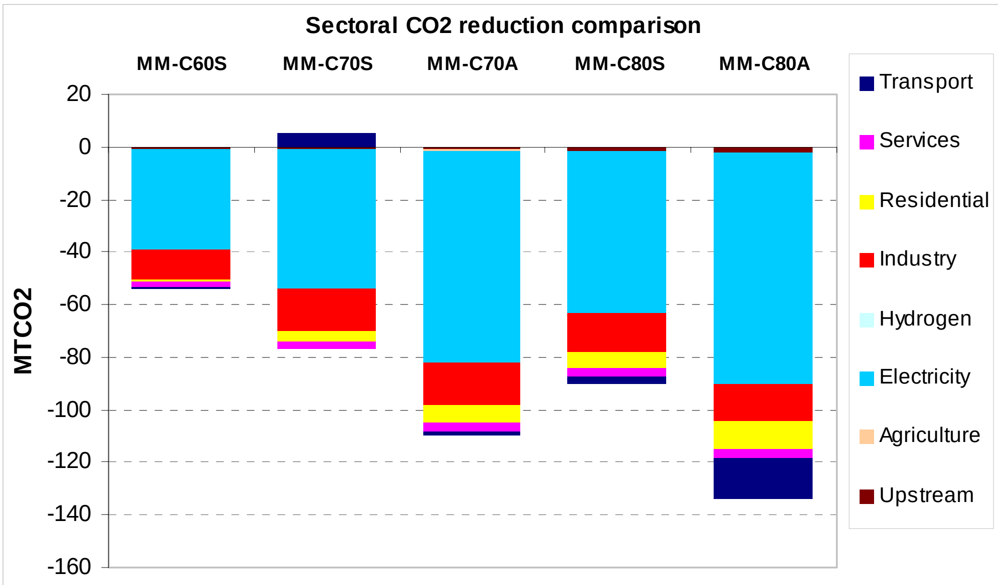


Figure 3.8 Comparison of the reduction in CO_2 emissions by sector in 2020 based on SLT and ALT trajectory cases

Figure 3.9 provides information on CO_2 reductions across sectors in 2030; an interesting pattern emerges concerning how emission reductions are accounted for. It appears that the transport sector has started emitting significantly more relative to the baseline; however, this is not the case as the emission reductions associated with hydrogen are transport-related but accounted for separately. Another interesting observation in the 80% constrained ALT run is that lower levels of abatement occur in industry compared to other runs, whilst emissions are relatively lower from the transport sector. Another way to consider emission reductions is by end use sector – see Figure 3.10 - where reductions in electricity and hydrogen production are allocated to end use sectors on the basis of where electricity and hydrogen are used. As can be seen, all sectors including transport, are contributing to overall reductions.

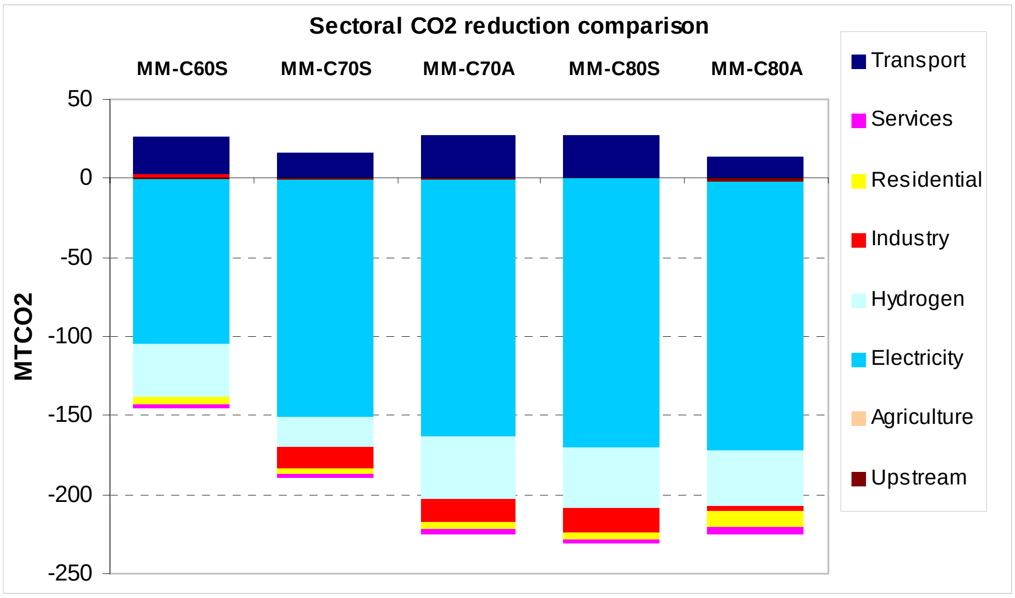


Figure 3.9 Comparison of the reduction in CO_2 emissions by sector in 2030 based on SLT and ALT trajectory cases

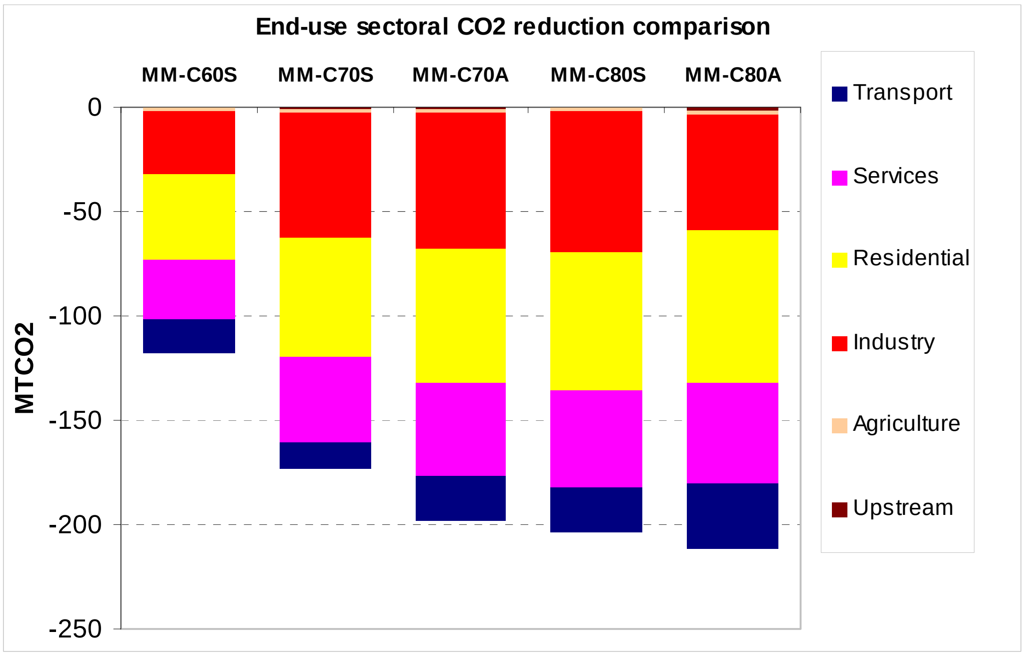


Figure 3.10 Comparison of the reduction in CO_2 emissions by END-USE sector in 2030 based on SLT and ALT trajectory cases

Finally, the emission reductions in 2050 are presented in Figure 3.11 and Figure 3.12. Limited variation is now seen between the two trajectories in terms of contribution of sectors to abatement (as they have now converged). In terms of sectoral contribution, the electricity sector contributes an additional 50 $MtCO_2$ reduction. The reductions from the transport sector are also much more significant (excluding those from hydrogen) as the sector virtually decarbonises in the 80% reduction cases, switching to high biofuel penetration to replace conventional transport fuels such as petrol and diesel. The residential sector also contributes more in absolute terms.

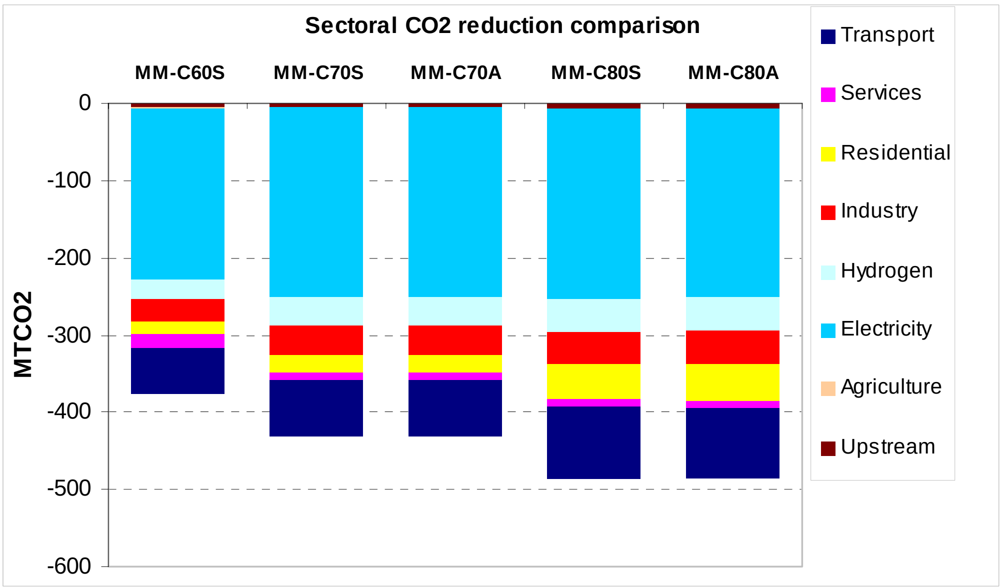


Figure 3.11 Comparison of the reduction in CO_2 emissions by sector in 2050 based on SLT and ALT trajectory cases

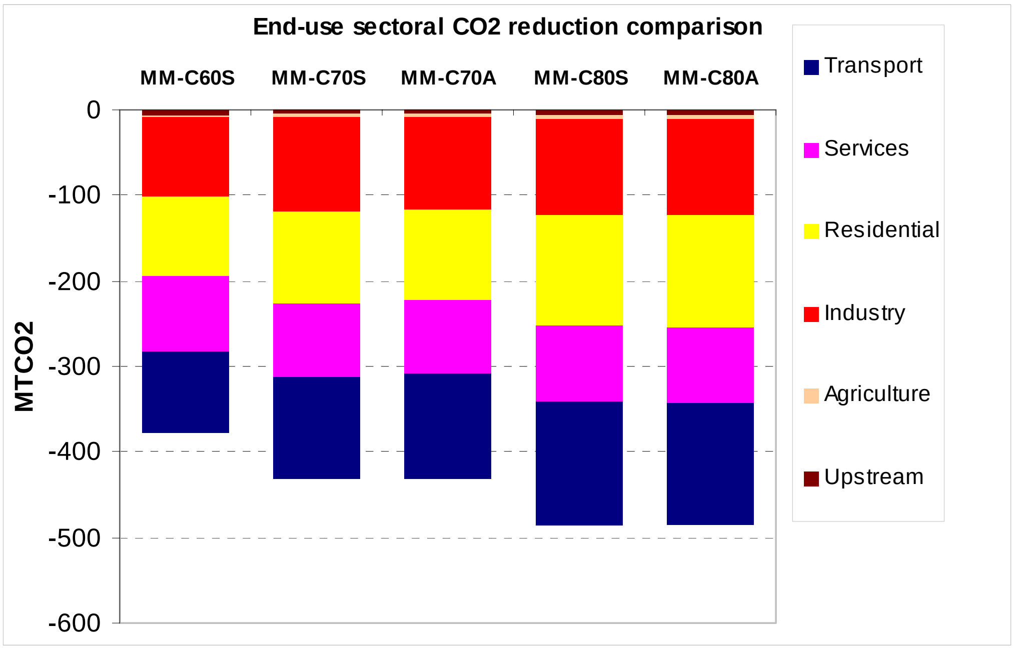


Figure 3.12 Comparison of the reduction in CO_2 emissions by END-USE sector in 2050 based on SLT and ALT trajectory cases

The above emission reductions have also been presented as cumulative emission reductions below in Table 3.1, Figure 3.13 and Figure 3.14. In particular, this illustrates the higher reductions under the alternative trajectory cases.

A number of interesting observations in 2050 can also be made from the other runs that were undertaken. Under the restricted wind generation / transport biomass cases (MM-C70BW / MM-C80BW), the transport sector has lower levels of abatement, particularly under the 80% case (76 $MtCO_2$ compared to 93 $MtCO_2$). Additional abatement is therefore undertaken in the residential sector (62 $MtCO_2$ compared to 46 $MtCO_2$). The electricity generation sector can still provide the same contribution to overall abatement in the 80% reduction case, using other low carbon technologies instead of wind (gas CCS and nuclear).

The restricted innovation case (MM-C80S1) realises a higher level of reduction from the residential sector but less from industry, presumably indicating that abatement measures are cheaper in this sector in an energy system that has not been able to innovate on low carbon technologies.

Table 3.1 Cumulative CO_2 reductions relative to base from 2000 in 2010 - 2050 (relative to base cases)

Total Cumulative CO_2 reductions, $MtCO_2$	MM-BASA	MM-C60S	MM-C70S	MM-C70A	MM-C80S	MM-C80A
2010	0.0	-27	-60	-140	-104	-183
2020	0.0	-344	-504	-848	-676	-1,068
2030	0.0	-1,235	-1,778	-2,428	-2,197	-2,832
2040	0.0	-3,112	-4,207	-5,039	-4,996	-5,757
2050	0.0	-6,287	-7,933	-8,821	-9,214	-10,046

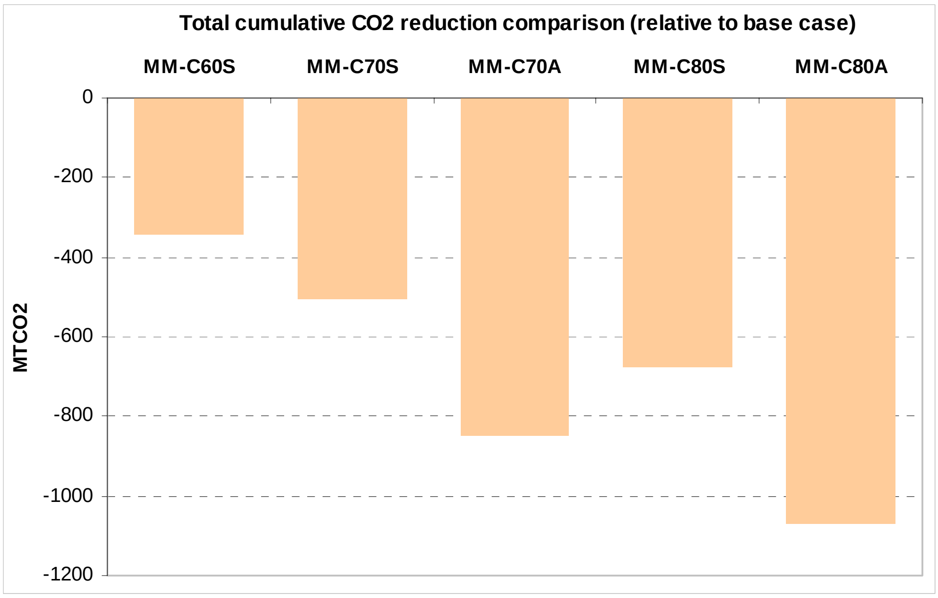


Figure 3.13 Cumulative CO_2 reductions relative to base from 2000 in 2020 for SLT / ALT core cases

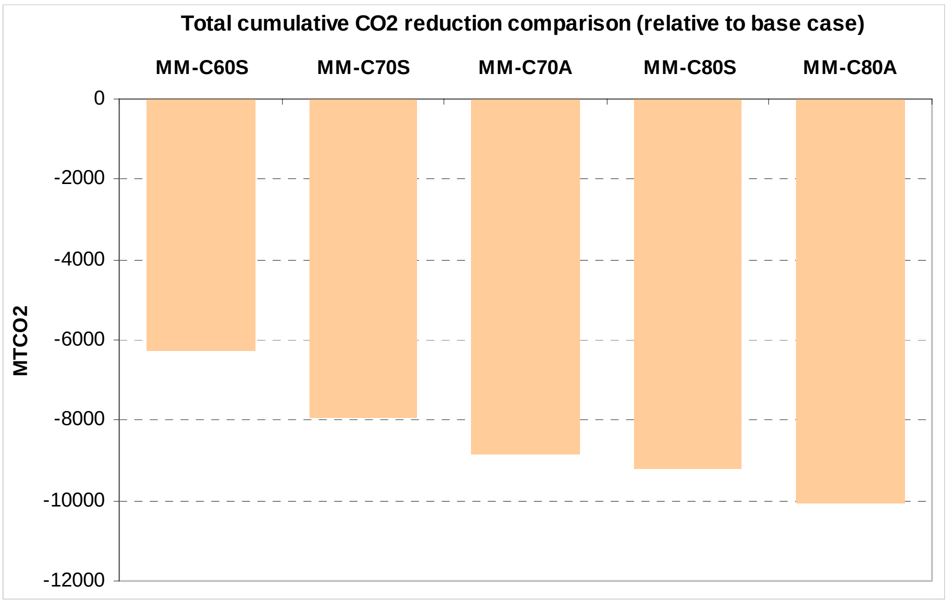


Figure 3.14 Cumulative CO_2 reductions relative to base from 2000 in 2050 for SLT / ALT core cases

The following Table 3.2 and Figure 3.15 also show the increasing level of decarbonisation of the electricity and hydrogen sectors as CO_2 constraints are tightened (hydrogen is only taken up from 2030). By 2050 electricity production is almost completely decarbonised in almost all cases. Higher levels of decarbonisation of hydrogen production generally occur at higher CO_2 constraints compared to electricity generation. The reduction in emissions from hydrogen production generally reflects a switch from production of hydrogen from fossil fuel sources to production by electrolysis.

Table 3.2 CO_2 emissions per kWh for electricity and hydrogen in 2000-2050 for selected model runs

CO_2 emissions from electricity sector, $kgCO_2/kWh$	MM-BASA	MM-C60S	MM-C70S	MM-C70A	MM-C70BW	MM-C80S	MM-C80A	MM-C80BW
2000	0.573	0.573	0.573	0.573	0.573	0.573	0.573	0.573
2010	0.521	0.512	0.506	0.496	0.506	0.498	0.479	0.498
2020	0.490	0.400	0.362	0.273	0.359	0.335	0.251	0.346
2030	0.556	0.293	0.152	0.113	0.152	0.089	0.086	0.101
2040	0.596	0.158	0.075	0.082	0.074	0.066	0.077	0.071
2050	0.650	0.115	0.040	0.050	0.042	0.033	0.039	0.036

CO_2 emissions from hydrogen sector, $kgCO_2/kWh$	MM-BASA	MM-C60S	MM-C70S	MM-C70A	MM-C70BW	MM-C80S	MM-C80A	MM-C80BW
2030	0.682	0.682	0.683	0.682	0.727	0.683	0.241	0.241
2040	0.682	0.587	0.253	0.241	0.310	0.004	0.072	0.107
2050	0.682	0.300	0.141	0.084	0.059	0.000	0.000	0.029

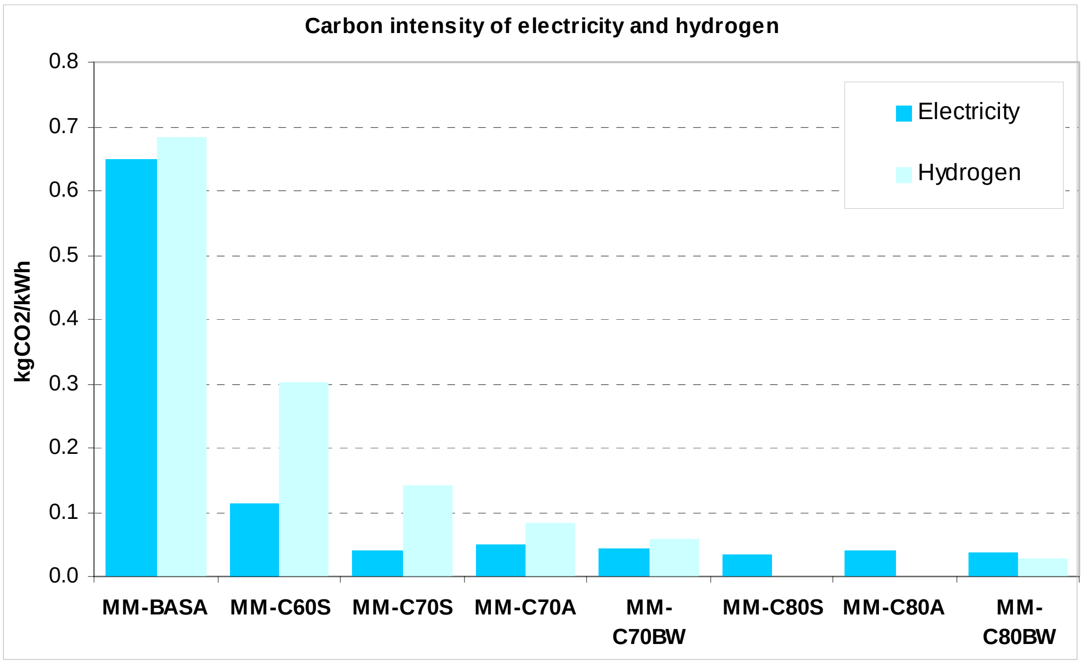


Figure 3.15 CO_2 emissions per kWh for electricity and hydrogen in 2050 for selected model runs

3.2 Technology pathways

Electricity generation

As shown in the previous section on CO_2 emission reductions, the electricity generation sector plays a key role in enabling the UK energy system to move to a lower carbon system. The sector therefore undergoes radical changes, from a sector in the base case dominated by new coal plant to one made up of low carbon generation technologies.

Figure 3.16 shows the generation mix from 2000 to 2050 under the 70% SLT constraint. The main difference with the 60% SLT case is the significant uptake of nuclear in 2050 (and the resulting lower levels of wind and coal CCS generation). The overall level of generation is higher in 2050. Other smaller differences include earlier penetration of coal CCS (in 2020 albeit at a low level) and no gas-based generation in 2050.

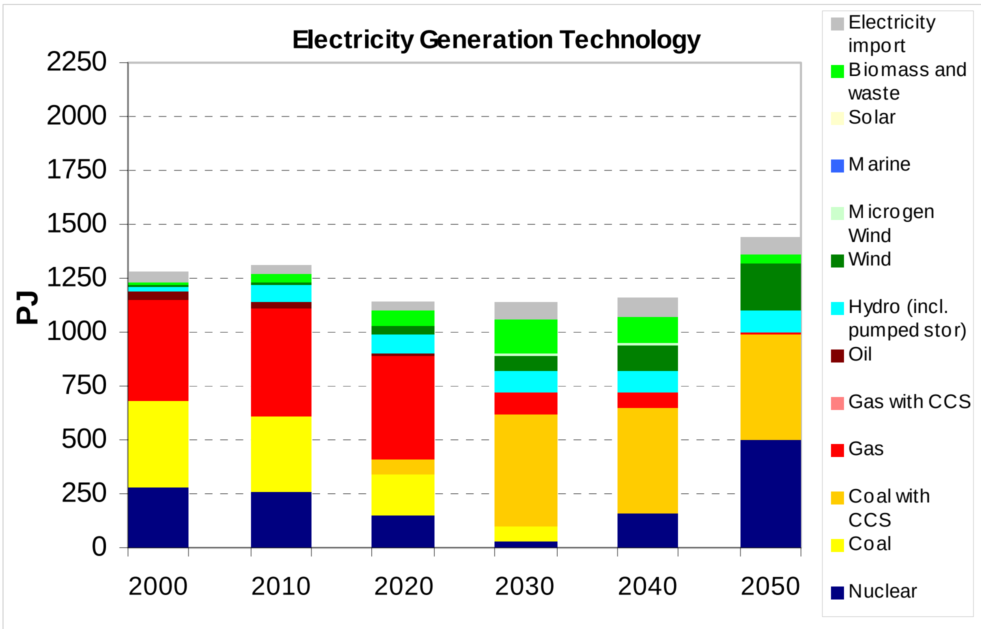


Figure 3.16 Comparison of the electricity generation by fuel technology for 70% constrained (SLT) CO_2 runs

Figure 3.17 shows the situation under an 80% constraint. Wind generation plays an increasingly important role post-2020, and particularly in 2050 with the significant increase in the level of electricity generation. The costs of additional network capacity required for this increase in transmission are included in the model. The additional electricity demand appears to be due to a switch from gas boilers to electric boilers in the final period. Very high levels of wind generation are reached (and in the restricted innovation model run (MM-C80S1)) due to limited constraints on offshore wind technologies. By 2050, wind appears to be cost-competitive with nuclear, the costs of which remain at the same across the time period. In future modelling work, there may need to be further consideration of the relative competitiveness of these technologies, with consideration of limits on intermittent renewables and costs over time of nuclear. It is our understanding that assumptions concerning wind have been revisited since the EWP 2007 analysis, with more account taken of intermittency across wind technologies through the need for storage technologies, thereby increasing costs. Other technology categories that feature at a low level include gas CCS (from 2030) and marine technologies in 2050.

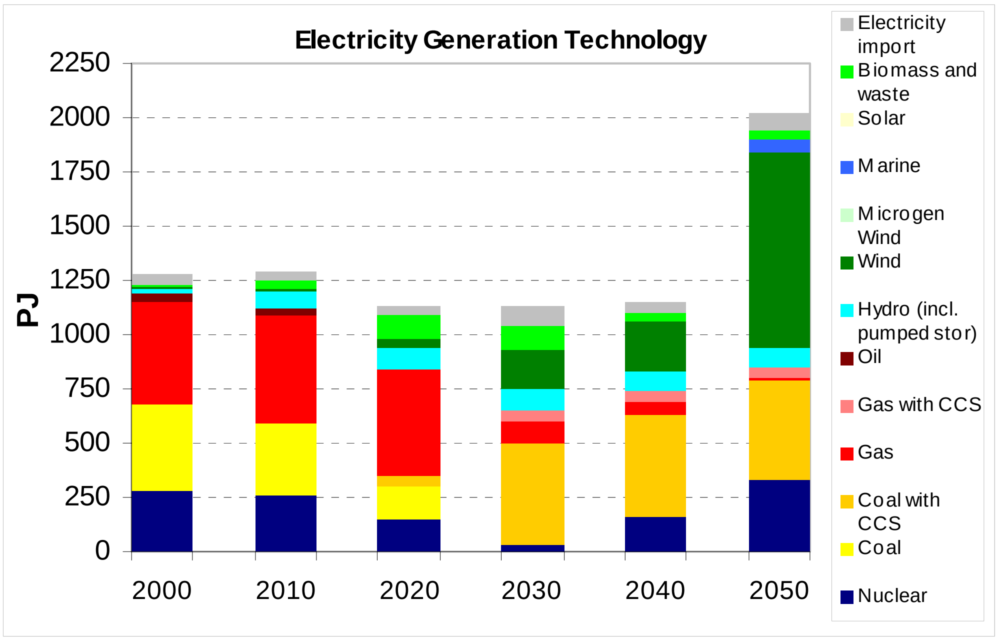


Figure 3.17 Comparison of the electricity generation by fuel technology for 80% constrained (SLT) CO_2 runs

Three important observations emerge from the results relative to the comparable 60% reduction case:

- Overall electricity generation is higher under both the 70% and 80% cases driven by increasing end-use sector demand plus hydrogen production from electrolysis
- Nuclear emerges as an important technology contributing to electricity generation in 2040 / 2050, due to increases in electricity demand and the increased constraint level resulting in lower levels of gas generation.
- Coal CCS and wind generation remain as important low carbon generation technologies

In most cases, CCS (coal) appears to be meeting its storage limits due to the annual storage limits within the model and does not increase in the higher constrained runs. This seems surprising given some recent studies have suggested the UK sequestration resource might be sufficient for hundreds of years of storage of CO_2 from fossil plant with CCS at projected energy demands. It is clear that the annual limits on transport and storage may be relatively conservative. The storage and transport issues are currently being reviewed under the UKERC modelling research programme.

The generation mix in 2050 across the SLT and ALT (alternative) constrained model runs is shown in Figure 3.18. The alternative trajectory cases (MM-C70A / MM-C80A) do not provide any additional insights when compared in 2050. However, the more stringent constraints in 2020 lead to the uptake of coal CCS in 2020, and a more rapid reduction in conventional coal plant.

Restricted wind generation scenarios (MM-C70BW / MM-C80BW) are also shown in Figure 3.18. Limited change in 2050 (and across the time horizon) is observed, as the wind constraint does not affect levels observed in the 70% constrained case (see Figure 3.16). However, in the 80% constraint case, the wind constraint (of 505 PJ) does have an impact, significantly reducing wind generation, and overall levels of generation. As a result, gas CCS generation is much more significant and levels of nuclear generation are higher.

Figure 3.19 shows the impact of higher resource costs and restricted innovation (post-2010) on the electricity generation sector. In the higher resource cost case (MM-C80SH), a similar generation picture can be seen as that observed for MM-C80S. Marine becomes part of the technology mix earlier, in 2040, while very low levels of microgeneration can also be observed. The restricted innovation case (MM-C80S1) run results in an even higher level of electricity generation than MM-C80S. Wind generation dominates, accounting for approximately 60% of total generation. The question of interest is why the model prefers the offshore wind technology to additional nuclear generation or more CCS (which has not hit its storage capacity bounds). Under the restricted innovation case, block investment in the AP1000 cannot be taken due to forced constraints; the model therefore invests in the more expensive non-block investment.[10] The costs of the non-block investment option remain the same over time (as they do for the block investment option); such assumptions may need to be re-considered in the future to take account of learning in building this type of nuclear plant. Despite being fixed at 2010 cost and efficiency levels, offshore wind is able to compete with this more expensive nuclear option.

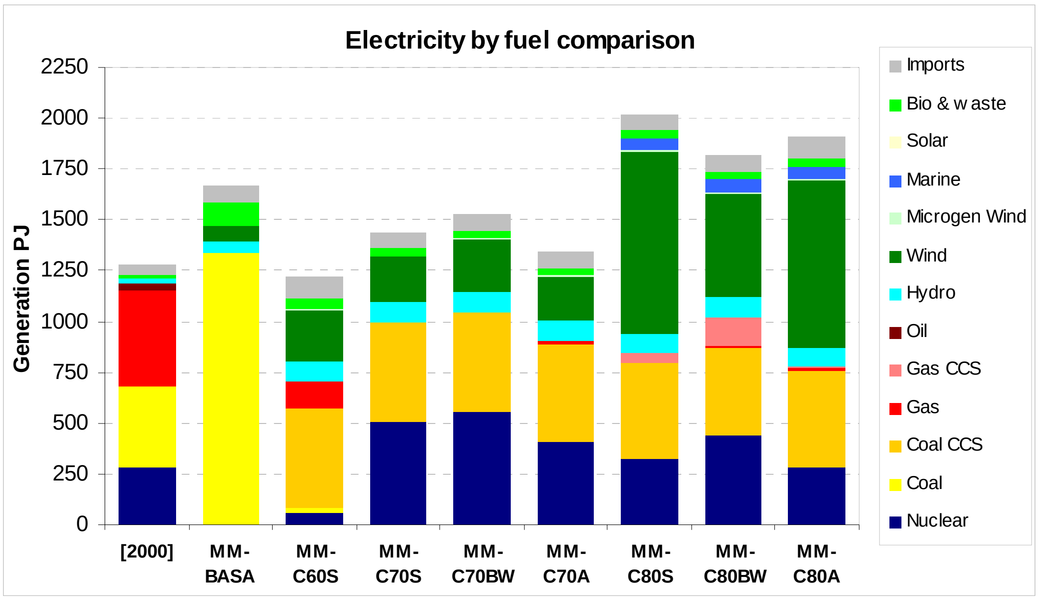


Figure 3.18 Comparison of the 2050 electricity generation by fuel technology for baseline and constrained CO_2 runs

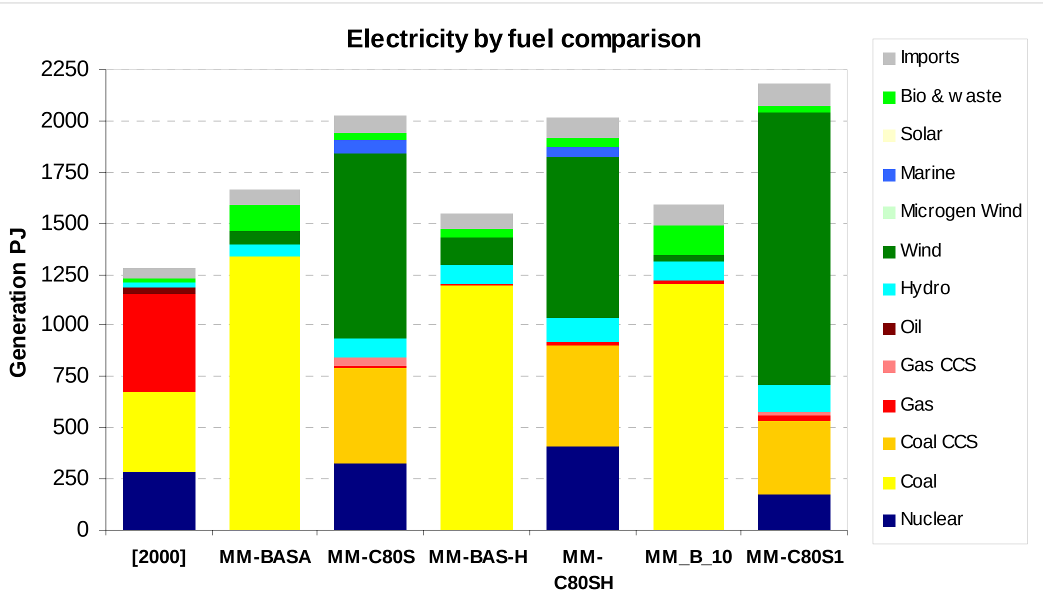


Figure 3.19 Comparison of the 2050 electricity generation by fuel technology for baseline and 80% constrained CO_2 runs, including restricted innovation and higher resource cost cases

The results of sensitivity runs to explore how the electricity sector changes in future years in the absence of new nuclear build and CCS technologies is shown in Figure 3.20.

[10] The removal of the block investment technology is a way of modelling restrictions in innovation of 3rd generation technologies.

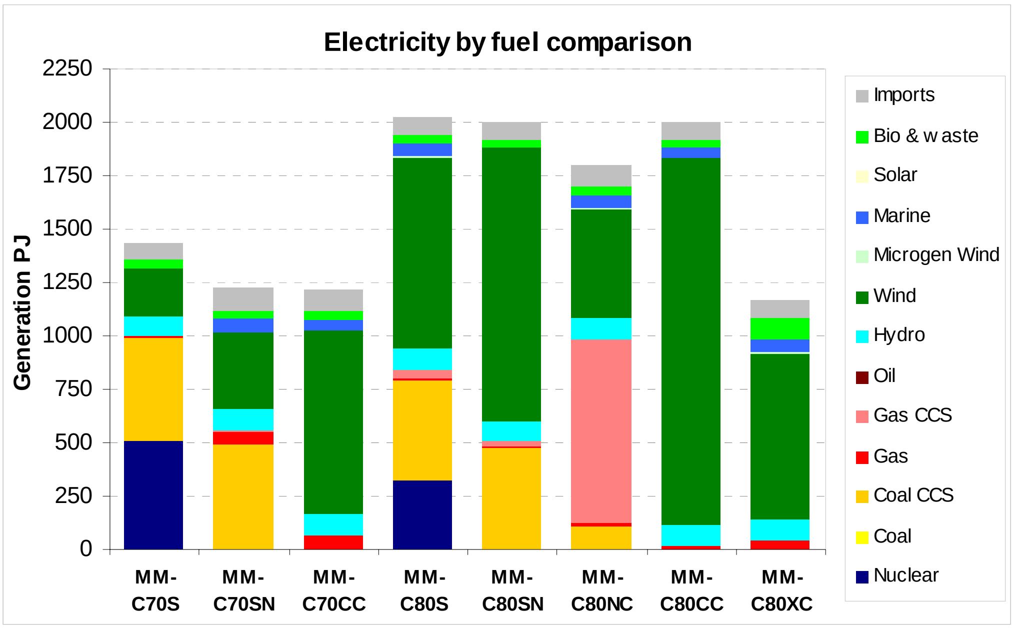


Figure 3.20 Comparison of the 2050 electricity generation by fuel technology for 70% and 80% constrained CO_2 runs for no nuclear and no nuclear / CCS model runs

Electricity generation levels decrease with the introduction of 'no nuclear' in 2050 under the 70% case (MM-C70SN). Wind generation increases as a result, and low levels of gas generation and marine feature. In the 80% case (MM-C80SN), generation levels remain broadly the same; additional wind generation accounts for all of the output previously provided by nuclear power. In addition, the contribution of marine disappears. The introduction of biomass and wind resource constraints in the 80% case (MM-C80NC) results in gas CCS becoming a significant generation technology, accounting for up to 50% of overall output. CCS storage capacity is almost reached - as in other cases. The levels of gas CCS generation are higher than coal CCS generation because the carbon intensity of this generation type is lower –this results in higher generation levels per tCO_2 stored. This appears to be why gas-based CCS is chosen rather than coal.

When nuclear and CCS are excluded from the technologies available, under both the 70% and 80% cases (MM-C70CC / MM-C80CC) in 2050, wind dominates. This is what might be expected, given the lack of other widely deployable low carbon electricity generation technologies. This current version of the model does not have sufficient constraints to ensure wind generation does not dominate to this extent.[11] A further sensitivity was therefore undertaken on the 80% reduction case that included resource constraints for wind and biomass (MM-C80XC). This shows a significant reduction in levels of wind generation, and therefore in overall electricity generation. This reduction in electricity generation means that end use sectors are using less low carbon electricity, using less energy (via the demand response feedback, uptake of conservation and more efficient end-use technologies.

[11] The model has since been updated to reflect more realistic bounds on offshore wind, and better account for issues of intermittency and grid stability.

Transport sector

The transport sector reflects significant technological evolution across the model horizon under stringent carbon reductions, reflecting a key role that this sector can play in reducing emissions. In this section, some of the key findings are highlighted from the analysis, followed by a more detailed overview.

- Under the base case (in the absence of constraints), the transport sector is already moving towards more efficient technologies e.g. hybrids.
- Large reduction targets for CO_2 lead to overall energy demand decreases as vehicles become more efficient, but also as a result of demand reduction in response to higher energy prices.
- A more important role for biomass emerges in later periods, particularly biomass-to-liquid fuels (BtL), than seen in the EWP analysis. This is particularly observed under some of the 80% reduction cases, including the no nuclear and CCS cases, where most of the fuel is biomass derived. (Constraints in these cases on biofuels in transport result in an increased role for petrol and diesel, as would be expected).
- With the exception of the restricted innovation case, the use of diesel and hybrid vehicles in 2050 is at the same level to that observed in the base case(s) due to constraints on fleet profile. The high level of conventional diesel vehicles is enabled due to the use of BtL (Biomass-to-liquid fuels or second generation biodiesel), replacing diesel.
- When the most stringent constraints are applied (80% reduction in CO_2, no nuclear /CCS, restricted biomass) there is significant increased uptake in both petrol and diesel hybrid technologies.
- Comparing runs there is a degree of switching between methanol fuel cell, E85 flex-fuel vehicles and petrol-hybrid cars that seems to indicate that in the final period there is a relatively fine balance between the cost effectiveness of CO_2 savings between them.
- In periods preceding 2050, hydrogen use is highest in the base case. Lower levels in the constrained cases reflect the fact that the hydrogen production in the base case is through carbon intensive fossil fuels. Much of the hydrogen that is used in the last period under the 80% constrained cases is from hydrogen production from electrolysis, using low carbon electricity.

Transport fuels

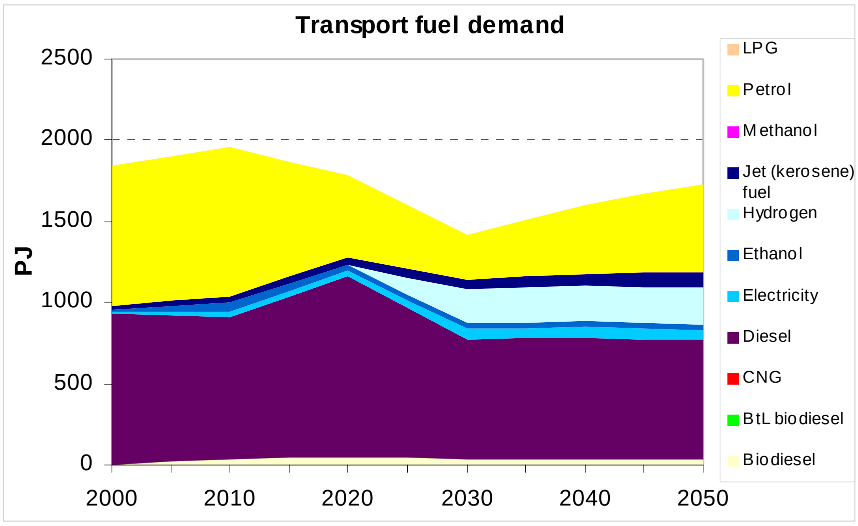
The change in transport fuel consumption (type and level) over time is illustrated for the base case, and 70% and 80% SLT constrained cases in Figure 3.21. In the base case, transport fuel use is dominated by petrol and diesel over the time horizon, with hydrogen making a significant contribution post-2030 (13% in 2050). This suggests that hydrogen does not need a carbon constraint to become an important energy source for this sector but actually has relative attractive technology costs and efficiency levels to ensure its take up. Overall demand decreases to 2030, primarily due to the switching of the car fleet to hybrid vehicles. The proportion of diesel car penetration is constrained in the model which means that after 2030 increased demand is met by petrol fuelled cars.

Imposing 70% and 80% (SLT) constraints leads to three key changes in fuel use trends:

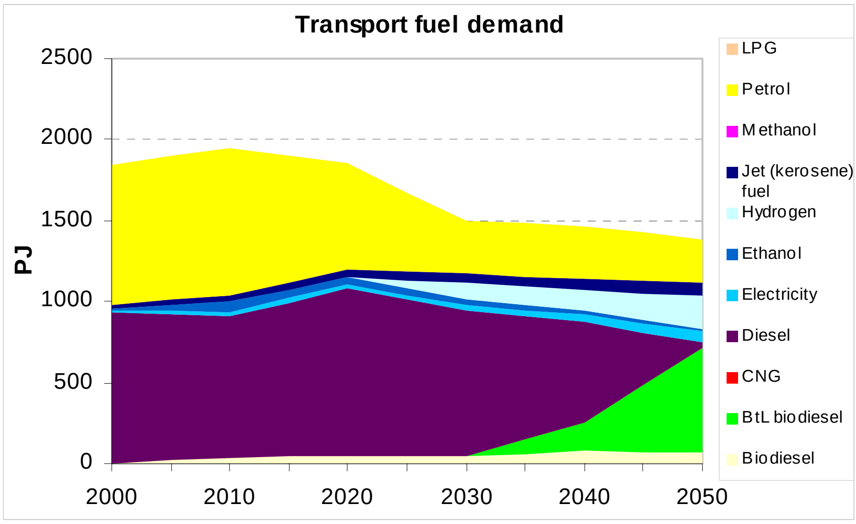
- Overall energy demand decreases after 2030, primarily due to the uptake of more efficient vehicle technologies.
- Use of biofuel rises significantly post-2030, as the transport sector increasingly contributes to emission reductions. In the 80% reduction cases, by 2050 biofuels account for over 60% of total transport fuels leading to no further use of conventional road transport fuels (petrol and diesel).[12] Hydrogen accounts for most of the remaining road transport demand. There are clearly questions concerning whether in reality enough biomass would be readily available to supply this proportion of transport demand. Hence, the additional sensitivity which has been undertaken to constrain the transport sector’s use of biofuels (see results for MM-C70BW / MM-C80BW).
- In periods preceding 2050, hydrogen use is highest in the base case. Lower levels in the constrained cases reflect the fact that the hydrogen produced in the base case is produced using carbon intensive fossil fuels.

[12] Levels of duty on biofuels do not change on the basis of the uptake of such fuels.

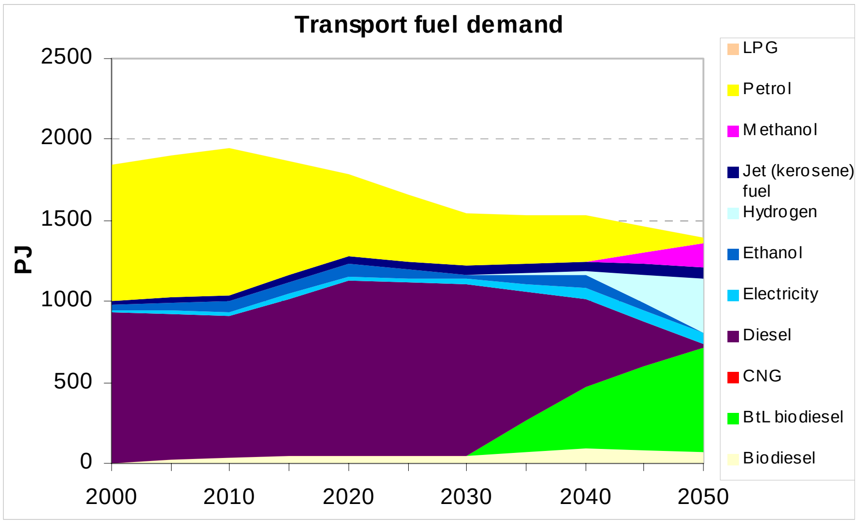
Relative to the 60% SLT case (see Figure 3.22), overall consumption in 2050 under the 70 / 80% reduction cases is lower (potentially due to greater demand responses under the higher constraints). More BtL but less ethanol is observed in the fuel mix. The level of diesel consumption (due to higher levels of biodiesel) is also lower in the more constrained cases. Fuel consumption in the 80% constrained case appears slightly higher than in the 70% case. This is because of relative changes in the balance of use fuels of different carbon intensity – here the system is optimising itself to CO_2 emission reductions rather than energy reductions.



Base



MM-C70S



MM-C80S

Figure 3.21 Comparison of transport fuel consumption for baseline and 70% / 80% SLT constrained CO_2 runs

Figure 3.22 compares the above transport fuel consumption in 2050 with that under the constrained transport biomass / wind case and runs using the alternative trajectories. The biomass constrained runs have an obvious impact, with lower levels of use under both the 70% and 80% cases. The 70% case (MM-C70BW) has lower levels of biomass use (particularly BtL) and as a result, higher diesel consumption. In the 80% case, the level of BtL is slightly lower but no methanol is present in the mix. As a result, petrol use increases, as does diesel but only marginally.

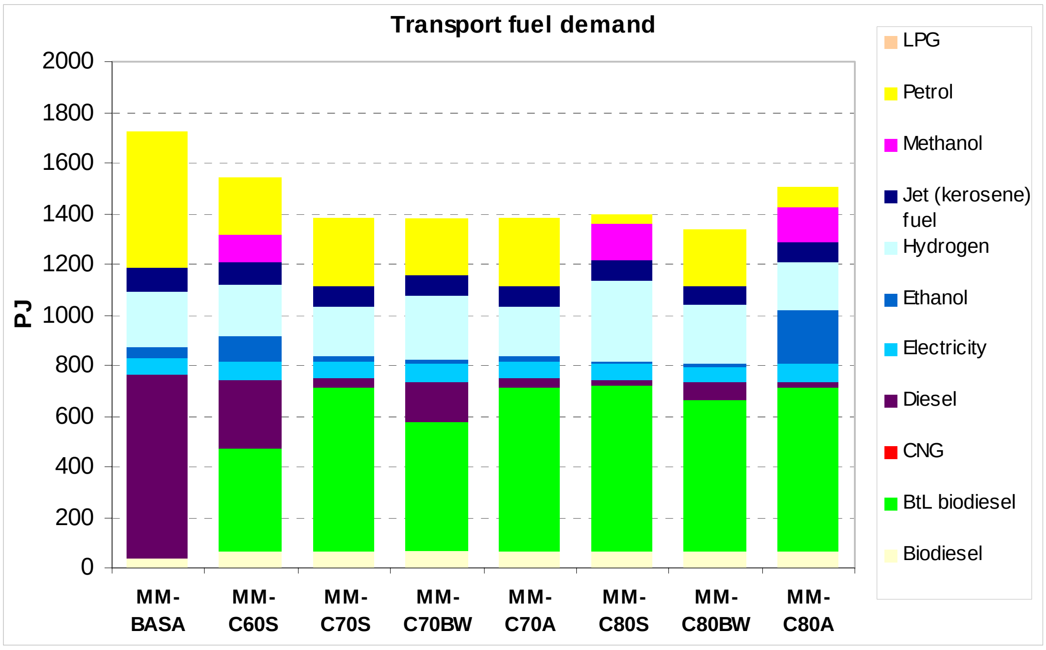


Figure 3.22 Comparison of the 2050 transport fuel consumption for baseline and constrained CO_2 runs

Under alternative trajectories, no significant differences are observed in the 70% reduction case (MM-C70A) relative to MM-C70S. In the 80% ALT case, a significant difference is observed in the uptake of bioethanol and reduced use of hydrogen, leading to an overall increase in fuel consumption. This appears to be due primarily to a switch in the final period from the introduction of hydrogen fuel cell to E85 flex-fuel cars instead. Fuel cells (FC) have over twice the efficiency of internal combustion engines (ICE), so the switch from FC vehicles to ICE powered E85 vehicles leads to the observed increased energy requirements. Net CO_2 emissions are still similar due to the much lower emissions from ethanol production relative to hydrogen. The reason for this switch is not completely clear, but is likely due to a small marginal difference in the cost-effectiveness of CO_2 reductions between the two options.

Analysis of the impact of higher resource prices and restricted innovation on the transport sector in 2050 is shown in Figure 3.23. Under the restricted innovation run (based on an 80% reduction by 2050), the change from the base case (MM_B_10) is significant. Over 85% of energy use is from biofuels. Hydrogen, which features in other cases, does not play a role due to the assumption of no further innovation in such technologies post-2010. Overall levels of energy use remain at a high level due to lack of innovation in more efficient technologies.

The higher resource cost base case (MM-C80SH) shows a fairly large contribution ~ 30% from BtL fuel, and much lower levels of diesel and petrol than observed in the base case where central resource costs are assumed. In addition, hydrogen also plays a more significant role. Under an 80% constraint, BtL use further increases as a replacement for diesel while the amount of hydrogen use decreases by 50%, replaced by petrol and methanol. This is probably due to higher carbon intensity of the hydrogen production compared to petrol use.

The *no nuclear / CCS* sensitivity runs provide some interesting insights, as shown in Figure 3.24. In the 80% reduction case (MM-C80CC), hydrogen production falls (probably due to fewer opportunities for production in the absence of CCS). Petrol use increases as a result. With additional constraints on biomass (MM-C80XC), BtL biodiesel (2nd G) use decreases whilst methanol is no longer used, leading to an overall decrease in use of transport fuels. This is enabled by bigger demand response and move to more efficient hybrid vehicles using BtL biodiesel (2nd G).

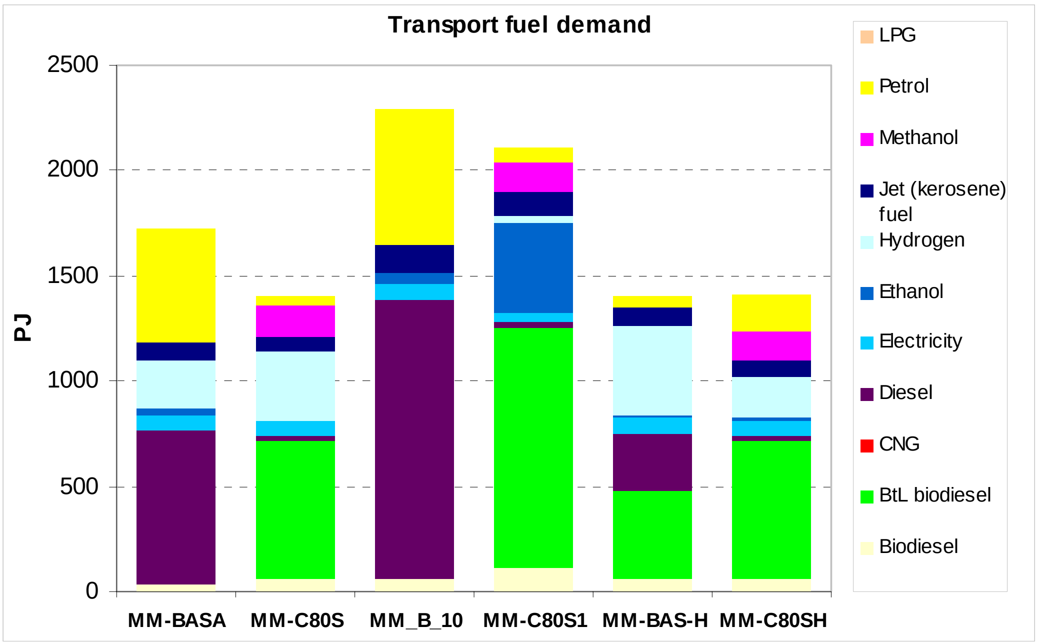


Figure 3.23 Comparison of the 2050 transport fuel consumption for baseline and constrained CO_2 runs, including restricted innovation and higher resource cost cases

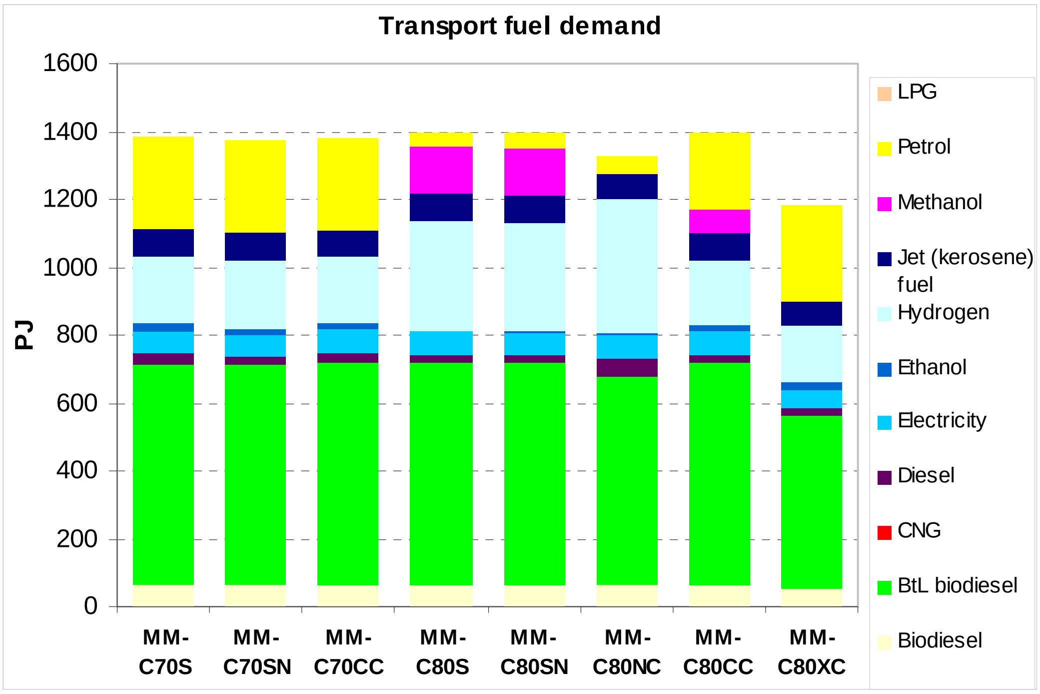


Figure 3.24 Comparison of the 2050 transport fuel consumption for 70% and 80% constrained CO_2 runs for no nuclear and no nuclear / CCS model runs

Transport technologies

The trends in the transport sector fuel consumption can be further understood when we consider the types of technologies taken up for road transport modes. Figure 3.25 and Figure 3.26 compare road transport technologies in 2050 under a range of different scenarios. A very interesting observation is that, with the exception of the restricted innovation case, the use of diesel and hybrid vehicles is at the same level to that observed in the base case(s) in 2050. The high level of conventional diesel vehicles is enabled due to the use of BtL, replacing diesel.

Technology profiles for the 70% reduction cases are similar. They differ from the 60% reduction case, having no flex-ethanol, methanol fuel cell or conventional petrol vehicles. A lower demand and petrol hybrids ensure levels of demand are met. In the 80% reduction cases, MM-C80S uses methanol fuel cell vehicles with less use of petrol hybrids. The same is true of the ALT case, which in addition uses flex-ethanol vehicles. The biomass restricted case only changes in terms of the types of fuel being used in the same technologies (see Figure 3.22).

The restricted innovation case also uses flex-ethanol vehicles in the final period plus some expensive methanol fuel cell vehicles (see Figure 3.26). The high resource price case uses less hydrogen but more petrol hybrids (as mentioned before perhaps due to the carbon intensity of the relative options). It is interesting to note that the level of fuel use in 2050 in diesel-based technologies is the same. In effect, this is because the capacity of these technologies based on a user constraint (to ensure a petrol-diesel mix) has been reached.

The observed switching between methanol fuel cell, E85 flex-fuel vehicles and petrol-hybrid cars seems to indicate that in the final period there is a relatively fine balance between the cost effectiveness of CO_2 savings between them. Changes happening elsewhere in the model affecting the amount of CO_2 needing to be saved may be causing this 'flipping'. Hence the relative favourability of higher efficiency hybrids running on conventional fossil petrol compared to biofuel powered E85 flex-fuel and methanol fuel cell vehicles may be determined by the amount of CO_2 savings required. In reality, there is no reason why hybrid E85 flex-fuel vehicles could not be produced, as there are relatively few technical and low cost differentials to go from a regular ICE to a flex-fuel ICE[13]. In this case it would seem these would be the most likely option selected, were they included in the model.

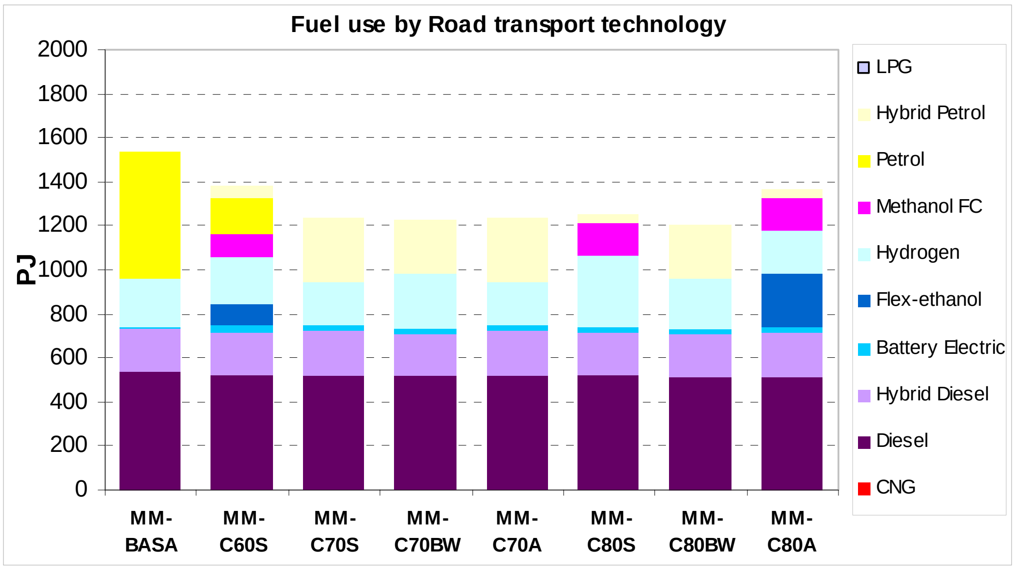


Figure 3.25 Comparison of the 2050 fuel consumption by road transport technology type for baseline and constrained CO_2 runs

[13] This additional option was not included in the model when it was originally developed to avoid over-complexity in the number of technology option combinations.

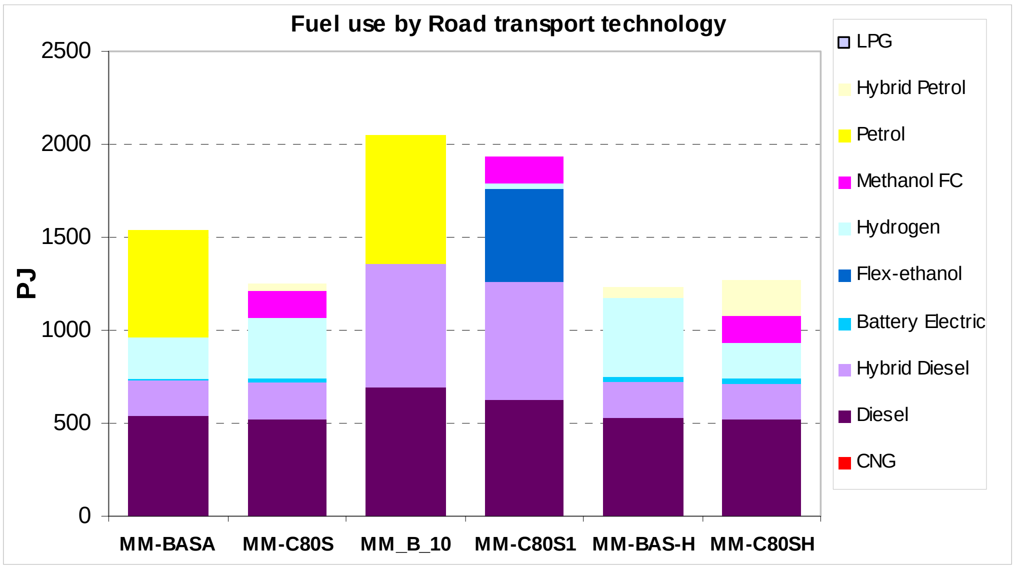


Figure 3.26 Comparison of the 2050 fuel consumption by road transport technology type for baseline and constrained CO_2 runs, including restricted innovation and higher resource cost cases

Considering the road transport sector as a whole, both petrol and diesel hybrid technologies are taken up in significant proportions with the proportions increasing to a peak around 2030 (in all but the restricted innovation scenarios). At this point they account for between 50-60% of demand in the SLT and ALT runs, 30% in the restricted innovation run and over 75% in the high resource price runs. This peak is followed by a decrease in later periods as liquid biofuels used in conventional vehicles become more cost effective. It is worth noting that it seems unlikely in the real world that the market would switch back to less efficient conventional vehicles once hybrids had become so dominant. In the restricted biofuel scenarios (MM-C70BW and MM-C80BW) this swing back towards conventional vehicles does not occur.

Looking at the passenger car sub-sector, **petrol hybrids** gradually increase their market share from 2010 to almost entirely replace petrol equivalents by 2030 in most scenarios. However, diesel hybrids are not taken up at all in most of the runs. They are only taken up from 2020 in the 80% SLT and 80% SLT high resource cost scenarios until 2020, and again peak in 2030 before being replaced with conventional diesels using BtL in the final periods. Conversely, **diesel hybrids** begin to be taken up right from the first period by HGVs and become the predominant technology in LGVs and buses by 2030. After 2030, LGVs remain almost exclusively diesel hybrids for all future periods under all scenarios.

Hydrogen demand in later periods is driven, perhaps unsurprisingly, in part by buses, but less obviously by HGVs. LGVs do not contribute to any of the hydrogen demand in any scenario and cars only in the final period of the 80% SLT and 80% SLT with restricted biomass scenarios. Hydrogen technology also does not appear in the aviation sector in any of the scenarios.

Electricity demand for transport is primarily for rail, but in later periods is also due to battery-electric cars in all but the restricted innovation case (and to a lesser extent 2-wheelers, where it quickly replaces petrol in all scenarios). However, when biomass imports become further restricted it is still hybrid vehicles that are the next preferred technology in the car sector.[14] It should be noted that in this version of the model a 5% penetration rate has been imposed on battery-electric vehicles out to 2050. We believe that in future analyses this constraint should be removed to ensure that the model is allowed to decide, on a cost basis, whether such battery-electric vehicles play a role in the vehicle mix. We think that under an 80% constraint they would play an increasing role in later periods.

Further breakdowns by mode of specific vehicle technologies can be found in Annex 1 for the 70% and 80% SLT scenarios.

[14] Plug-in hybrid technologies are not included in this version of the model to ensure consistency with EWP 07 analysis.

As already discussed, the *no nuclear / CCS* sensitivity runs provide additional insights, as shown in Figure 3.27. The main changes include increases in the use of first petrol hybrids (MM-C80CC), and then diesel hybrids (still using BtL biodiesel) when additional constraints on biomass are applied (MM-C80XC).

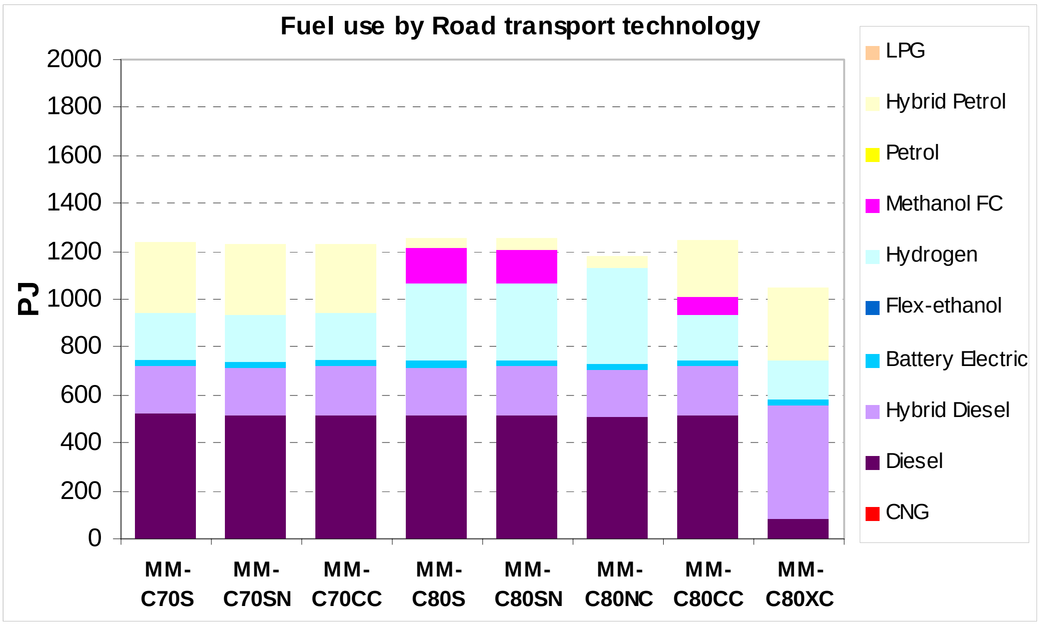


Figure 3.27 Comparison of the 2050 fuel consumption by road transport technology type for 70% and 80% constrained CO_2 runs for no nuclear and no nuclear / CCS model runs

Demand response

There are a number of demand-side responses to the introduction of CO_2 constraints in the system. The opportunities for carbon reduction in the end use demand sectors include:

- Fuel switching (e.g. lower carbon vehicle fleet in the transport sector)
- Use of more efficient *demand devices* that provide the end use energy services (e.g. uptake of condensing boilers in the residential sector)
- Uptake of conservation measures resulting in lower demand for energy
- Endogenous reductions in the overall level of demand, due to behavioural changes from price feedback mechanisms

The first two options are very much in evidence in the results presented for the electricity generation and transport sectors. Uptake of conservation measures can be seen across other end-use sectors such as residential, commercial and industry.

Figure 3.28 shows the different levels of conservation across the core model runs undertaken. An interesting observation is that despite further constraints being imposed, limited additional conservation is taken up above the levels seen in 60% constrained run. This suggests that there is limited additional cost-effective potential – further conservation measures are likely to be significantly more expensive. Under the restricted innovation case, the uptake of conservation has also been restricted and hence the comparatively low levels.

It is only when significant additional constraints are imposed that levels of conservation increase significantly. This can be seen for the no nuclear and no nuclear / CCS cases with biomass and wind constraints. Due to the severe constraints faced in these scenarios, expensive conservation options are taken, primarily in the residential sector. In most cases, in 2050, the residential sector accounts for approximately 50% of conservation, whilst the service and industry sectors account for 25% each. In these severely constrained cases, the residential sector accounts for just under 60% of conservation.

In the base case, conservation levels are constrained to Defra estimates of efficiency uptake through 2020 while in the constrained runs the model is given the freedom to choose cost-effective uptake in later years. Conservation in the restricted innovation case is limited to approximately 25% of BRE's maximum estimated potentials.

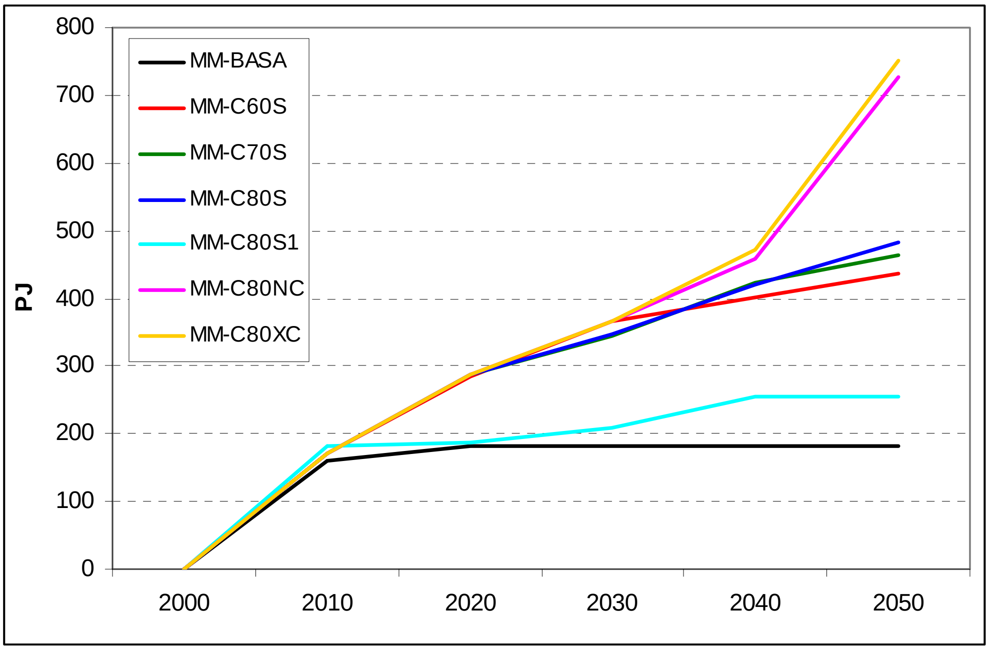


Figure 3.28 Levels of energy conservation under different scenarios

The Macro version of the model endogenously calculates a demand response, reflecting consumer behaviour response to changes in price. As explained in the *EWP 07 MARKAL analysis* report, *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.*

The responsiveness of different sectors will be dependent on demand decoupling factors (DDFs) that are input as part of the calibration process. These reflect the relationship between trends in the overall economy as represented by GDP, and the movement of the individual demand sectors. A factor of 0 means demand grows at the GDP growth rate; a factor of 2 means demand is flat, whilst -1 would mean that demand is growing faster than GDP. Under the calibration process, these factors are used to ensure that GDP output and demands converge to a reasonable level with the desired GDP growth and model demands seen under the standard MARKAL. Once calibrated under the base case, the model can then run under an emission constraint.

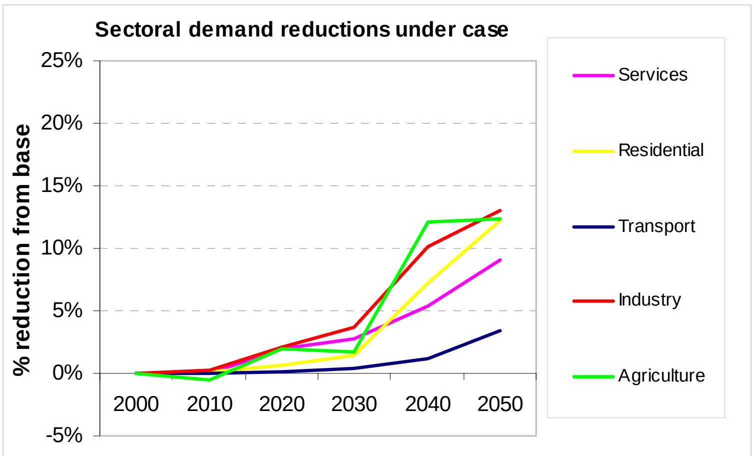
Demand feedback/rebound effects can occur in real systems when the energy costs decrease resulting in an increase in demand. One of the most often referred to of such direct rebound effects is when lower costs due to improved home energy efficiency (e.g. energy efficient lighting or insulation) measures. Such improvements can result in a higher service demand (e.g. lights left on longer), eroding some of the gains that would otherwise be attained. Alternatively, financial savings made in energy efficiency improvements may be spent elsewhere on other goods or services that have their own impacts. Such effects would be implicitly included within the overall Macro model demand response but cannot be explicitly measured.

Variation in sector demand response is presented in Figure 3.29 for the following SLT cases: 60%, 70% and 80% reduction cases plus the following sensitivities - restricted innovation case (MM-C80S1) and no nuclear / CCS case with additional biomass / wind constraints (MM-C80XC). The first point of interest is the relative response between sectors, the largest reductions seen in the residential, industry and agriculture sectors. Transport is the least responsive sector, most likely due to the relatively inelastic demand response, and a relatively large range of alternative technologies to negate the need for large demand responses.

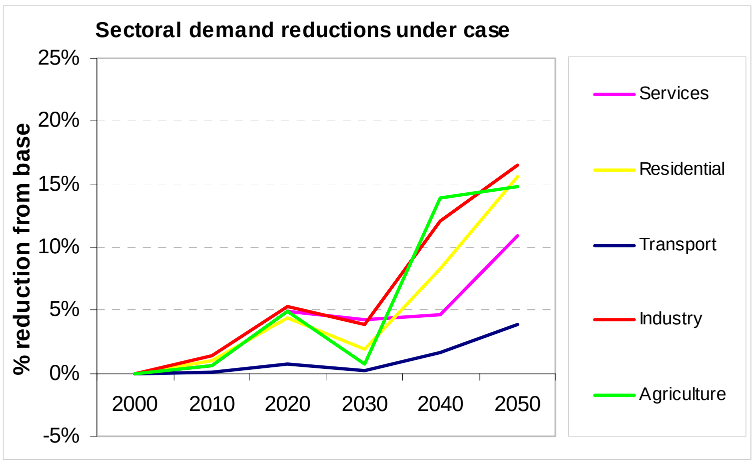
As the constraints get more severe, demand response becomes an increasingly important mechanism to help minimise the marginal costs of abatement. This is reflected in Figure 3.29; under the 60% constraint, demand reductions of around 9-13% in 2050 can be observed (excluding transport). In 2030 – when constraints are lower, demand responses are below 5%. Transport also reflects these demand response trends but at lower reduction levels.

Under an 80% constraint, the reductions are between 15-20% in 2050. This suggests that where low carbon options are more expensive, demand reductions through this response feedback are even greater as the system tries to minimise costs. Interestingly, the demand response trend follows the marginal abatement cost trends presented in section 3.3. This shows that level of marginal costs is a significant driver of the demand response. Some of the most significant demand responses are seen in the no nuclear / no nuclear and CCS cases, particularly where wind and biomass constraints are also imposed. Reductions of between 20-27% are seen across all sectors, except the transport sector.

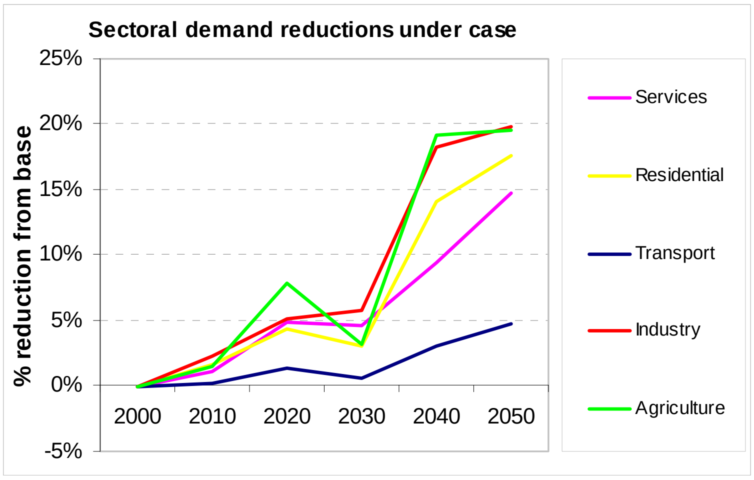
The demand reductions shown in Figure 3.29 for selected runs are cumulative reductions across all the different demands within each sector. In Annex 2, the individual demand responses for each sector have been provided for the SLT 80% reduction case.



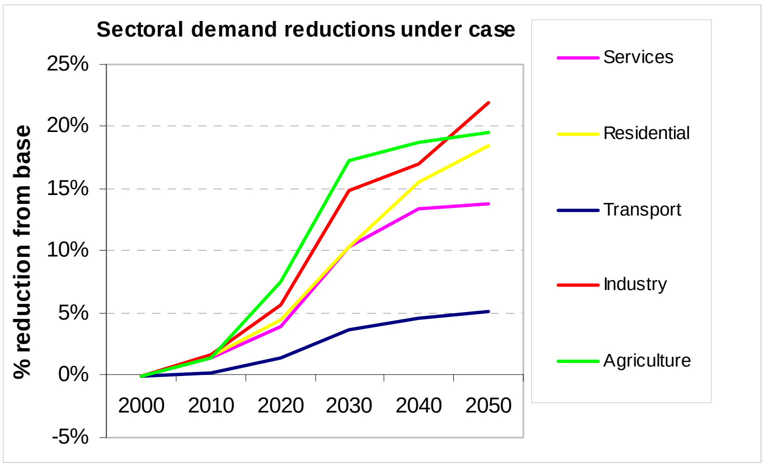
MM-C60S



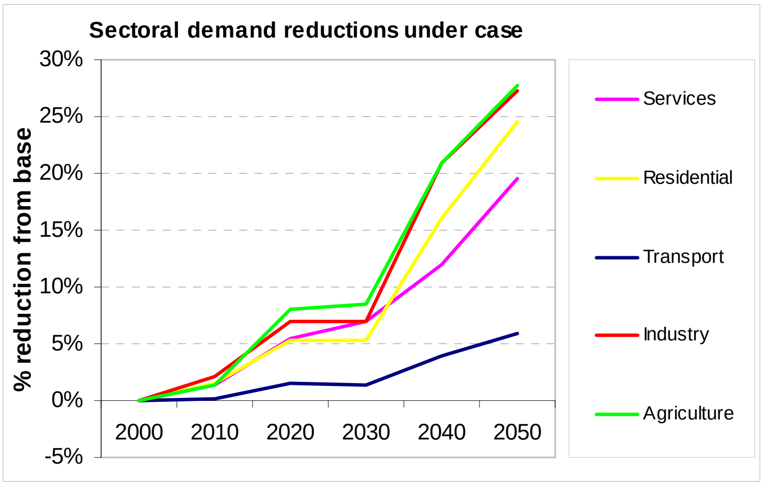
MM-C70S



MM-C80S



MM-C80S1 (relative to restricted innovation baseline – MM_B_10)



MM-C80XC (note expanded Y-axis scale)

Figure 3.29 Reductions in overall energy service demand by sector relative to baseline for different constrained CO_2 runs

3.3 Economic impacts

Marginal abatement costs

The marginal abatement costs are derived directly from the model, and calculated as a result of the imposition of an overall carbon constraint. They represent the costs of abating the final tonne of CO_2 to meet a given constraint. The highest marginal costs are associated with those runs where constraints are most stringent or technologies to reduce emissions are unavailable / cost more.

Table 3.3 lists the marginal costs in 2050 for each model run. The highest costs observed are for the 80% reduction cases, with a cost range of £208-395/tCO_2 (or £762-1448/tC). It is the no nuclear / CCS with biomass and wind constraints case where the highest values are observed, primarily due to the lack of available low carbon abatement technologies in the electricity generation sector.

Table 3.3 Marginal costs of abatement in 2050 for all constrained model runs

Model run	Description	£/tonne CO_2 in 2050	£/tonne C in 2050
MM-C80XC	No nuclear / CCS plus wind / biomass resource constraints	395.0	1448.3
MM-C80S1	Restricted innovation	305.6	1120.5
MM-C80BW	Wind / biomass resource constraints	287.8	1055.3
MM-C80NC	No nuclear plus wind / biomass resource constraints	250.9	920.0
MM-C80A	Standard assumptions with alternative trajectory	250.8	919.6
MM-C80SH	Higher resource prices	236.1	865.7
MM-C80SN	No nuclear	231.7	849.6
MM-C80S	Standard assumptions with straight line trajectory	214.8	787.6
MM-C80CC	No nuclear / CCS	207.9	762.3
MM-C70SN	No nuclear	201.1	737.4
MM-C70CC	No nuclear / CCS	179.0	656.3
MM-C70BW	Wind / biomass resource constraints	174.2	638.7
MM-C70A	Standard assumptions with alternative trajectory	162.6	596.2
MM-C70S	Standard assumptions with straight line trajectory	144.9	531.3
MM-C60S	Standard assumptions with straight line trajectory	64.8	237.6
MM-C60	Standard assumptions with EWP 07 constraint	105.0	385.0

Figure 3.30 and Figure 3.31 illustrate how marginal costs get progressively higher over time, as CO_2 constraints get more stringent. The alternative trajectories (MM-C70A / MM-C80A) both have higher costs in earlier years than the equivalent SLT cases (MM-C70S / MM-C80S) due to higher constraints. In 2050, costs are also higher, as potentially cheaper options used to abate in earlier periods have reached the capacity of their implementation.

Interestingly, some of the constrained cases (MM-C80S, MM-C70S, MM-C70A) appear to have lower costs in 2030 than in 2020. This small reduction probably reflects that the model has low carbon technologies available at a lower cost at this point i.e. 2030, in the time horizon. This appears to be the case, given that there is no indication of a reduction under the MM-C80S1 during this period, as would be expected with restricted innovation. This is the only run where costs go up significantly between 2020 and 2030. In addition, under the 70% reduction case, marginal costs appear negative, implying that further reductions have benefits; it is not clear why this anomaly occurs.

The biomass / wind constrained runs (MM-C80BW, MM-C70BW) are higher than their comparative SLT cases after 2040 for the 80% reduction case and after 2030 for the 70% reduction case. This would be expected as it is only in the later time periods that the model is using significant amounts of wind generation / biofuels in the transport sector.

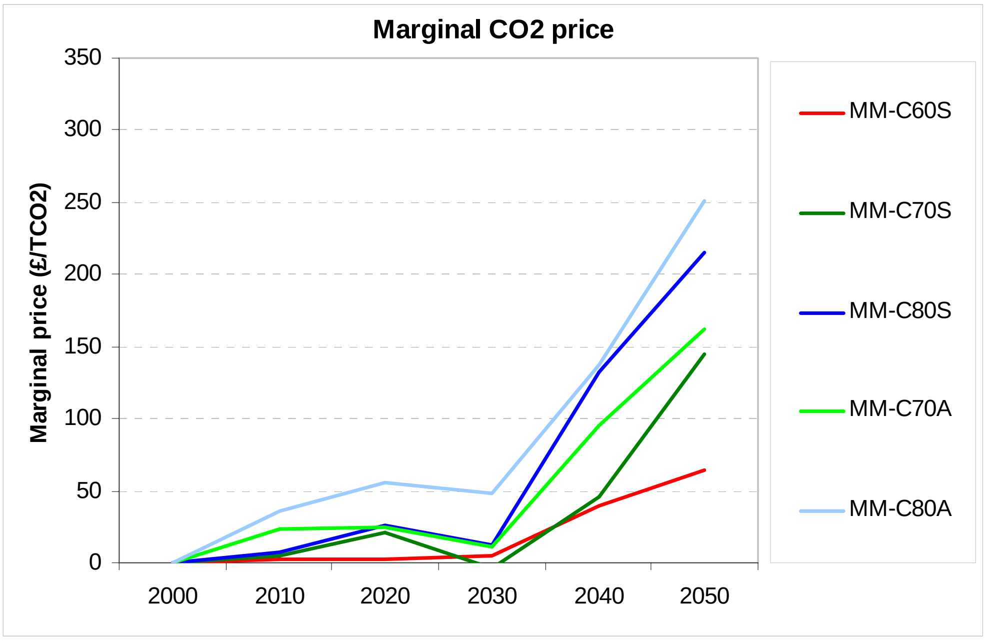


Figure 3.30 Comparison of marginal cost of CO_2 for SLT and ALT CO_2 constrained runs

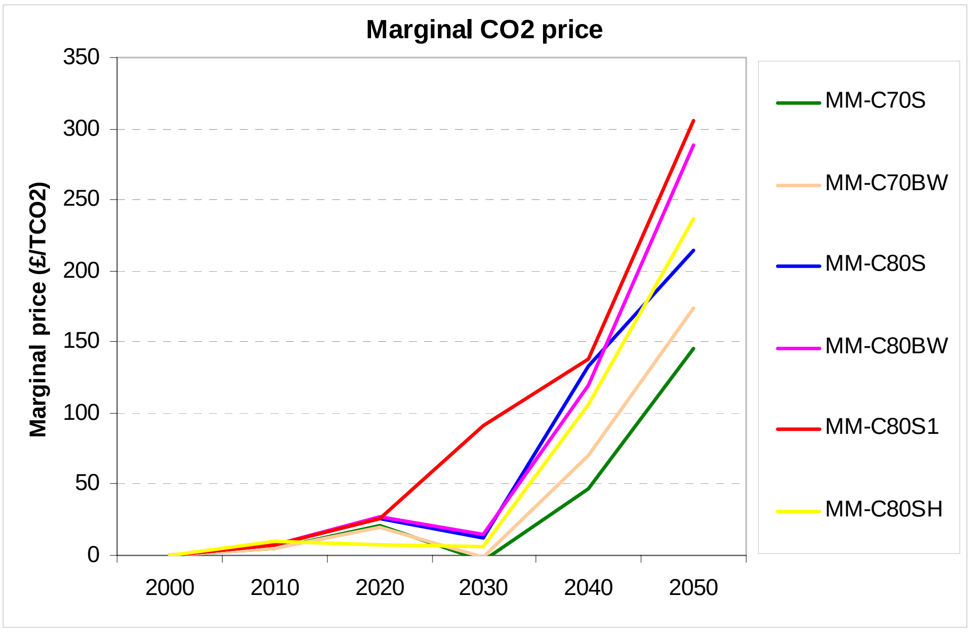


Figure 3.31 Comparison of marginal cost of CO_2 for SLT CO_2 constrained runs – biomass / wind constraints, higher resource price and restricted innovation runs

Total energy system costs

An energy cost parameter is calculated by the Macro version of the MARKAL model. Figure 3.30 shows how energy costs change relative to the base case over the model time horizon. Energy costs are actually shown to decrease up to 2040, and significantly increase in the final time period.

As explained in the *EWP 07 MARKAL analysis* report, *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 tend to fall then rise as the higher unit costs outweigh the behaviour reductions.*

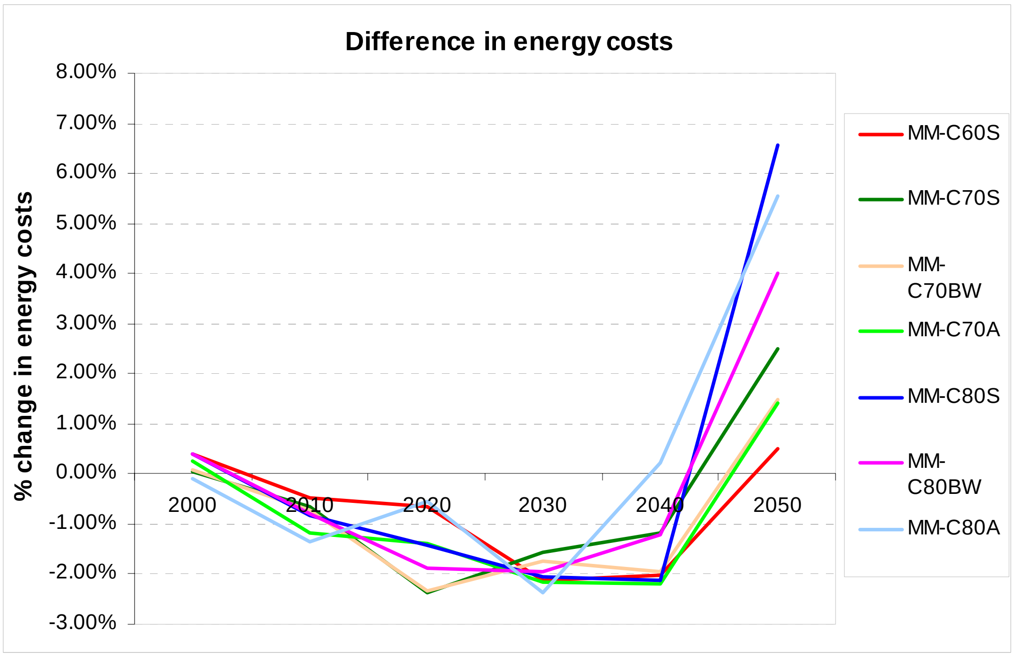


Figure 3.32 % change in energy costs relative to baseline for different constrained CO_2 runs – SLT, ALT and biomass / wind constrained cases

Macro parameters – GDP, Investment, Consumption

As described in the *EWP 07 MARKAL analysis* report, *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.* 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 costs (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.

The implication is that the energy system within the economy accounts for a decreasing share of overall GDP, and therefore may have a lesser impact even if system costs do increase over time. However, given the CO_2 constraints being imposed, leading to major structural change in the energy system, the impact on GDP is not insignificant.

In the EWP 2007 model runs, a 0.8% (£B22.2) loss in GDP was estimated based on the SLT 60% reduction run (see Figure 3.33). The most significant GDP losses in the EWP 07 analysis were observed under the 60% restricted innovation post-2010 case at 1.5% (or £B42.0).

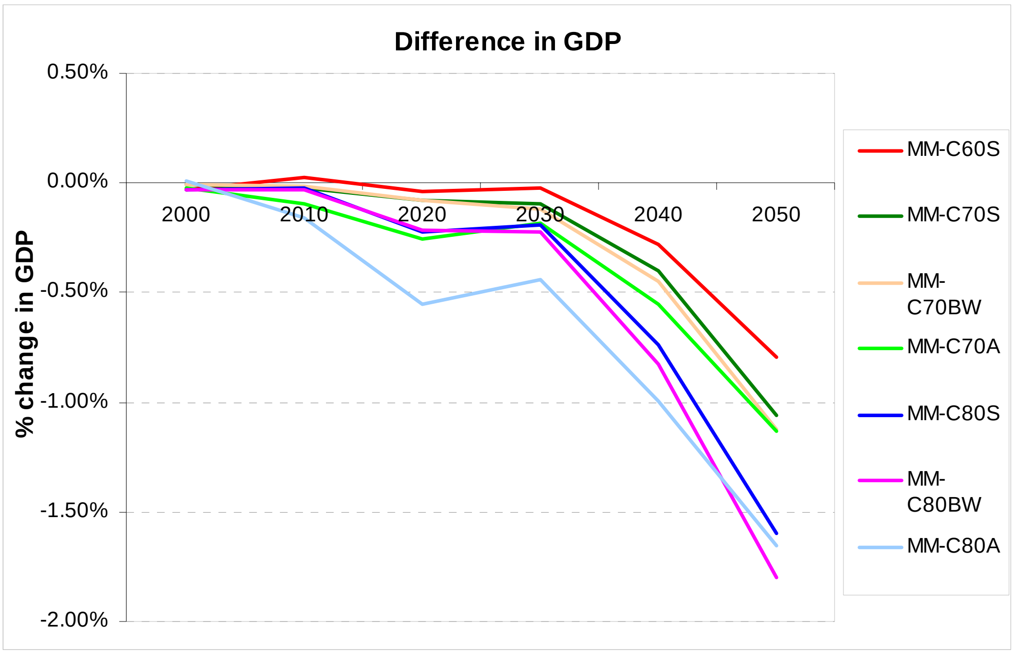


Figure 3.33 % change in GDP relative to baseline for different constrained CO_2 runs – SLT, ALT and biomass / wind constrained cases

In this analysis, all 70% reduction cases lead to estimated GDP losses of around 1.1% in 2050. Cumulative losses are of course greater for the MM-C70A case (alternative trajectory) where higher constraints are imposed across the emissions reduction trajectory. For the 80% reduction cases, losses are between 1.6 and 2.0% except for the high resource cost and restricted innovation cases, where losses are 1.1% (£B31.6) and 2.6% (£B73.0) respectively. GDP losses range from 1.60% under an 80% constraint, 1.71% if new nuclear build is restricted, and 1.95% where new nuclear build and biomass / wind is restricted. Losses increase to 1.83% for the 80% constraint if new nuclear build and CCS is restricted, and 2.18% where new nuclear build, CCS and biomass / wind is restricted. Again, the 80% alternative trajectory leads to greater cumulative GDP losses.

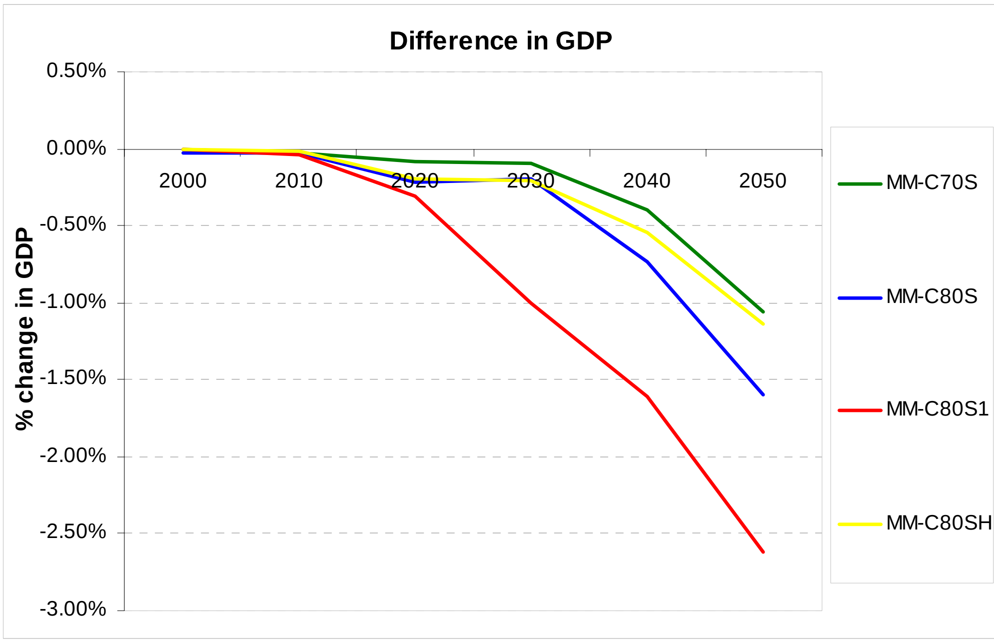


Figure 3.34 % change in GDP relative to baseline for different constrained CO_2 runs – SLT, restricted innovation and higher resource cost cases

Figure 3.35 and Figure 3.36 show the impacts of the CO_2 constraints on economy wide levels of consumption and investment. Investment levels decline significantly post-2030, driven by the additional costs of meeting the emission reduction targets. As would be expected, the reduction in investment levels increases as the reduction target becomes more stringent. The rise in 2030 (relative to 2020) probably reflects the lower marginal costs of abatement (see Figure 3.30 and Figure 3.31). Consumption levels reflect an inverse trend to that seen in Figure 3.32, with higher consumption pre-2040, driven by the demand response to reduce to energy consumption but post-2040, significant reductions as energy system costs increase greatly.

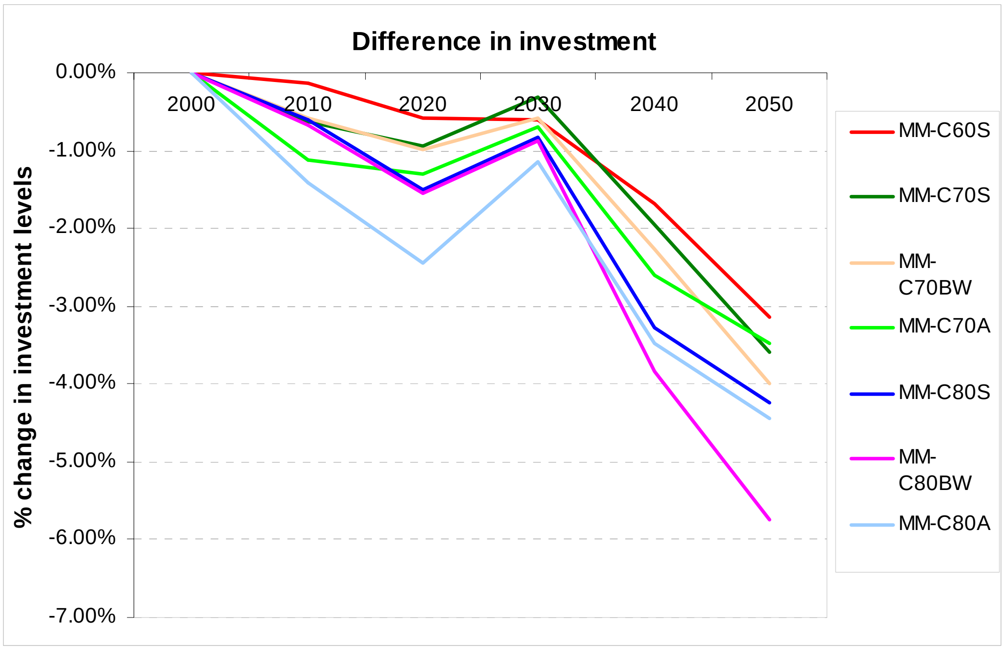


Figure 3.35 % reductions in investment levels relative to baseline for different constrained CO_2 runs – SLT, ALT and biomass / wind constrained cases

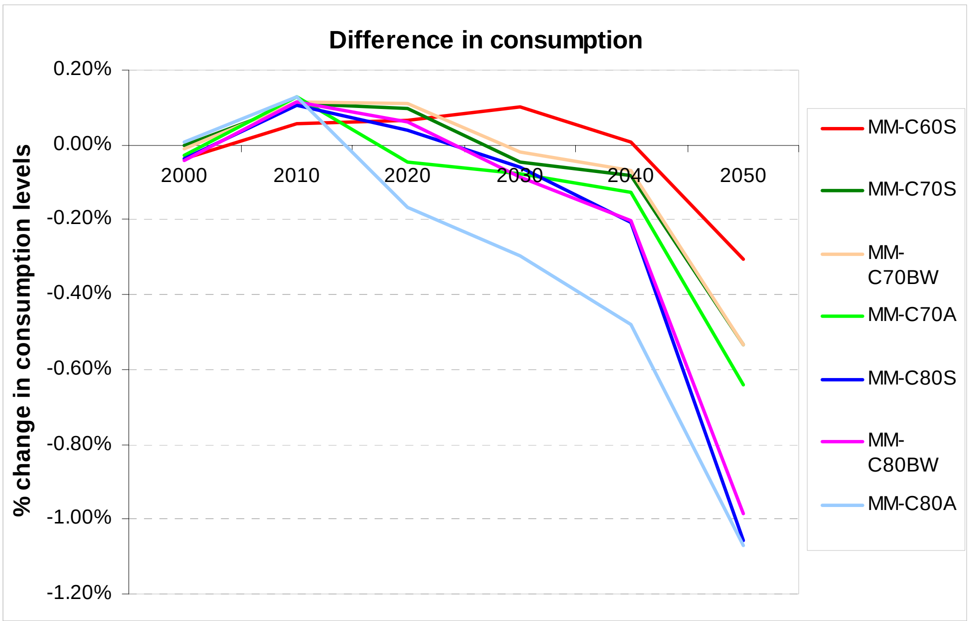


Figure 3.36 % change in investment levels relative to baseline for different constrained CO_2 runs – SLT, ALT and biomass / wind constrained cases

3.4 International aviation

The results of the international aviation model runs are presented and discussed briefly in this section under the following three headings:

- System evolution
- Technology pathways
- Economic impacts

The assumptions for international aviation have already been discussed briefly in section 2.2 (and in more detail in Annex 5). It should be noted that the results for aviation are only indicative because of the uncertainties in the technology and abatement costs.

3.4.1 System evolution

Relative to the model runs excluding international aviation, there is a transition in trends in early periods where the primary and final energy demands are similar (with the exception of aviation fuel) through to later periods where they begin to diverge. The major changes in the final periods when 60% SLT carbon constraints are imposed include:

- The increased use of oil (used almost exclusively for aviation jet fuel),
- Increase in biomass for BtL fuel in the transport sector,
- A decrease in the use of coal and coke, and an increase in gas and nuclear energy in later periods.

These trends are highlighted in Figure 3.37. The model appears unable to make the same level of reductions in the international aviation sector that it is making in other sectors, so providing additional pressure for increased CO_2 reductions outside this sector.

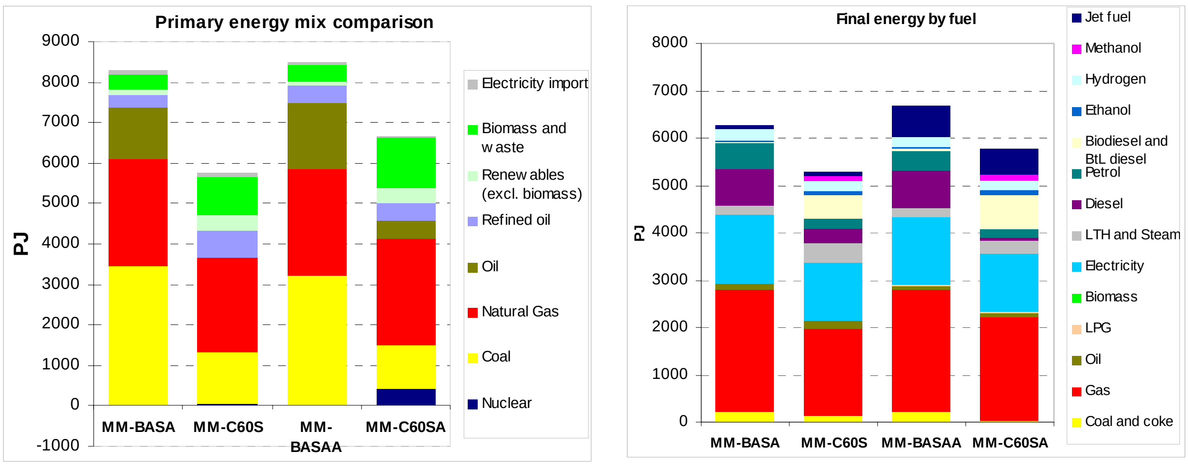


Figure 3.37 Changes in 2050 primary and final energy demand from baseline for 60% SLT regular and international aviation model runs

The trends in CO_2 emissions reductions across the economy are presented in Figure 3.38, whilst changes in fuel use and service demand in the aviation sector are presented in Figure 3.39. These charts clearly reflect the earlier observations related to primary and final energy demand and illustrate that the aviation sector is not able to make the same level of contributions as other sectors to achieve the 60% reductions in CO_2 emissions by 2050. This leads to the need for additional abatement action by these other sectors to achieve the targets, despite a considerable demand reduction response in the aviation sector, as shown in Figure 3.39.

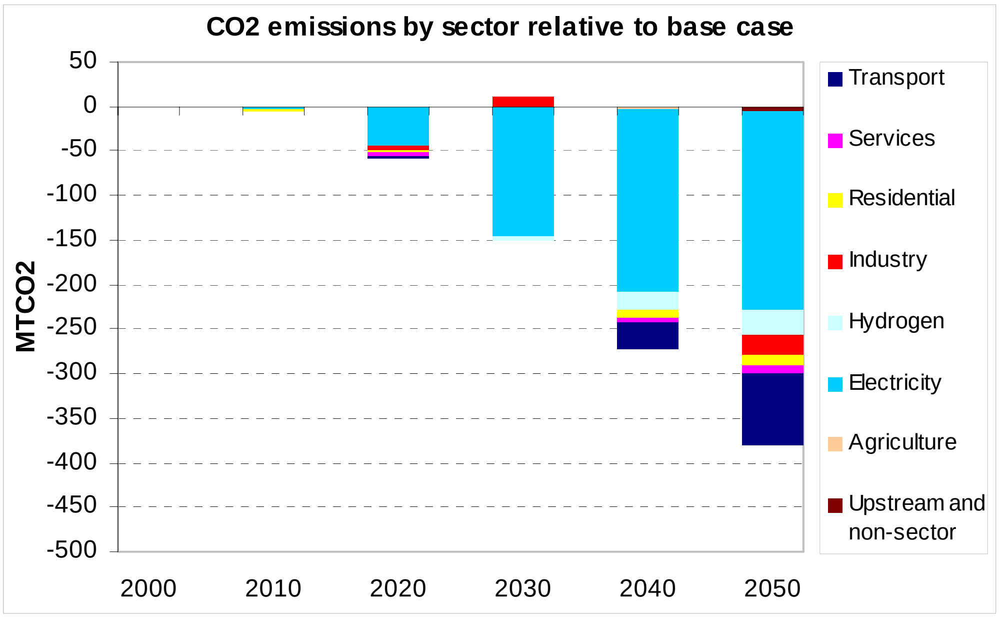


Figure 3.38 Reduction in CO_2 emissions by sector – relative to international aviation baseline

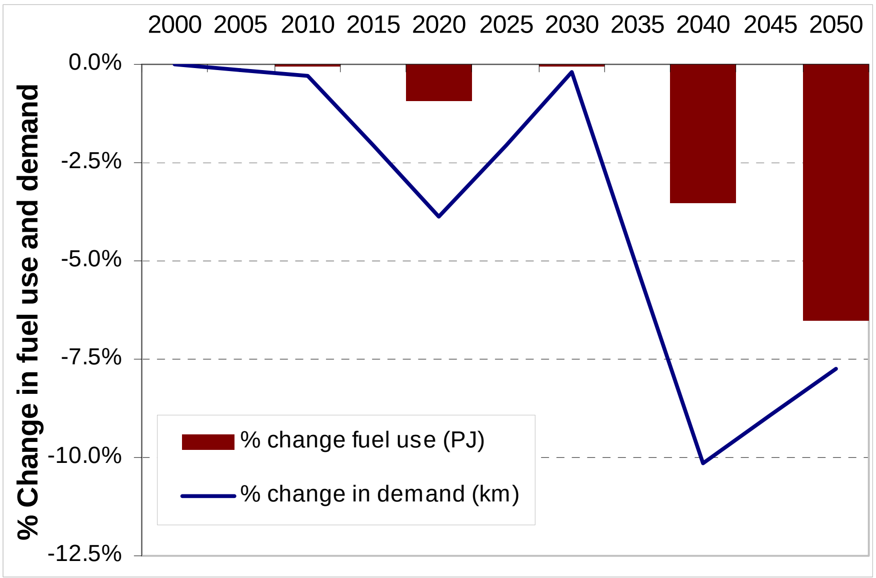


Figure 3.39 Reduction in fuel use (/CO_2 emissions) and demand by aviation for 60% SLT CO_2 reductions relative to international aviation baseline

This significant demand response results due the need to abate emissions from this sector whilst lacking alternative technological mitigation options or fuel switching options. The Macro model includes a single elasticity across all sectors and sector-specific demand decoupling factors, which are similar but not the same as elasticity. These demand decoupling factors are determined via the model calibration process and are not exogenously derived/supplied. Responsiveness to price is also then determined by other factors such as alternative mitigation options. Therefore, the demand response of this sector does not reflect a specific elasticity that might be considered realistic but rather a response determined by the need to abate, taking account of other options. This level of demand response may not be considered realistic in this sector due to the relative inelastic price response to rises in prices in this sector. However, the marginal price of abatement is relatively high by 2040, and therefore this high price signal could potentially lead to such a response.
The following Table 3.4 also shows the additional cumulative reductions in CO_2 emissions resulting from inclusion of international aviation under the 60% SLT reduction constraint, relative to the case without the international aviation sector included.

Table 3.4 Cumulative emissions savings from 2010 under 60% CO_2 SLT reduction constraints with international aviation, $MtCO_2$

Total CO_2 emissions change, $MtCO_2$	**2010**	**2020**	**2030**	**2040**	**2050**
C60 SLT saving	-27	-344	-1,235	-3,112	-6,287
C60 SLT with International Aviation saving	-26	-365	-1,393	-3,524	-6,849
Additional cumulative saving	**1**	**-21**	**-158**	**-412**	**-562**

3.4.2 Technology pathways

Comparisons of the difference in the fuel and technology selection by 2050 in the electricity and transport sectors are presented in Figure 3.40 and Figure 3.41. For the international aviation runs, the main differences in the electricity sector include an overall increase in electricity generation, a decrease in gas generation and a large increase in nuclear generation.

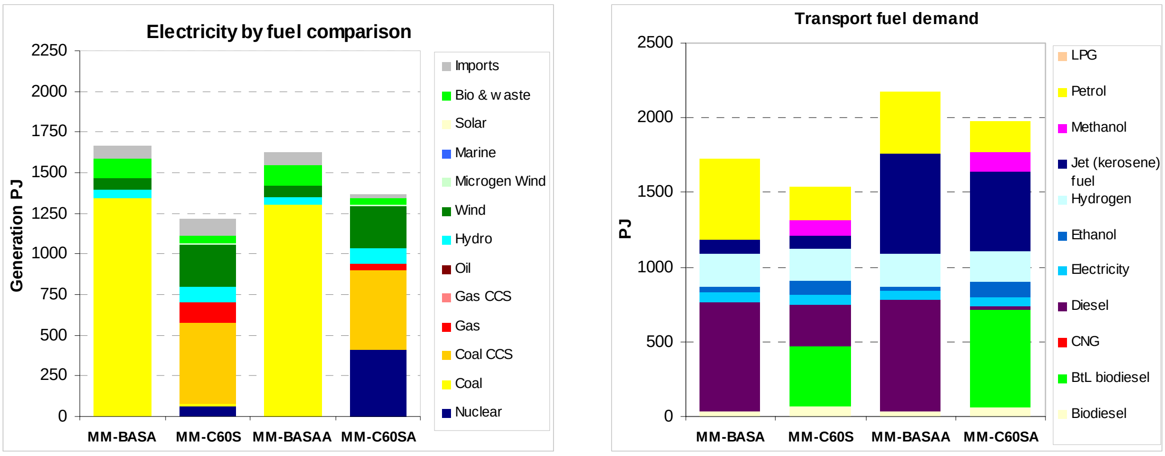


Figure 3.40 Technology uptake in 2050 for electricity generation and transport sectors for 60% SLT regular and international aviation model runs

In the transport sector the need for proportionally larger CO_2 reductions in non-aviation sectors leads to both an increased uptake of BtL diesel and also increased use of hydrogen by HGVs in 2030 and 2040 instead of hybrid diesel vehicles. This results in both reduced CO_2 emissions and lower energy use due to the use of the higher efficiency hybrid technology.

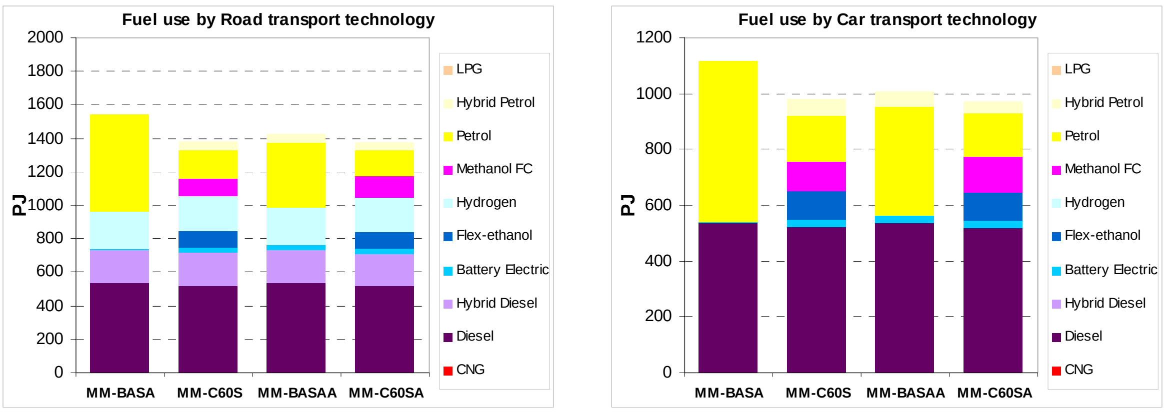


Figure 3.41 Technology uptake in 2050 for electricity generation and transport sectors for 60% SLT regular and international aviation model runs

In the aviation sector itself it is clear that there are no significant technological changes made as a result of CO_2 constraints. Figure 3.42 seems to indicate that there is simply a reduction in the demand for aviation, as the balance of the two kerosene technologies utilised does not change when constraints are put in place. The model also takes up the more efficient (and cost-effective) advanced BWB airframe aircraft up to their maximum share constraint as soon as they become available.

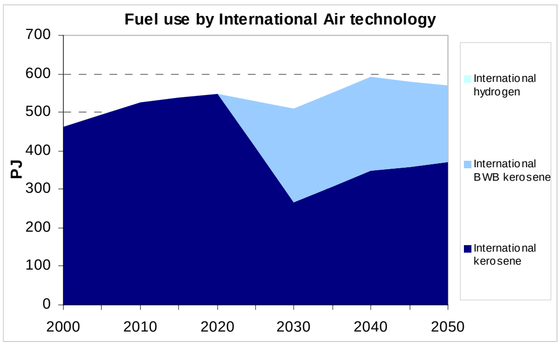
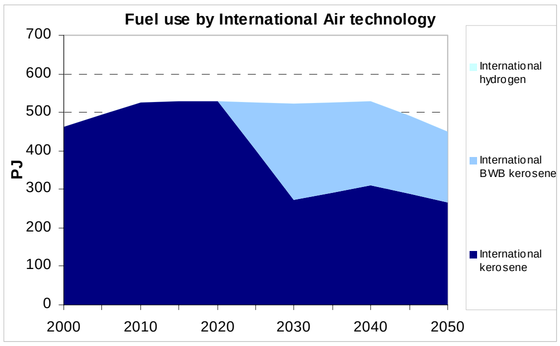
MM-BASAA	MM-C60SA
	

Figure 3.42 Technology uptake for international aviation in the baseline and 60% SLT model runs

In the absence from the model of biomass derived synthetic aviation fuel (similar to BtL diesel), there are limitations concerning where mitigation can be undertaken to reduce CO_2 emissions in the aviation sector, other than by reducing the aviation demand significantly (discussed earlier and also in the following section). It is possible that the availability of such a fuel in the model may affect the balance of technology/fuel uptake across the transport sector. However, the high pre-tax cost of such a fuel and the current tax exemption of aviation fuel may still provide a significant barrier to uptake. This is the trend in road transport sector where BtL is only taken up in significant quantities in later periods to meet CO_2 constraints.

3.4.3 Demand response

Figure 3.43 and Figure 3.44 illustrate the overall sectoral demand response and the transport sector demand response to the imposition of the 60% SLT carbon reductions on the energy sector when international aviation is included.

The increased demand response in the transport sector appears to be almost entirely due to reductions in aviation demand on applying the CO_2 constraints. With the exception of agriculture (and domestic shipping) there do not appear to be any significant changes in the demand response of other sectors as a result of inclusion of international aviation. Therefore this would indicate that the additional savings needed outside of aviation are achieved through technological means.

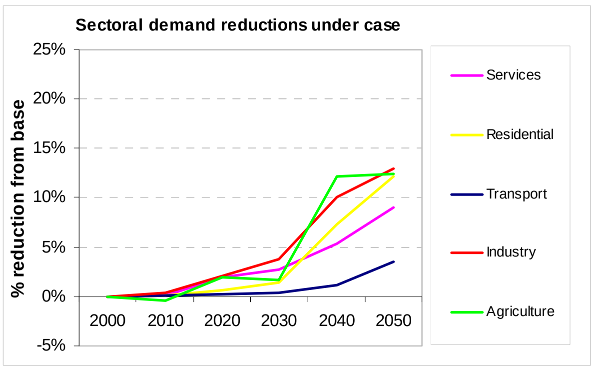
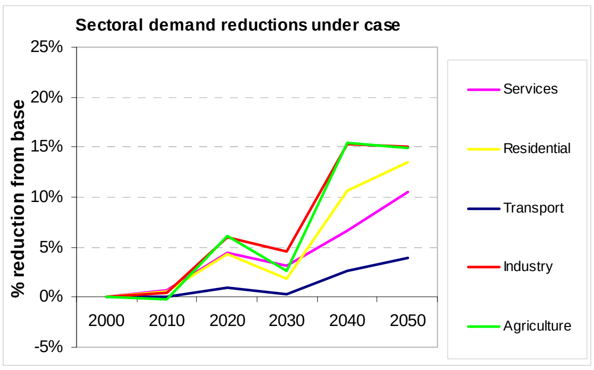
60%SLT with regular model	60% SLT including international aviation
	

Figure 3.43 Sectoral demand response – 60% SLT constrained run with international aviation (relative to international aviation base case)

60%SLT with regular model	60% SLT including international aviation

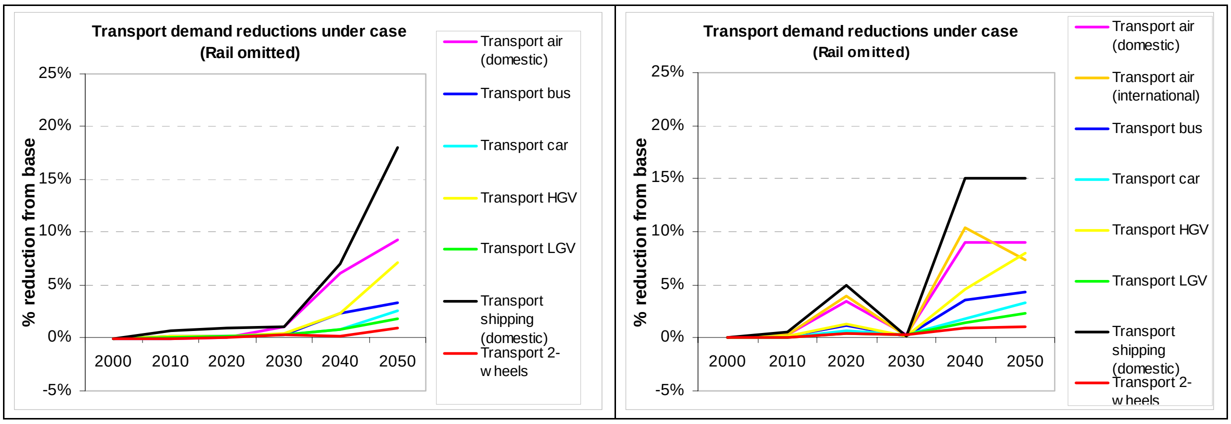


Figure 3.44 Transport sector demand response – 60% SLT constrained run with international aviation (relative to international aviation base case)

As already discussed, the high demand response appears to be the only way aviation is able to reduce its impact further under CO_2 constraints relative to the baseline case. It should be emphasised that such demand reduction would have other potentially high welfare and GDP costs that are not accounted for in the modelling. As such, the demand effects observed in the modelling are only highly aggregate and are not based on DfT elasticity factors.

3.4.4 Marginal CO_2 prices and GDP impacts

The changes in the marginal CO_2 price and impact on GDP of different scenario runs are presented in Figure 3.45 and Figure 3.46 respectively.

Figure 3.45 show how marginal costs of CO_2 abatement get progressively higher over time, as CO_2 constraints become more stringent. Inclusion of international aviation into the model also results in significantly higher 2050 abatement costs under the 60% SLT constraint – 97 £/tCO_2 compared to 65 £/tCO_2 for the regular 60% SLT model run. As previously noted, this is because other sectors have to compensate for the aviation sector's relative inability to reduce its emissions other than by demand reduction. This results in the marginal abatement costs for the 60% SLT constraint with the inclusion of international aviation being mid-way between those of the non-aviation 60% and 70% SLT constrained model runs.[15]

[15] This energy economy-wide marginal cost of CO_2 abatement is one of the factors that influences the demand response – i.e. the model can decide it is more desirable to reduce demand if it gets too high, as discussed in the previous section.

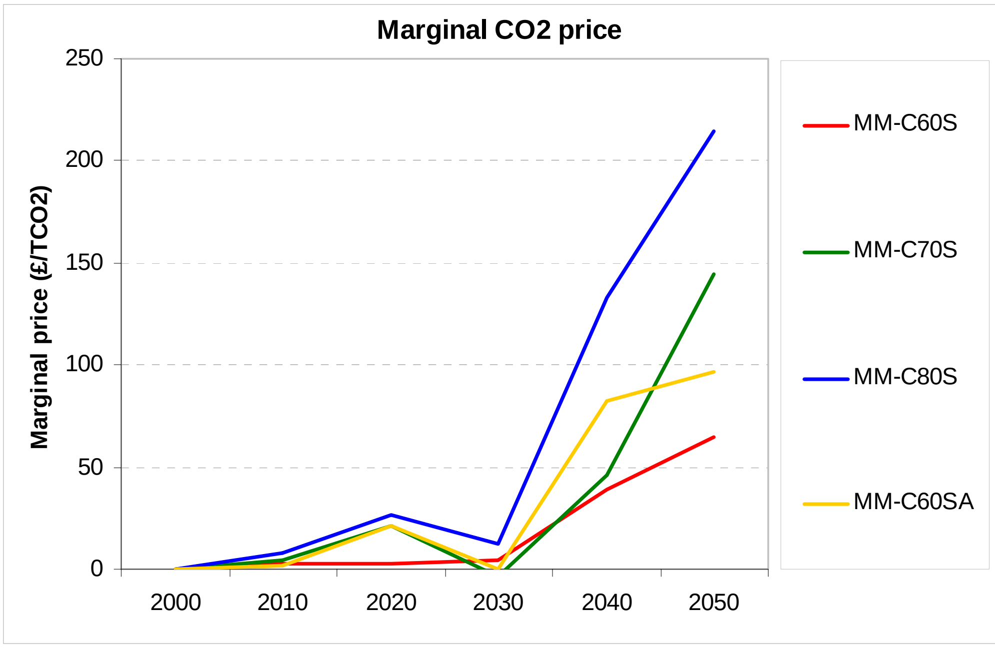


Figure 3.45 Comparison of marginal cost of CO_2 for SLT, ALT and international aviation CO_2 constrained runs

These increased marginal CO_2 abatement costs are also mirrored in the significantly higher GDP losses for the international aviation constrained run – as shown in Figure 3.46. In 2050 these reach 34.8 £Billion, compared to 22.2 £Billion for the 60% SLT run without international aviation (representing 1.24% compared to 0.79% of total GDP respectively).

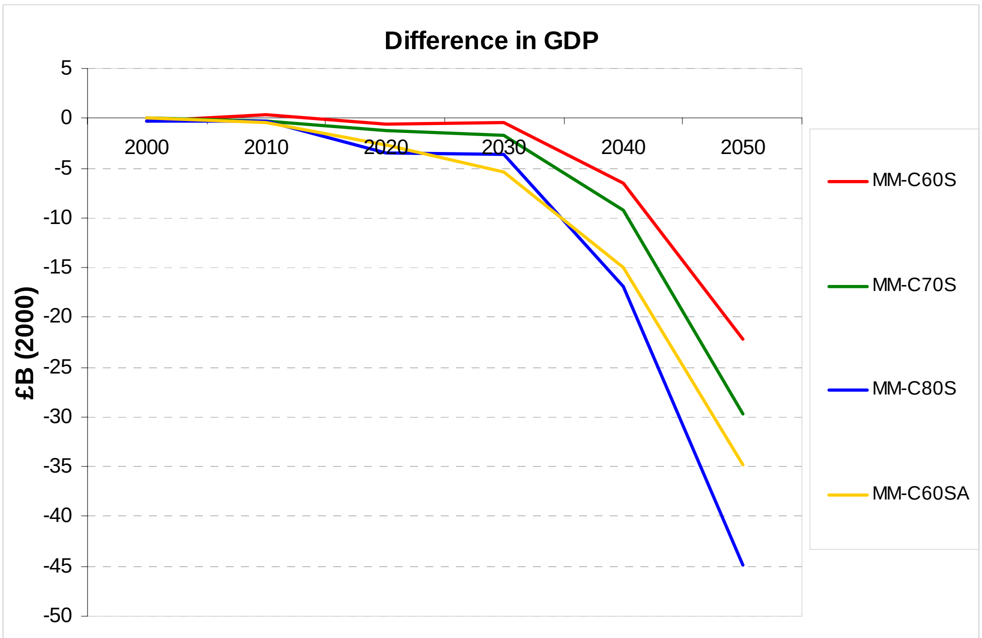


Figure 3.46 % change in GDP relative to the relevant baseline for different constrained CO_2 runs (MM-C60SA is relative to the international aviation baseline MM-BASAA, the remainder are relative to the regular baseline run MM-BASA)

4 Key insights and conclusions

The objective of the analysis described in this report has been to provide insights into the impacts (economic and technological) of imposing more stringent CO_2 constraints on the energy system – 70% and 80% reductions by 2050. This work builds on that undertaken as part of supporting analysis for the 2007 Energy White Paper (described in the *EWP 07 MARKAL analysis* report), where the impact of 60% reductions in 2050 was assessed. In addition, this analysis also considers the impact of including emissions from international aviation, and the implications for abatement in other sectors.

Although probably clear to the reader, it is important to highlight the comment in *EWP 07 MARKAL analysis* report that *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*. Hence it should be stressed that these are useful and informative insights based on the many assumptions in the model, not necessarily the definitive answers to challenging and complex energy issues.

There are a number of headline messages emerging from this analysis:

- Increasingly stringent constraints on the energy system force even more radical change on the energy system, in terms of energy mix and technology take-up, than seen in the previous 60% constraint runs. The choice of energy and technologies reflects the very many trade-offs in the system in moving to a lower carbon economy.

- Importantly, the energy system still has the necessary abatement options to be able to ensure that significant additional reductions in CO_2 can be met, even when the system is further constrained in terms of technological innovation and other cost-effective options.

- As concluded in the previous EWP 07 MARKAL analysis, all sectors contribute (fairly equally) to emission reductions (based on allocation of end-use emissions from electricity and hydrogen production) although the relative timings of contributions differ. The electricity sector is a key sector for realising emission reduction targets, almost fully decarbonising by 2050.

- Additional reductions in CO_2 emissions lead to higher marginal abatement costs, as abatement measures chosen by the model become increasingly more expensive (less cost-effective). This indicates that as constraints become more stringent, the energy system requires a higher CO_2 price signal to respond accordingly.

- The impacts on GDP are also more significant, as consumption and investment levels decrease further due to increasing energy payments. Under a 70% constraint, GDP decreases by 1.1% (£B29.8) in 2050 while under an 80% constraint it decreases by 1.6% (£B44.9). This compare to 0.8% reduction in 2050 under a 60% constraint (or £B22.2 loss).

- Inclusion of international aviation in the model results in significant additional burden on the other parts of the transport sector and on the wider energy system to provide additional CO_2 reductions, due to the inability of aviation to make significant emission reductions other than by reducing demand. This impacts on the marginal CO_2 abatement costs and GDP losses for the 60% STL runs with international aviation, which are similar to those in the (non-aviation) 70% SLT runs.

The three sections that follow do not reflect the findings of the analysis to assess the impact of the inclusion of international aviation. This is included in the fourth section, titled *International aviation.*

System evolution

System evolution considers changes in the primary and final energy demand across the time period, and the impact on CO_2 emissions.

Total **primary energy** use in the UK energy system under the base case first decreases to 2030, then rises to comparable levels in 2050 to those observed in 2000. This reduction to 2030 is due to the energy system, without any additional constraints, moving towards more cost-effective technologies (hybrid and hydrogen fuel cell vehicles cars in the transport sector) and conservation measures (in the base case). The introduction of carbon constraints leads to significant reductions in primary energy use, as the energy system moves to using energy more efficiently and using less energy (through increasing levels of conservation / endogenous demand response). Reductions are greater the more the system is carbon constrained; under an 80% constraint, primary energy has reduced by up to 37% by 2050. Under the 60% constraint, the reduction is approximately 31%. Final energy consumption follows a similar trend.

The evolution in the type of energy provides a picture in 2050 of significantly lower coal and gas use, and limited use of transport based fossils fuels. Renewables and nuclear (for electricity generation) are much more significant, while biomass provides much of the energy needs of the road transport sector. Compared to the system under a 60% reduction, differences in 2050 under a 70% reduction constraint include use of nuclear in the electricity generation sector and less use of fossil fuels in the transport sector.

The 80% constraint has much higher levels of renewable use, driven by increasing electricity generation from wind. Natural gas use is noticeably lower, with end use sectors (particularly residential sector) shifting from natural gas use to low carbon electricity. Constraining levels of biomass inevitably leads to increased use of refined oil products, whilst limits on wind generation leads to the take-up of gas CCS (Carbon Capture and Storage) and increased levels of nuclear generation. Limits to key carbon abatement technologies in the electricity generation sector (nuclear and CCS) result in increasing reliance on wind generation. Additional constraints to ensure more realistic wind penetration mean that end-use sectors have to rely more heavily on conservation and endogenous demand response rather than low carbon electricity as before.

By 2050, all end-use sectors are contributing to the significant reductions required to meet **CO_2 emission** targets. Relative to the 60% constrained case, under more stringent constraints, all sectors make additional contributions to mitigation, with the transport and residential sectors tending to contribute to a more significant proportion of total abatement in 2050. The transport sector is an interesting case as emission reductions are 'hidden' in the base case as the vehicle fleet moves to hybrid and hydrogen vehicles even in the absence of constraints. Therefore emission reductions are less obvious. Significant additional abatement above the baseline from this sector occurs post-2030 due to the increase in hydrogen use and then again in 2050 as oil-based fuels are increasingly replaced by biofuels.

The electricity generation sector, with the technological options to decarbonise fully, is critical to achieving the reductions in 2050 (and in other target years along the emission reduction trajectory) under both 70% and 80% constraints as was observed in the *EWP 07 MARKAL analysis*. Under an 80% constraint, it accounts for over 50% of the required emission reductions in 2050. However, it is worth noting that this is enabled by large amounts of wind generation (with little account for grid stability or constraint issues, planning etc) and a prominent role for CCS, a technological option still at the demonstration stage).

Technology pathways

The focus of the assessment of technological change was the electricity generation and transport sectors. These are key sectors to ensure the UK can move to a low carbon energy system. However, it is also important to recognise the role of other end use sectors all of which play a role in carbon reductions even though the technology pathways for those sectors have not been presented in detail.

In the previous analysis for the EWP 2007 where the impacts of a 60% reductions by 2050 were analysed, the **electricity generation sector** moved from a coal dominated base case to one that featured a diverse generation profile, with coal CCS and renewables the key technologies. The main changes observed from moving to a 70% reduction by 2050 is an overall higher level of generation delivered by nuclear generation. Coal CCS levels are the same because capacity bounds had already been reached while gas is no longer part of the mix. Under an 80% constraint, generation levels are even higher, made possible by large amounts of new offshore wind capacity. Marine technologies also feature but at low capacity levels. The additional electricity generation appears to be largely driven by end use sectors shifting away from gas to low carbon electricity.

Sensitivity analysis around key assumptions on wind, CCS and nuclear provide additional insights. Limits on new nuclear build result in wind generation filling the gap. However, if the role of wind generation is constrained, gas CCS becomes the significant generation technology, accounting for up to 50% of overall output. Gas CCS is chosen instead of coal CCS because higher levels of gas CCS generation can be achieved under a given CCS storage bound because the carbon intensity of this generation type is lower.

No nuclear or CCS build again leads to domination by wind generation due to limited constraints. Introducing constraints on the role of wind results in electricity generation output falling to the levels observed under the 70% constraint case. End use sectors invest significantly in additional conservation, and reduce their demand (through the endogenous demand response) in the absence of high levels of low carbon electricity previously available under the standard 80% constraint.

As previously mentioned, under the base case (in the absence of constraints), the **transport sector** is already moving towards more efficient technologies e.g. hybrids. Large reduction targets for CO_2 lead to overall energy demand decreases as vehicles become more efficient but also as a result of demand reduction in response to price increases. A more important role for biomass emerges in later periods, particularly biomass-to-liquid fuels (BtL), than seen in the EWP analysis. In the 80% reduction cases, by 2050 biofuels account for over 60% of total transport fuels leading to limited or no further use of conventional road transport fuels (petrol and diesel). Constraints on biofuels in transport result in a greater role for petrol and diesel

In periods preceding 2050, hydrogen use is highest in the base case. Lower levels in the constrained cases reflect the fact that the hydrogen production in the base case is through carbon intensive fossil fuels. Much of the hydrogen that is used in the last period under the 80% constrained case is from hydrogen production from electrolysis, using low carbon electricity.

Considering technologies used in the road transport sector, it is interesting to observe that with the exception of the restricted innovation case, the use of diesel and hybrid vehicles in 2050 is at the same level to that observed in the base case(s) due to constraints on fleet profile. The high level of conventional diesel vehicles is enabled due to the use of BtL (Biomass-to-liquid fuels or second generation biodiesel), replacing diesel. A 70% reduction in 2050 leads to some changes from the previous 60% analysis, with no flex-ethanol, methanol fuel cell or conventional petrol vehicles in the mix. A reduced demand and petrol hybrids ensure levels of demand are still met. In the 80% reduction cases, methanol fuel cell vehicles are taken up with less use of petrol hybrids. The uptake of different technologies suggests that differences in relative unit costs of these technologies in 2050 are small.

Demand response is an important feature of the MARKAL Macro model, enabling the model to reduce costs through reductions in consumer demand for energy rather than have to invest in higher cost, low carbon technologies. As emission constraints get more stringent, demand response becomes an increasingly important mechanism to help minimise the marginal costs of abatement; under the 60% constraint, demand reductions of around 9-13% in 2050 can be observed (excluding transport). In 2030 – when constraints are lower, demand responses are below 5%. Transport also reflects these demand response trends but at lower reduction levels. Under an 80% constraint, the reductions are between 15-20% in 2050. This suggests that where low carbon options are more expensive, demand reductions are even greater as the system tries to minimise costs. Interestingly, the demand response trend follows the marginal abatement cost trends, indicating that the level of marginal costs is a significant driver of the demand response.

The relative response between sectors differs, with the largest reductions seen in the residential, industry and agriculture sectors. Transport is the least responsive sector, most likely due to a relatively inelastic demand response.

The system can also reduce demand through the uptake of conservation measures. Relative to the analysis of a 60% reduction, the use of conservation does increase when emission constraints are tightened but only by limited levels. Under the 60% case, most cost effective conservation has been taken, with potential remaining for more expensive conservation measures. Expensive conservation measures are taken up, particularly in the residential sector, in the most constrained cases e.g. no nuclear or no nuclear / CCS, with additional bounds on wind generation and biomass resources.

Economic impacts

Marginal abatement costs increase significantly as emission reduction targets are increased. For the 60% reduction case (under the EWP analysis), costs were approximately £65/tCO_2 (£240/tC). These increase to £145/tCO_2 (£530/tC) under a 70% constraint and £215/tCO_2 (£790/tC) under an 80% constraint. Where additional constraints are put on the system, these costs are pushed up further, with £395/tCO_2 (£1450/tC) under the 80% reduction case, where CCS / nuclear technologies are not available, and additional wind generation and biomass resource constraints are introduced. The marginal costs also differ across the time horizon; under the alternative emission reduction trajectory (where emission reduction targets are markedly higher in earlier years), costs are unsurprisingly higher than seen under the core SLT cases. In many of the runs, a reduction in costs in 2030 relative to 2020 indicates the emergence of more cost-effective low carbon technologies.

The Macro model also makes a direct calculation of **GDP**, based on the interactions between the energy sector and the rest of the economy, and how this impacts on levels of consumption and investment. In the EWP 2007 model runs, a 0.8% (£B22.2) loss in GDP was estimated based on the SLT 60% reduction run. The most significant GDP losses in the *EWP 07 MARKAL analysis* were observed under the 60% restricted innovation post-2010 case at 1.5% (or £B42.0).

In this analysis, all 70% reduction cases lead to estimated GDP losses of around 1.1% in 2050. Cumulative losses are of course greater for the MM-C70A case (alternative trajectory) where higher constraints are imposed across the emissions reduction trajectory. For the 80% reduction cases, losses are between 1.6 and 1.8% except for the high resource cost and restricted innovation cases, where losses are 1.1% (£B31.6) and 2.6% (£B73.0) respectively. Again, the 80% alternative trajectory leads to greater cumulative GDP losses.

International aviation

The inclusion of international aviation emissions in the energy system results in the need for significant additional reductions in CO_2 across the system. This is due to the apparent inability of the aviation sector to achieve reductions though technological or fuel switching means – relying on demand reduction to contribute to emissions reductions required under the 60% reduction case.

Under 60% CO_2 constraints, the wider system changes resulting from the inclusion of international aviation include a substantial increase in nuclear electricity generation and increased use of BtL diesel and hybrid petrol car technologies in the transport sector.

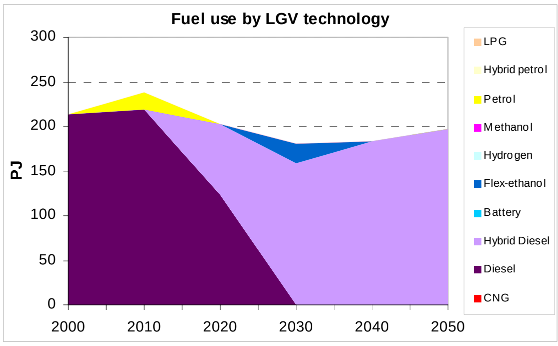
The resulting 2050 marginal CO_2 abatement costs (97 £/tCO_2) and GDP losses (1.24%, 34.8 £Billion) of 60% constrained runs are mid-way in between those reached by the 60% and 70% constrained runs without international aviation.

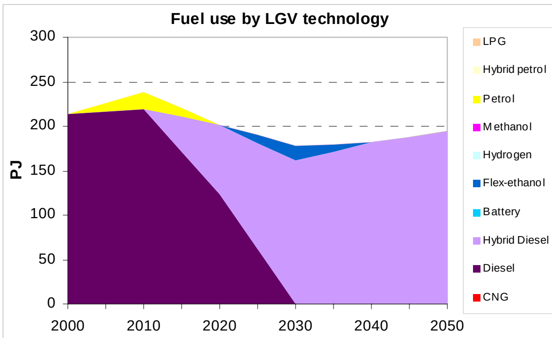
Annexes

Annex 1: Transport technologies in Base, 60%, 70% and 80% SLT constrained cases

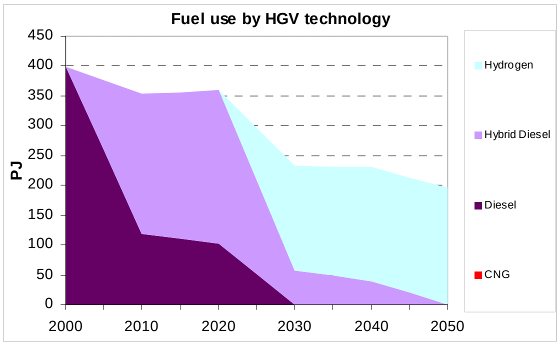
Mode **MM-BASA** **MM-C60S**

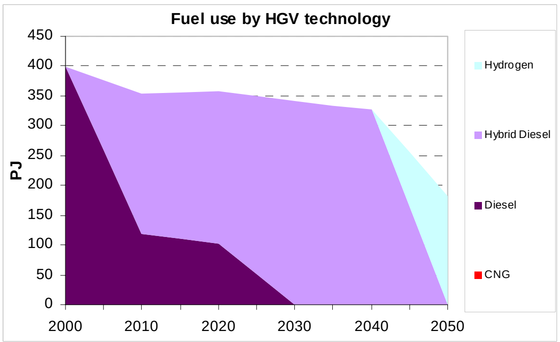
LGVs



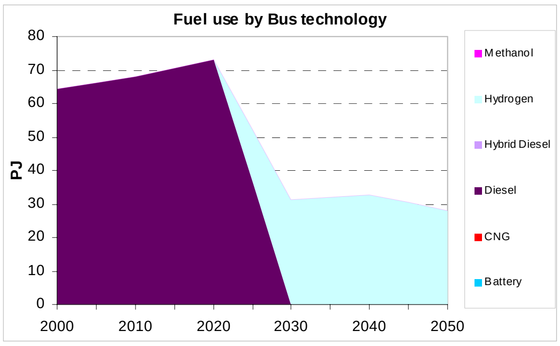


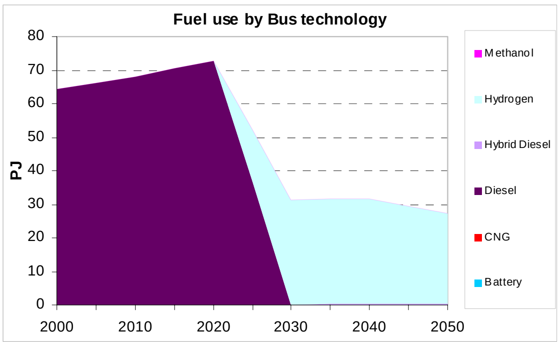
HGVs



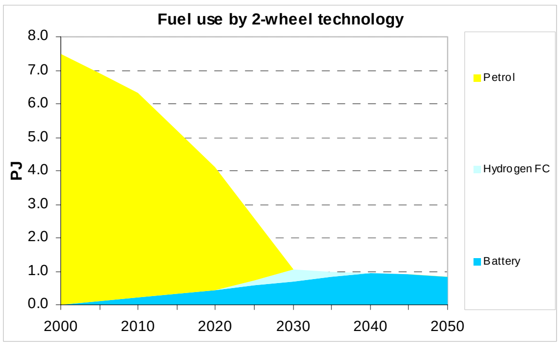


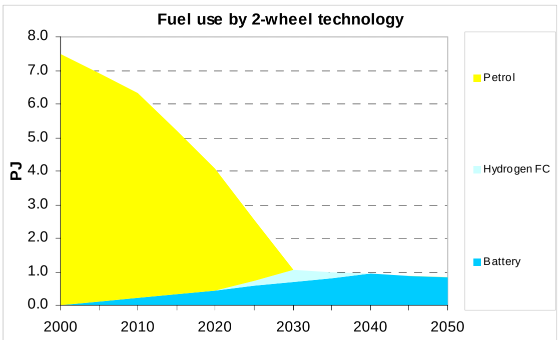
Buses





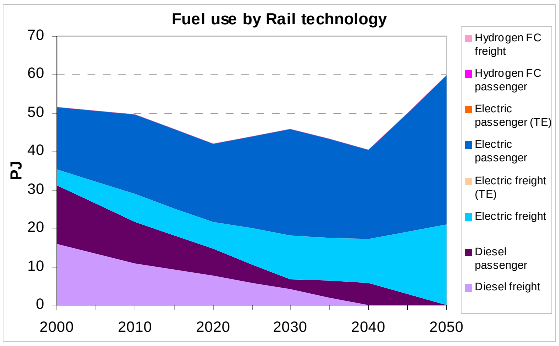
2-wheels

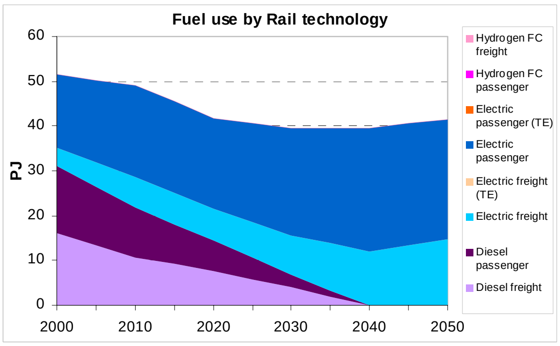




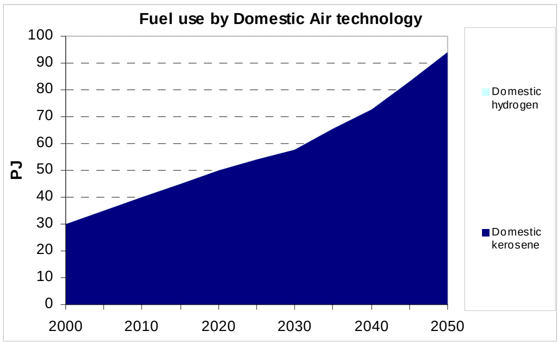
Mode **MM-BASA** **MM-C60S**

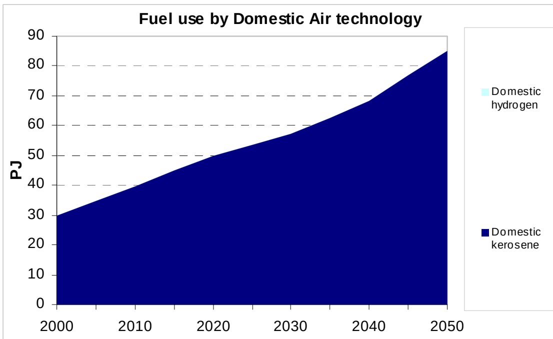
Rail





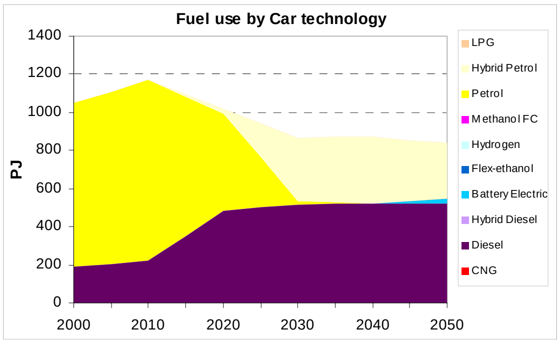
Air (dom)

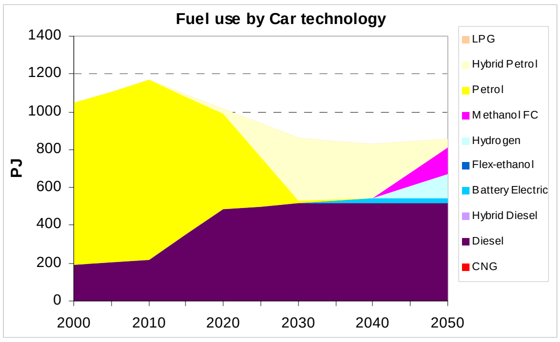




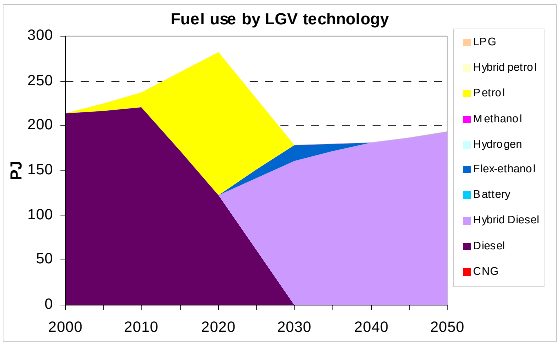
Mode **MM-C70S** **MM-C80S**

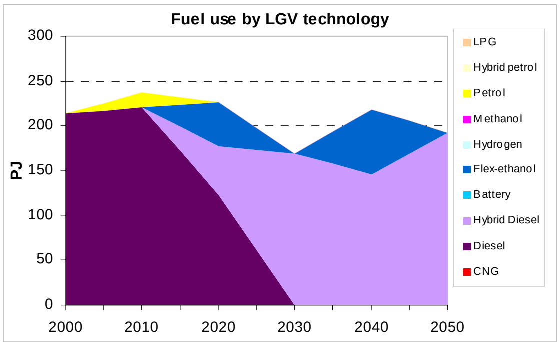
Cars



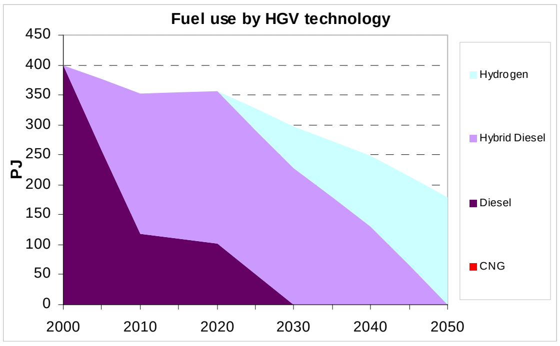


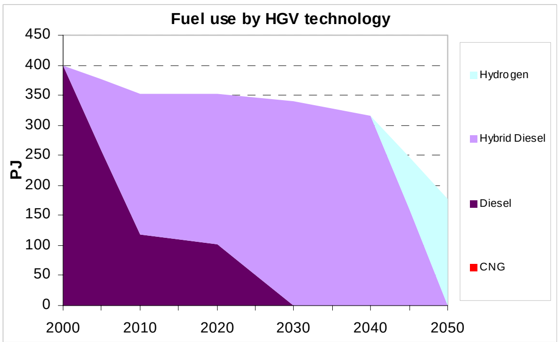
LGVs

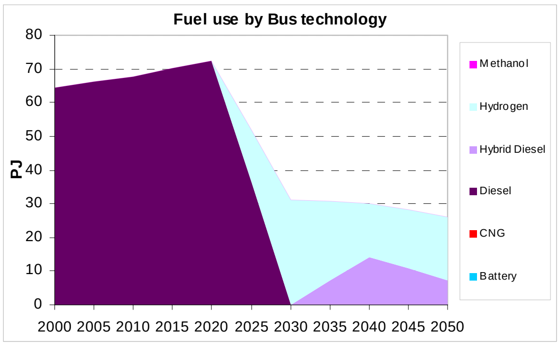
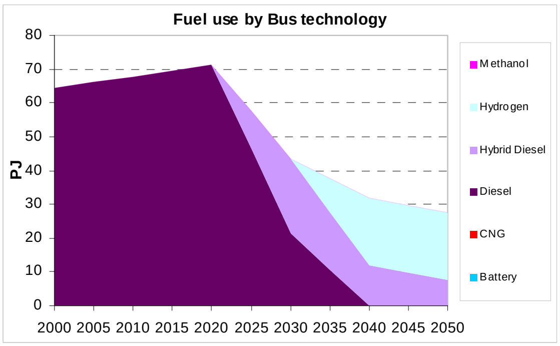
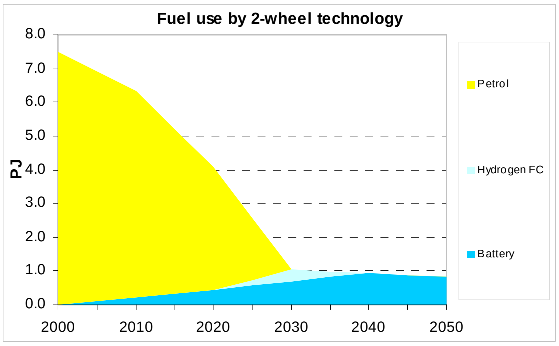
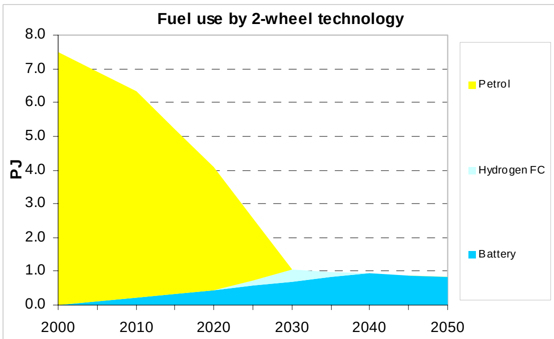
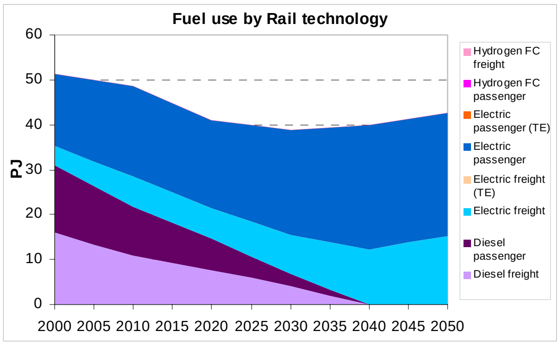
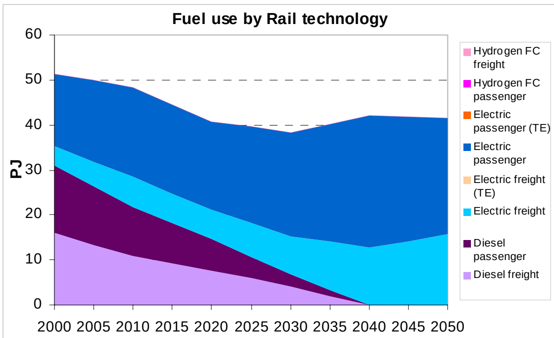
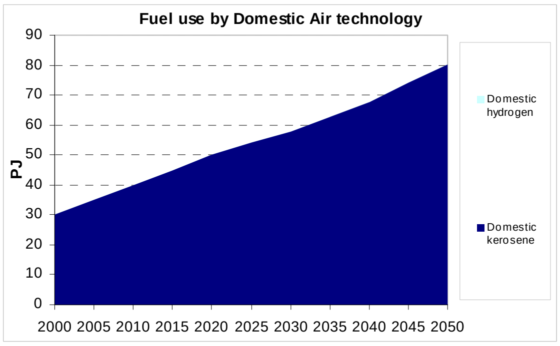
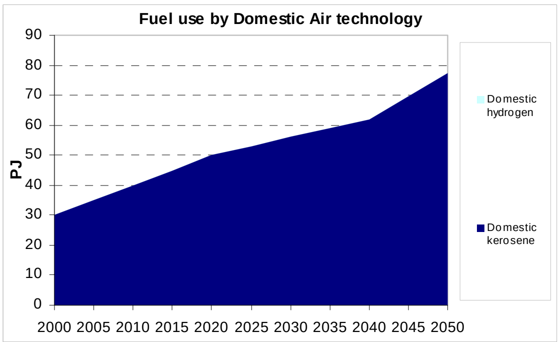




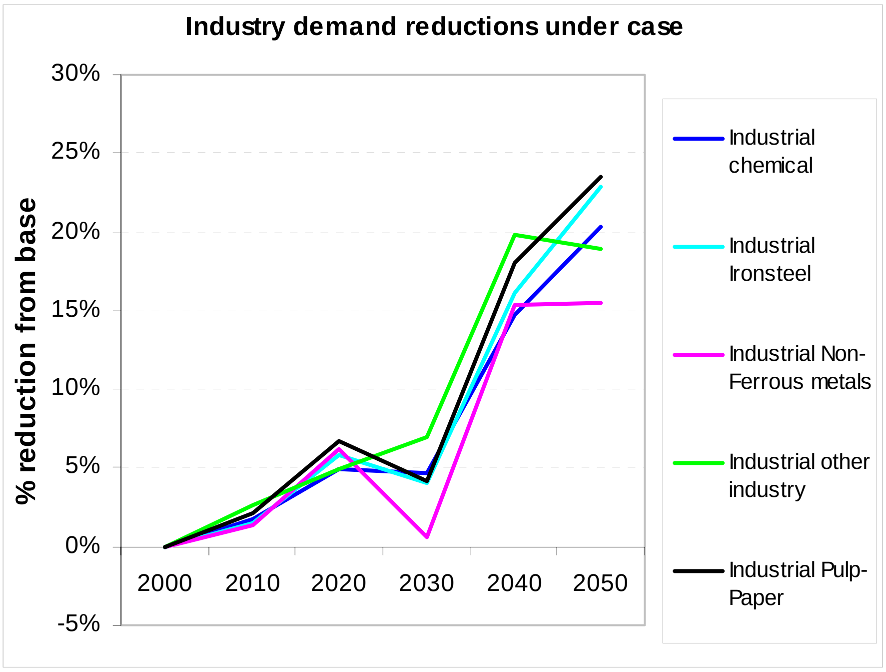
HGVs

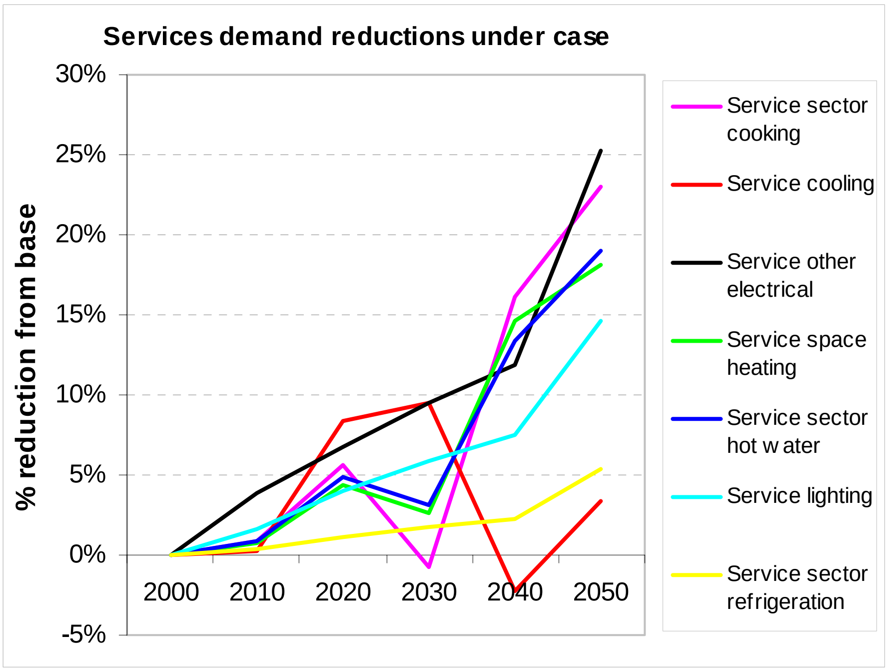


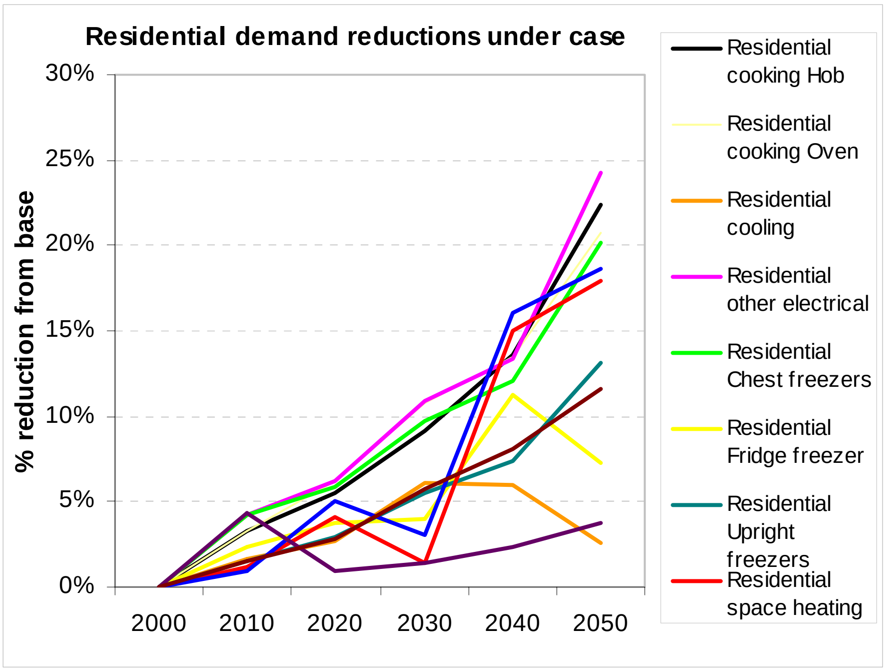


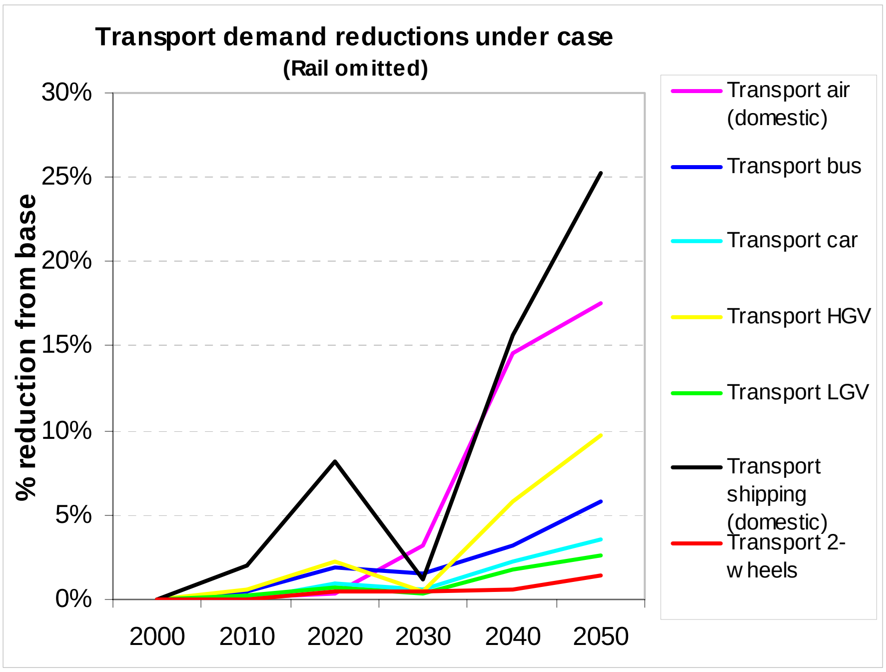
Mode	**MM-C70S**	**MM-C80S**
Buses		
2-wheels		
Rail		
Air (dom)		

Annex 2: Sector-specific demand responses for 80% SLT constrained case






Residential demand reductions under case
% reduction from base
30%
25%
20%
15%
10%
5%
0%
2000
2010
2020
2030
2040
2050
Residential cooking Hob
Residential cooking Oven
Residential cooling
Residential other electrical
Residential Chest freezers
Residential Fridge freezer
Residential Upright freezers
Residential space heating


Transport demand reductions under case
(Rail omitted)
% reduction from base
30%
25%
20%
15%
10%
5%
0%
2000
2010
2020
2030
2040
2050
Transport air (domestic)
Transport bus
Transport car
Transport HGV
Transport LGV
Transport shipping (domestic)
Transport 2-w heels

Annex 3: Model set up and checking

Prior to undertaking the set of model runs, a process of model set-up and checking was undertaken. This was to ensure that model runs were consistent with analysis undertaken as part of the 2007 Energy White Paper (EWP) MARKAL work (PSI/AEA, 2007[16]).

In the first instance, several key MARKAL-Macro runs from the EWP work were run – base (MM-BAS) and constrained bases with 60% CO_2 constraint in 2050 (MM-C60) and 60% CO_2 in 2050 with Straight Line Trajectory from 2010 (MM-C60R), the results of which were then compared. In summary, the EWP runs could not be replicated exactly. This is essentially because the model software has been updated (to ANSWER 6 from 5). Changes to the underlying code have also been made since the runs by PSI – including updated GAMS 22.5 from 22.0 and updated MARKAL model code from version 5.4a to version 5.7c. In simple terms, the model software has been further developed since the EWP runs were undertaken.

Despite not replicating the model runs exactly, using the updated software the results are reasonably comparable. The principal differences identified are as follows:

- **Total system costs** are a very close match in the base case (B£1451.5 for the AEA rerun compared to B£1452.8) and simple 60% CO_2 constrained runs, but are slight further apart for the 60% SLT runs (B£ 1,441.8 for the AEA rerun compared to B£1,446.9).
- **Utility objective function** is an identical match
- **CO_2 emissions:** in the constrained case there is a small variation in 2020 emissions; a significant variation in the base case in 2030 due to large increase in coal.
- **Electricity output:** in the constrained case there is a small variation in total electricity output (down by 37 PJ in 2050); more pronounced differences in base case (with lower levels in later periods – down by 152 PJ in 2050). See Figure A3.1 and Figure A3.2.
- **Electricity technologies:** there is a significant difference in the constrained case for the nuclear technology in 2050 (up from 60 to 148 PJ). There is also some coal replaced by gas technologies in later periods in the base case. However apart from this differences are relatively few. See Figure A3.1 and Figure A3.2.
- **Marginal abatement costs:** There are small differences between simple 60% CO_2 constrained case (10% higher in 2040 / 50 in the AEA reruns), but more significant differences in the 60% SLT constrained case particularly from 2040 to 2050 where values increased much more sharply up to 104 £/tCO_2 in the AEA rerun, compared to from 65 £/tCO_2 in the PSI case.
- **Demand levels:** demand levels were also checked; in both baseline and constrained cases, the differences are relatively small (a few %). Larger percentage changes are often on relatively small demand sectors.
- **Macro parameters:** GDP, Investment, Consumption and Energy Costs are also all reasonably close between the PSI cases and the AEA reruns.

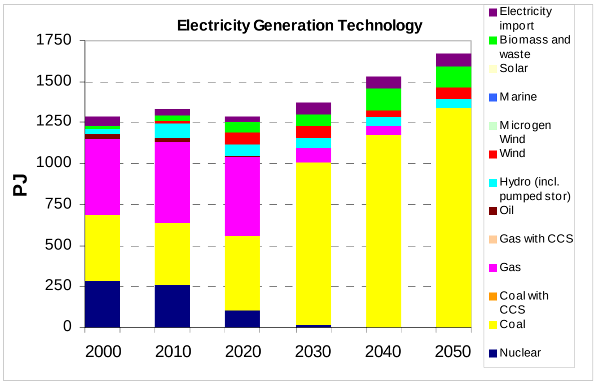
Based on internal discussions and with PSI and Gary Goldstein AEA initially proposed to live with these differences. Such differences are small at the aggregate level and are likely to be lost in the noise of increasingly significant CO_2 constraints anyway. This was subsequently agreed with Defra at the interim meeting, as significant additional time and resources could have been invested in trying to resolve differences that may not be resolvable based on the modelling software that we are using.

However, following the interim meeting subsequent dialogue with Gary Goldstein revealed it was possible to relatively easily temporarily revert to the earlier GAMS and MARKAL code used by PSI. Doing this resolved the discrepancies between the AEA reruns and original PSI EWP 07 runs to the extent that the results were identical. The new model runs for this work for Defra (presented in this report) were therefore then rerun using this older model codes to ensure full comparability and consistency with the EWP 07 results.

MM-BAS: PSI original run **MM-BAS: AEA rerun**

[16] "Final Report on DTI-DEFRA Scenarios and Sensitivities using the UK MARKAL and MARKAL-Macro Energy System Models", Final Report prepared by the Policy Studies Institute for the Department of Trade and Industry (DTI) and the Department of Environment, Food and Rural Affairs (DEFRA). Dr Neil Strachan and Ramachandran Kannan, Policy Studies Institute; Steve Pye, AEA Energy and Environment. May 2007.

(GAMS 22.0 and MARKAL v5.4a)



(GAMS 22.5 and MARKAL v5.7c)

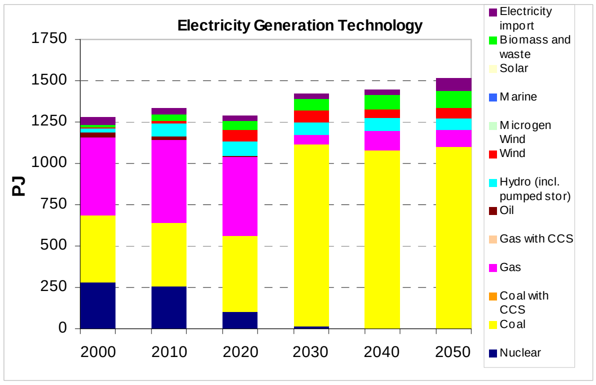
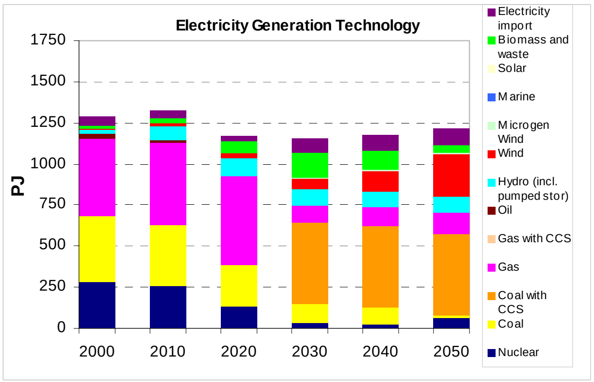


Figure A3.1 Electricity Output by Generation Technology: Comparison of original PSI runs of base case with AEA reruns

MM-C60R: PSI original run
(GAMS 22.0 and MARKAL v5.4a)



MM-C60R: AEA rerun
(GAMS 22.5 and MARKAL v5.7c)

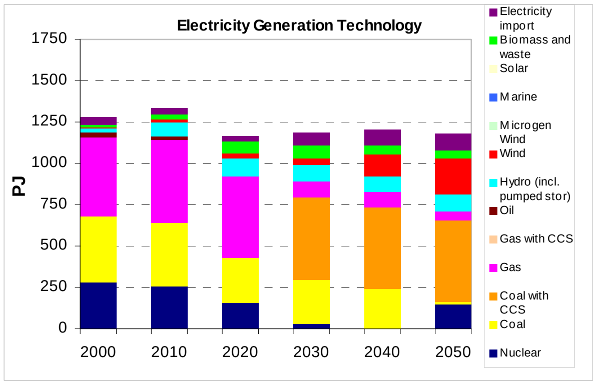


Figure A3.2 Electricity Output by Generation Technology: Comparison of original PSI runs of 60% CO_2 SLT case with AEA reruns

Annex 4: Technical modelling information

70% and 80% SLT / ALT model runs

Item	
Model databases	UK Markal 2-7 v15 PSI MM - GAMS22.0 - AEA29Aug07.mbd / UK Markal 2-7 v16 PSI MM - IntAviation - AEA4Sep07
GAMS version	22.0
MARKAL version	5.4a
ANSWER version	6.2.6

Run No.	Run Name	Date / Timing
1	MM-C70S	28/08/2007 14:49
2	MM-C80S	28/08/2007 14:49
3	MM-C80S1	28/08/2007 14:49
4	MM-C80SH	28/08/2007 14:49
5	MM-C70A	28/08/2007 14:49
6	MM-C80A	28/08/2007 14:49
7	MM-C70BW	31/08/2007 12:16
8	MM-C80BW	31/08/2007 12:51
9	MM-C70SN	16/10/2007 11:56
10	MM-C80SN	16/10/2007 12:19
11	MM-C80NC	16/10/2007 18:00
12	MM-C70CC	25/10/2007 19:19
13	MM-C80CC	25/10/2007 18:55
14	MM-C80XC	25/10/2007 08:36

60% SLT international aviation model runs

Item	
Model database	UK Markal 2-7 v16 PSI MM - IntAviation – AEA4Sep07.mbd
GAMS version	22.0
MARKAL version	5.4a
ANSWER version	6.2.6

Run No.	Run Name	Date / Timing
15	MM-BASAA	19/09/2007 17:47
16	MM-C60SA	20/09/2007 12:49

Annex 5: Technology assumptions for aviation

The following section is an extract from Chapter 8 of PSI/AEA, 2007[17] that summarises the aircraft technology assumptions developed as part of the MARKAL transport module update work carried out in 2006 for UK ERC / DTI. Both the domestic and international aviation technology datasets were already included in the UK MARKAL Macro model version used in the 2006 Energy Review and 2007 Energy White Paper modelling work. However, international aviation was effectively switched off (with demand set to zero) in the EWP analysis.

General

The aviation vehicle dataset (split into domestic and international aircraft) was primarily based upon a number of UK reports from DfT and Defra, plus information from IPCC's 1999 report and on data from IEA H2FC (2005) for hydrogen fuelled aircraft (see references section). An aircraft lifetime of 30 years is assumed (intermediate value in the 25-35 year range in IPCC, 1999). Average annual km of domestic (1 million km) and international (1.7 million km) aircraft were estimated from Civil Aviation Authority (CAA, 2006) statistics on annual km and fleet numbers by aircraft type for 2000, selecting a mix of representative aircraft according to those utilised by DfT (2003) in emission forecasts. Average seating occupancy for domestic (64%) and international (77.9%) aircraft were taken from DfT statistics for 2000.

Table A5.1 Air transport technologies – basic assumptions for new aircraft

Year 2005	Annual km	Tank size, MJ	Tank size, litres	Normal av. range, km	Capacity /Seats	Load Factor
Air (domestic)	1,000,000	995,044	28,320	4,867	156	65%
Air (international)	1,700,000	2,878,972	81,938	10,123	355	80%

Efficiency

Fuel consumption for year 2000 domestic and international aircraft was calculated from global figures on fuel usage and km travelled from Defra (2005). Year 2010 efficiency improvements (-18.7%) were based on 10% improvement in engines from IATA (2006) and 5% reduction for minimum airframe improvements and 4.9% for minimum operational/Air Traffic Control (ATC) improvements from ADL (2000). Incremental improvements were calculated for kerosene aircraft in 10 year steps to 2050 with -50% energy use relative to 2000, based on engine, airframe and operational improvements from ADL (2000) and on IPCC (1999).

New airframe concepts (such as the Blended Wing-Body) are introduced for international aircraft in 2020, with reductions in energy use of -10% compared to conventional kerosene in 2020, dropping to -30% by 2050 (maximum potential according to IPCC, 1999). Cryogenic hydrogen fuelled aircraft are introduced from 2020 with efficiencies 27.5% poorer than conventional kerosene aircraft (IPCC, 1999), falling to 20% poorer by 2040 (IEA H2FC, 2005), with improvements in line with conventional aircraft thereafter.

Table A5.2 Air transport technologies – efficiencies of new aircraft

Technology	Efficiency (MJ/km)					
	2000	2010	2020	2030	2040	2050
Kerosene (domestic)	204.47	166.18	148.15	131.38	115.84	101.48
Hydrogen (domestic)			188.89	162.04	139.01	121.78
Kerosene (international)	284.40	231.15	206.06	182.74	161.12	141.15
BWB kerosene (international)			185.46	155.33	128.90	98.81
Hydrogen (international)			262.73	225.38	193.35	169.38

[17] "Final Report on DTI-DEFRA Scenarios and Sensitivities using the UK MARKAL and MARKAL-Macro Energy System Models", Final Report prepared by the Policy Studies Institute for the Department of Trade and Industry (DTI) and the Department of Environment, Food and Rural Affairs (DEFRA). Dr Neil Strachan and Ramachandran Kannan, Policy Studies Institute; Steve Pye, AEA Energy and Environment. May 2007.

Table A5.3 Air transport technologies – gCO2/pkm of new aircraft

Technology	Equivalent emissions (gCO2/km)					
	2000	2010	2020	2030	2040	2050
Kerosene (domestic)	144.8	117.6	104.9	93.0	82.0	71.8
Hydrogen (domestic)			265.9	228.1	195.7	171.4
Kerosene (international)	72.3	58.8	52.4	46.5	41.0	35.9
BWB kerosene (international)			47.1	39.5	32.8	25.1
Hydrogen (international)			132.8	113.9	97.8	85.6

Notes: With the assumption on seating capacity and load factors in Table A5.1, and for illustrative comparison a hydrogen emission factor of 100 gCO2eq/MJ (based on H_2 from reforming of natural gas).

Capital costs

The seating capacities of domestic (156) and international (355) aircraft were estimated from the mix of representative short and long-haul aircraft utilised by DfT (2003) in emission forecasts. In the absence of other data these seating capacities were used to scale capital costs of conventional kerosene domestic and international aircraft using the formulae and methodology outlined in AVITAS (2005).[18] Cryogenic hydrogen planes are assumed to be 25% more expensive than conventional kerosene aircraft (IEA H2FC, 2005) in 2020 and falling to 20% more expensive by 2040 and a further 1% less per 5-year period thereafter. Blended Wing-Body (BWB) concepts are expected to be ultimately cheaper to build according to information on Boeing’s website. In 2020 it is assumed that the new concept will be 10% more expensive than conventional international aircraft, with this differential dropping by 5% in the first two periods (to 2030), 2% in the following two (to 2040) and 1% per period thereafter.

Table A5.4 Air transport technologies – capital costs of new aircraft

Technology	Capital Cost (£k, 2000)					
	2000	2010	2020	2030	2040	2050
Kerosene (domestic)	44,269,217	44,269,217	44,269,217	44,269,217	44,269,217	44,269,217
Hydrogen (domestic)			55,336,521	54,218,497	53,123,061	52,049,757
Kerosene (international)	70,896,049	70,896,049	70,896,049	70,896,049	70,896,049	70,896,049
BWB kerosene (international)			77,985,653	70,382,052	67,594,923	66,249,784
Hydrogen (international)			88,620,061	86,829,572	85,075,258	83,356,389

O&M costs

Year 2000 operating costs for conventional aircraft were calculated from CAA (2006) financial statistics and annual km for UK airlines for 2000, taking the maintenance costs only. The average aircraft annual km assumptions were used to calculate different values for domestic and international aircraft. Operating costs were assumed to decline at a rate 1% per annum (on recommendation by DfT) between 2000 and 2030, and at a reduced rate of 0.5% per annum from 2030 to 2050 (with no further decreases thereafter). For hydrogen-fuelled aircraft, additional costs were added for assumed 3 replacements of the cryogenic hydrogen storage tanks in the aircraft’s lifetime. Operating costs for BWB kerosene aircraft were assumed to be the same as conventional equivalents.

[18] AVITAS are a leading provider of aircraft market valuation information.

Table A5.5 Air transport technologies – operating costs of new aircraft

Technology	Operating Cost (£k/year, 2000)					
	2000	2010	2020	2030	2040	2050
Kerosene (domestic)	897,260	826,863	747,800	676,297	643,233	611,785
Hydrogen (domestic)			1,244,778	1,027,740	906,020	822,613
Kerosene (international)	1,525,342	1,405,667	1,271,260	1,149,705	1,093,496	1,040,035
BWB kerosene (international)			1,271,260	1,149,705	1,093,496	1,040,035
Hydrogen (international)			2,709,171	2,166,538	1,853,820	1,650,025

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