AEA Energy & Environment
From the AEA group

Optimising delivery of carbon reduction targets: integrating air quality benefits using the UK MARKAL model

Report to Department of Environment, Food and Rural Affairs (Defra)

Restricted Commercial

Issue 3 (Final)

November 2008

Title	Optimising delivery of carbon reduction targets: integrating air quality benefits using the UK MARKAL model
Customer	Defra
Customer reference	
Confidentiality, copyright and reproduction	
File reference	
Reference number	Issue 3 (Final)

Steve Pye
Central House
14 Upper Woburn Place
London, WC1H 0JN

t: 0870 190 6554
f: 0870 190 5545

AEA Energy & Environment is a business name of AEA Technology plc

AEA Energy & Environment is certificated to ISO9001 and ISO14001

Author	Name	Steve Pye Tom Palmer
Reviewed by	Name	Heather Haydock
	Signature	
	Date	24th November 2008

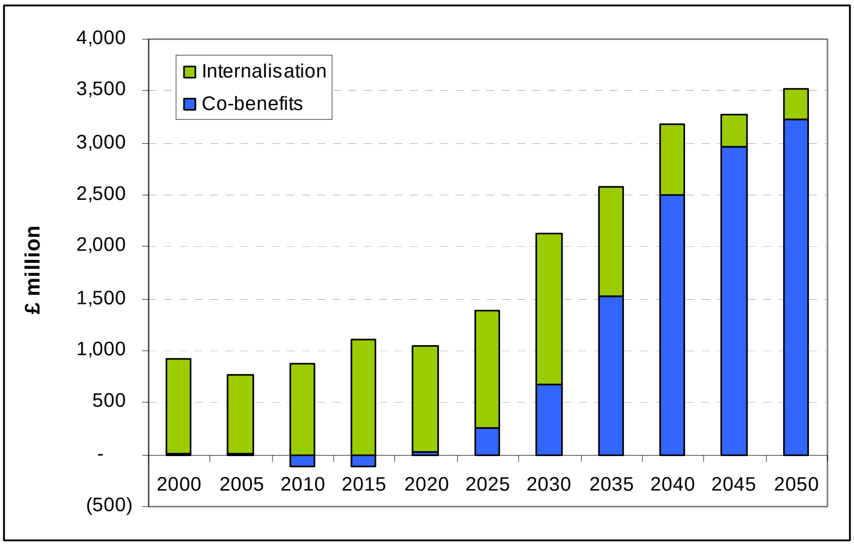
Executive summary

Many measures or policies that are introduced to reduce Greenhouse Gas (GHG) emissions also act to reduce air pollutant emissions, and the associated externalities. This is primarily because of the emissions of both types of pollution from the combustion of fossil fuels. The importance of estimating these ancillary benefits (or co-benefits) is to understand the full impacts on society from climate policy. Whilst the full benefit of GHG reductions from climate policy will mostly be experienced by future generations, the ancillary co-benefits of climate policy occur now.

To date, UK MARKAL analysis has not captured these co-benefits. In this analysis, the UK MARKAL Elastic Demand model was run to assess the impact of stringent carbon reduction targets (33% in 2020, 80% in 2050 relative to 1990 levels) on air quality emissions.

Significant co-benefits are realised under this modelling (as shown by the blue shaded bars in the figure below). These are associated with the significant changes in the system post-2030, when the system uses limited fossil fuels. Costs are seen in earlier years due to the uncertain assumptions on PM_{10} emissions from biomass use in the residential sector. In 2050, the annual undiscounted reduction in damage costs exceeds £3 billion.

Co-benefits of climate policy (under 33/80 trajectory) on AQ pollutant emissions (NOx, PM_{10}, SO_2) with and without damage costs internalised (annual undiscounted, £ million) under 33/80 trajectory



NB. Capital costs annualised based on technology specific discount rate

Internalising damage costs in the model optimisation results in increased benefits (as shown by the green shaded bars), particularly before 2030, where higher levels of fossil fuel use exist. These increased benefits are due to power plant switching to coal generation with FGD and the residential sector not using biomass.

Internalising damage costs leads to lower (undiscounted) losses in economic surplus over the model horizon. This is based on the model balancing the need to meet energy service demands against the cost of emission taxes and the abatement requirements under a stringent carbon constraint.

A similar comparison is difficult to make in terms of discounted costs due to the way the model is set up. However, an important conclusion can be drawn from this analysis; that the inclusion of AQ damage costs on the model results in higher total system costs although these costs are not significantly higher, reflecting the many synergies between AQ damage cost reduction and carbon mitigation.

In summary, there are significant synergies between climate and air quality policy. There is limited conflict between policy objectives due to the use of biomass (reducing CO_2 but increasing PM_{10}). However, the PM_{10} emission factors are highly uncertain.

Acknowledgements

The authors of the report acknowledge the important contributions by:

Melanie Hobson, Anne Wagner (AEA) and Nazmiye Ozkan (PSI) for their work in helping set up the model to track air quality pollutants.

Paul Watkiss (PWA) for providing the AQ damage cost functions, and advice on how to use them in this analysis.

Neil Strachan and the team at KCL, who are the lead developers of the UK MARKAL model, and provided the updated MED version for use in this project.

Table of contents

1 Introduction

The proposed Climate Change Bill will introduce legislation that will require the UK to meet carbon reduction targets (to be determined) out to 2050. The Bill also proposes the setting up of a independent Committtee on Climate Change (CCC), to advise Government on the level at which to set nearer and long term carbon budgets, with at least a 60% reduction proposed in 2050 (relative to 1990 levels). The CCC will put forward recommendations on future carbon reduction targets in December of this year. [1]

During the course of 2008, AEA, in association with the Policy Studies Institute (PSI), have been undertaking a range of analysis using the UK's MARKAL Elastic Demand model (MED) to support the work of the Committee, in particular to inform the recommendations on longer term budget setting. In view of the MARKAL analysis for the CCC, Defra have requested that AEA undertake additional analysis, to assess the impact of future carbon reduction targets on air quality emissions, and the associated externalities on the model solution.

Importantly, to date analyses in the UK using MARKAL have not considered the external costs associated with air pollution. Air pollution has a number of important impacts on human health, as well as on the natural and man-made environment. These include impacts of short-term and long-term exposure to air pollution on health, damage to building materials, effects on crops (reduced yield) and impacts on natural and semi-natural ecosystems (both terrestrial and aquatic). These impacts have a number of important economic or social costs – known as external costs or externalities, as they are not included in the price of goods or services.

Many measures or policies that are introduced to reduce Greenhouse Gas (GHG) emissions also act to reduce air pollutant emissions, and so reduce these impacts and externalities. This is primarily because of the emissions of both types of pollution from the combustion of fossil fuels. The importance of estimating these ancillary benefits (or co-benefits) is to understand the full impacts on society from climate policy, as is recommended in policy appraisal guidance. Whilst the full benefit of GHG reductions from climate policy will mostly be experienced by future generations, the ancillary co-benefits of climate policy occur now. These co-benefits provide economic incentives for countries to reduce emissions, and also alter the relative attractiveness of different abatement measures in terms of their full economic costs.

In this report, we have undertaken analysis using the latest UK MARKAL model to assess the impact of future reduction targets on combustion related air quality pollutants – SO_2, NOx and PM_{10}. In addition, we have assessed the impact of including damage costs of air pollutants in the model optimisation on the technology and fuel choices made by the model. MARKAL will optimise to find the least cost mix of technologies and energy types to meet a given demand; if external costs of air pollution are also considered in the model optimisation, this has an impact on such choices.

This analysis builds on a study submitted to Defra in early 2008, titled *Air quality emissions tracking in the UK MARKAL model*. The focus of this earlier study was to incorporate air quality pollutant coefficients in the model, and undertake some diagnostic runs to check model functioning and base year pollutant emission totals.[2] The source and assumptions concerning coefficients used are described in Annex 1 of this report. Note that in this earlier work we were using an earlier version of the UK MARKAL model, undertaking model runs using a 26/60 carbon reduction trajectory, and using standard MARKAL, not MARKAL elastic demand. Therefore, the results presented in this earlier report are not comparable with those presented in this report.

[1] Committee on Climate Change recently provided advice to Government to reduce Greenhouse gas emissions in the UK by at least 80% by 2050, see http://www.theccc.org.uk/
[2] This study used an earlier MARKAL model version so part of the work under this contract has been to update the model version being used by the CCC.

1.1 The UK MARKAL model

MARKAL portrays the entire energy system from imports and domestic production of fuel resources, through fuel processing and supply, explicit representation of infrastructures, conversion to secondary energy carriers (including electricity, heat and hydrogen), end-use technologies and energy service demands in the industrial, commercial, residential, transport and agricultural sectors. This comprehensive coverage allows for full interactions across different part of the system, including between energy end use sectors.

The basic problem that MARKAL (at least the standard version) needs to solve is how energy service demands in a given period can be met at least cost. This so-called model objective function is described as the minimisation of the total energy system discounted costs over the time horizon. Important concepts embodied in the model solution include perfect inter-temporal knowledge of future policy and economic developments, and consumer-producer equilibrium.

For the CCC, we have primarily been using a MARKAL-ED version of the UK model, which captures the response of demand sectors to changes in the price of delivering energy services. This is briefly described in the Box below.

MARKAL Elastic Demand (MED)

MED allows for both the supply and demand side to adjust to changes in prices. The price of producing a commodity affects the demand for that commodity, while at the same time the demand affects the commodity's price. A market is said to have reached an equilibrium at price *p** when no consumer wishes to purchase any less and no producer wishes to produce any more of each commodity at that price. Hence, MED seeks this supply/demand equilibrium point whereby maximizing both consumer and producer surplus (This also results in the minimisation of system costs). In contrast, in the standard MARKAL the objective function is to minimize the cost of supplying exogenously defined energy service demands.

The sum of consumer and producer surplus (economic surplus) is considered a valid metric of societal welfare in microeconomic literature, conferring strong validity to the equilibrium computed by MARKAL. Consumer surplus reflects the amount that consumers benefit by being able to purchase a product for a price that is less than they would be willing to pay. Such benefits will be reduced if prices increase, and demand for a product falls. The producer surplus is the amount that producers benefit by selling at a market price that is higher than they would be willing to sell for. If production costs rise, profits fall (based on consumers willingness to pay remaining the same) and producer surplus will reduce.

In particular, in MED the user needs to define demand functions which determine how each energy service demand varies as a function of the market price of that energy service. Hence, each demand has constant own-price elasticity in a given period[3]. The demand function is assumed to have the following functional form:

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

where
ES is a demand for some energy service;
ES_0 is the demand in the reference case;
p is the unit price of the energy service;
p_0 is the unit price in the reference case; and
$pelas_{ES}$ is the (negative) own-price elasticity of the demand.

In this characterization, ES_0 and p_0 are obtained by running standard MARKAL. ES_0 is the energy service demand projection as defined by the user exogenously (as a function of some social, economic and technological barriers). p_0 is the shadow price of that energy service demand determined endogenously by running the reference case. Then, the user specifies demand functions which allow demands to vary endogenously around these reference demand levels and prices.

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

[3] MARKAL-Micro variant includes cross-price elasticities as well. Hence, it allows for endogenous substitution between, for example, rail transport and truck transport.

The model is calibrated in its base year (2000) to within 1% of actual resources supplies, energy consumption, electricity output and installed technology capacity. The principal calibration source is DUKES 2006. In addition, considerable attention is given to near-term (2005-2020) convergence of sectoral energy demands and carbon emissions with the econometric outputs of the government energy model. The model solves in 5-year time steps for an optimal evolution of energy pathways and technology deployment and use.

A more comprehensive description of the model, its use in the UK and insights from the EWP 07 analysis can be found in Strachan et al. (2007).[4] Further model documentation can also be found on the UKERC website.[5]

1.2 Approach to study

Two analyses are reported in this study using the UK MARKAL elastic demand model:

- Assessment of the change in emissions (and damage cost estimates) of PM_{10}, NOx and SO_2 under a carbon reduction scenario of 33% in 2020, rising to 80% in 2050. The trajectory between 2020 and 2050 is based on equal percentage reductions at each of the 5 year model periods.
- The above analysis except with internalisation of the AQ damage costs in the model optimisation.

The emission coefficients used in this analysis are sourced from the National Atmospheric Emissions Inventory (NAEI), to ensure consistency with the UK inventory reporting. The MARKAL model provides a fairly comprehensive view of combustion emissions across these pollutants. Projected emission coefficients, particularly those used for the transport and electricity generation, are consistent with projections produced under the NAEI project, and reflect new legislation that will affect future emission levels. The model set-up is decribed in Annex 1 and 2 of this report.

In the first analysis, the basic approach to understanding the impact of climate policy on air quality emissions is to assess emission totals in a reference scenario or baseline model run, and compare these against emissions under a CO_2 reduction scenario. Reductions in damage costs can be calculated (off model) by applying damage cost functions (£/tonne) to emission reduction totals (see box below for further information on damage functions).

Marginal damage cost functions

There has been significant progress in the quantification and valuation of air quality impacts over the past decade, as well as advances in spatial modelling, which has led to national estimates based on extremely disaggregated data sets. The current 'best practice' approach for the detailed quantification of such benefits is referred to as the '*impact pathway approach'* a logical progression from emission, through dispersion and exposure to quantification of impacts and their valuation.

However, the application of a full impact pathway approach for marginal changes in air emissions is resource intensive. It is not practical or cost-effective to apply this methodology to all policy appraisals. Therefore, progress has been made to develop short-hand estimates of the marginal monetary benefits of air quality improvements, usually expressed as 'damage costs', i.e. the marginal social costs of air pollutant emissions, in cost (£) per tonne of pollutant.

The IGCB published a set of damage cost values for the UK as part of their remit to provide analysis and advice realting to the development and achievement of the Air Quality Strategy 2007.[6] These damage costs are based on values for a range of health impacts, including mortality and morbidity effects, and non-health impacts, such as damage to buildings and effects on crop yields, and also take account of both primary and secondary air pollution changes. The values of these were agreed following recommendation by the IGCB in

[4] Strachan N., R. Kannan, S. Pye (2007), 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 & Environment, May 2007

[5] Full documentation on the UK model can be found at the UKERC website - http://www.ukerc.ac.uk/ResearchProgrammes/EnergySystemsandModelling/ESMMARKALDocs08.aspx

[6] IGCB Air quality website, http://www.defra.gov.uk/environment/airquality/panels/igcb/index.htm

2005 and full methodology have been published alongside its updated third report (IGCB, 2007), though there are important caveats with application [7]. The values are now recommended by the IGCB for appraisal in cross department guidance values for damage costs in the UK[8] and were applied in the analysis of the air quality ancillary effects of the EWP 2007[9] .

The second analysis was undertaken to internalise damage costs in the model optimisation routine. The rational for such an analysis is that if you internalise the external costs of air quality pollutants, these additional costs may affect the decisions about investments in certain technologies. This is likely to have the effect on the model of moving away from high AQ polluting technologies more quickly, as the model looks to maximise discounted economic surplus (and minimise overall discounted system costs).

[7] The damage cost approach is intended for use across government, such as for project appraisals (project cost-benefit analysis) and Regulatory Impact Assessments (policy cost-benefit analysis). It is not, however, considered a replacement for detailed modelling and analysis. The use of damage costs is therefore only recommended for policies with a pollution reduction over a period of less than 20 years and: as part of a filtering mechanism to narrow down a wide range of policy options into a smaller number that are then taken forward for more comprehensive assessment; or where air quality impacts are expected to be ancillary to the primary objectives or are relatively small.

[8] http://www.defra.gov.uk/environment/airquality/panels/igcb/guidance/index.htm

[9] http://www.berr.gov.uk/files/file39198.pdf

2 The ancillary benefits of carbon reduction targets on air quality damage costs

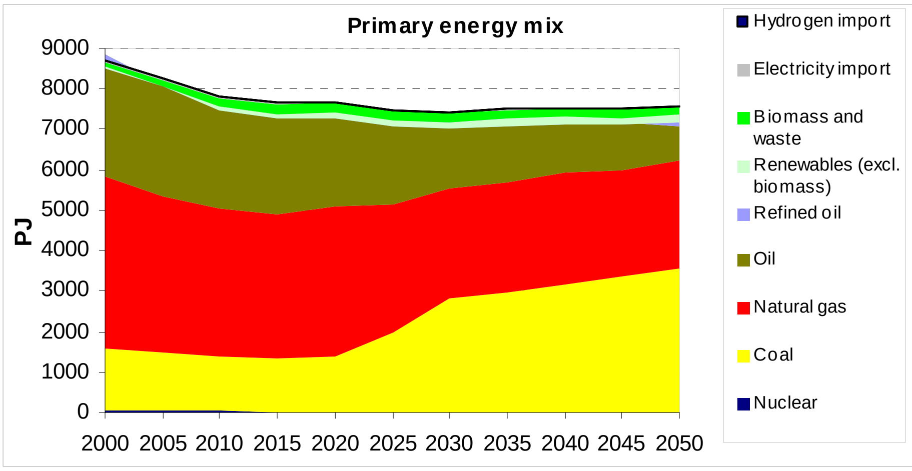
In this analysis, we have assessed the impact on air quality pollutant emissions (NOx, SO_2 and PM_{10}) of carbon reduction targets. The modelling has used a reduction trajectory based on annual reductions of 33% by 2020 and 80% by 2050 (relative to 1990 levels).

2.1 Evolution of energy system under carbon reduction targets

To understand the impacts on air quality emissions presented later in this section, it is important to describe the main changes to energy demand, energy types and technologies.

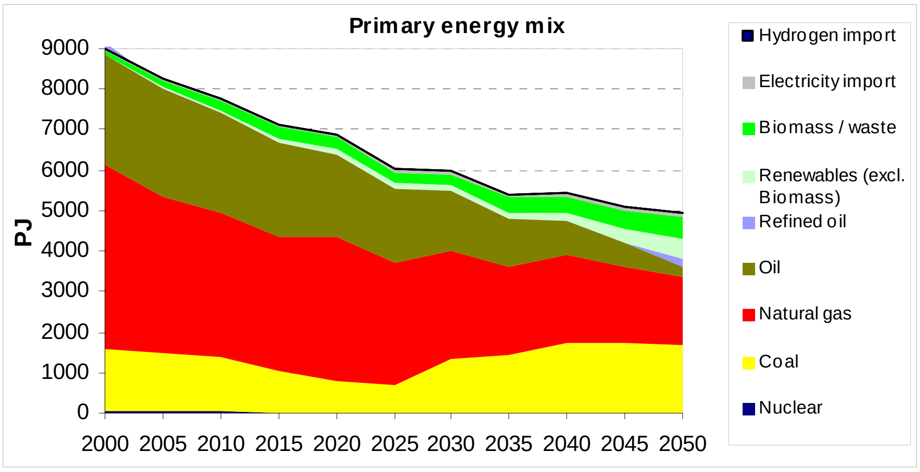
Under the baseline, the system maintains its fossil fuel intensity as would be expected. Coal use goes up, largely driven by increased uptake in power generation. (In the modelling, gas becomes relatively more expensive due to supply side constraints, and is increasingly used in more efficient end use applications). Oil use decreases, largely driven by increasing efficiency in the transport sector; the optimisation towards least-cost means less use of oil due to increasing commodity prices and technological progress.

Figure 2.1 Primary energy demand (PJ) under baseline, 2000-2050



Under constraints, a much lower fossil intensive system can be observed, with increasing uptake of renewable energy sources. The role for gas and coal is maintained; gas is still an important energy type for heating in energy end use applications and for use in industry, whilst coal is predominantly used in CCS-based electricity production.

Figure 2.2 Primary energy demand (PJ) under 33/80 case, 2000-2050



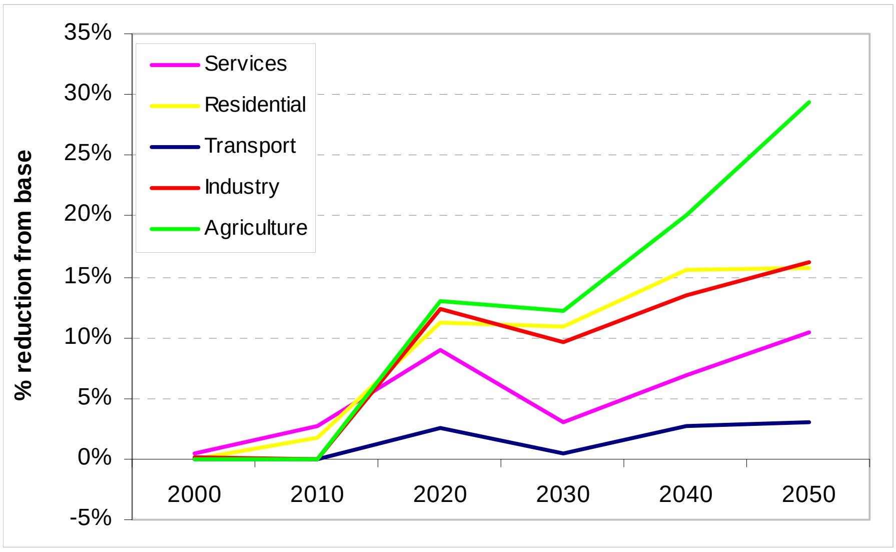
In terms of energy end use sectors, the following trends are described in Table 2.1.

Table 2.1 Energy end use sector evolution – from baseline to constrained case

Sector	Baseline	33/80 case
Electricity generation	Generation mix moves towards being coal dominated by 2050	Mix starts to move towards large scale CCS post-2030 (50%), and increased levels of nuclear. Renewables also play an increased role, accounting for over 20% generation by 2050.
Transport	Optimisation in the baseline results in large efficiency gains, and a move in later years (2040+) to increasing hydrogen / electricity powered vehicles. In 2050, about 60% of energy use is from direct fossil sources.	A similar profile to the baseline out to 2030 is observed. Post-2030, biofuels are shown to play a more significant role, as are hydrogen and electric powered vehicles. By 2050, diesel use is near zero, whilst petrol still accounts for about 25% of energy used.
Residential	Energy use profile does not change signfiicantly, with gas still dominating in 2050. The level of consumption also remains at a similar level across the time period.	In 2050, energy use less than 50% of that observed in the baseline, with electricity dominating. Efficiency saving are derived from more efficient boilers and use of heat pumps.

Another important feature of this model is that it allows for both the supply and demand side to adjust to changes in prices, using a set of price elasticities of demand for energy services. This is important in terms of an abatement option, as the model can now weigh up the loss in consumer surplus against system costs (which impact on producer surplus).

Figure 2.3 % Change in energy service demand by sector relative to baseline under 33/80 constraint, 2000-2050



The level of response is both a function of the assumed elasticity but also of the number of alternatives in a given sector for supplying energy, and mitigation options.

The model optimisation maximises discounted economic surplus. The impact of a carbon constraint results in losses of economic surplus; discounted losses under the 33/80 case are £123.6 billion (based on discount rate of 3.5%).

The following section describes what these changes mean in terms of reductions in air quality pollutant emissions.

2.2 Climate policy targets and reductions in emissions of AQ pollutants

It is clear that with a significant reduction in carbon emissions, there is also going to be a major impact on emissions of certain air quality pollutants. Whilst this is observed, an interesting insight is the significant reduction (relative to 2000 levels) under the baseline due to AQ legislation (Euro standards, LCPD, IPPC Directive) and the system optimisation, leading to increasing energy effiiciency.

The information on damage costs presented in this section of the report are calculated off-model, and do not feed into the model optimisation of economic surplus maximisation. Central damage cost estimates have been used.

Differences between emission levels in 2000 with national inventory totals are discussed and explained in Annex 2.

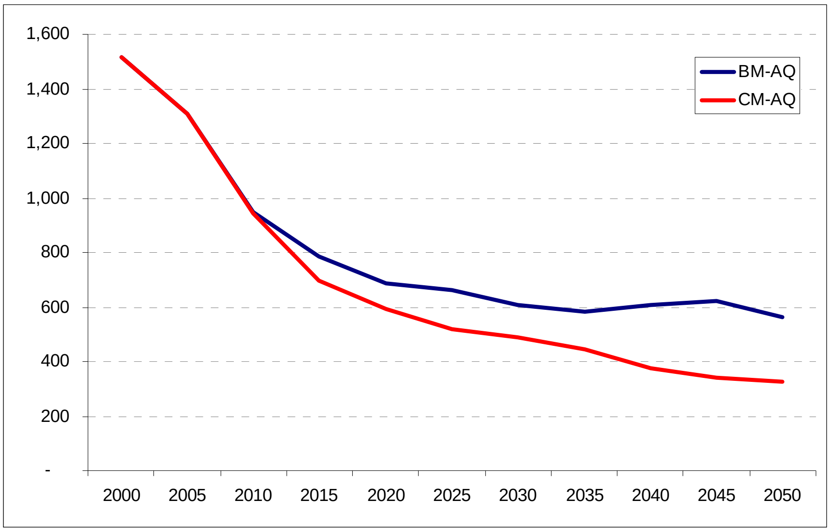
NOx emissions

NOx emission reductions under the baseline in 2015-2020 are mainly due to cleaner vehicles in the transport sector as a result of Euro standards, and the uptake of more efficient vehicles. Post-2015, emission totals continue to decrease until 2030, due to improvements in electricity supply abatement control (under LCPD) and the building of new more efficient plant.

The CO_2 constraint case leads to additional reductions (relative to the baseline) from 2015 (88 ktonnes, or 11%), increasing to 2050 (236 ktonnes, or 42%), as shown in Figure 2.4. Most of the reductions between 2015 and 2035 are from power generation sector, with a move to cleaner, lower carbon technologies (CCS, nuclear, wind generation etc).

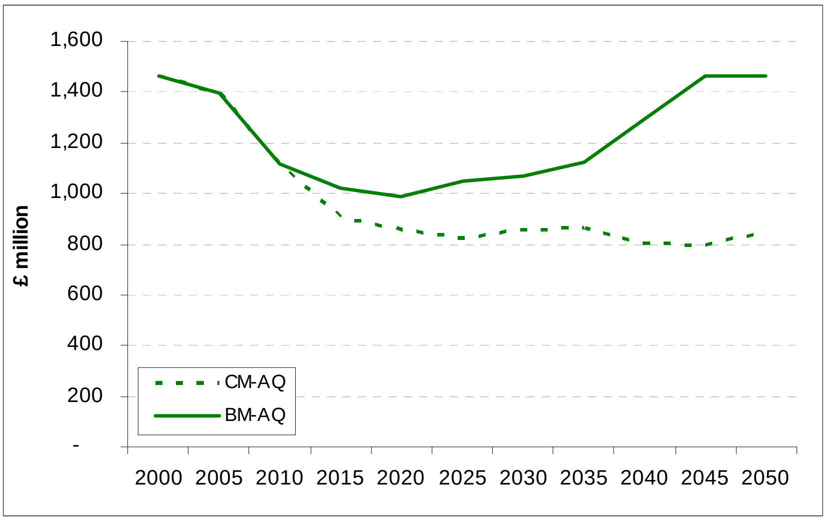
Post 2035, the transport sector provides equal reductions to the electricity generation sector (~35%), with the remainder primarily from the residential sector. In the transport sector, this is due to the increased uptake of hydrogen and electric vehicles. (In the absence of information on vehicles using biofuels, an assumption has been made that they at least meet Euro standards of conventional vehicles). In the residential sector, this reflects a move away from gas to more electricity-based heating.

Figure 2.4 NOx emissions (ktonnes) under baseline and 33/80 cases, 2000-2050



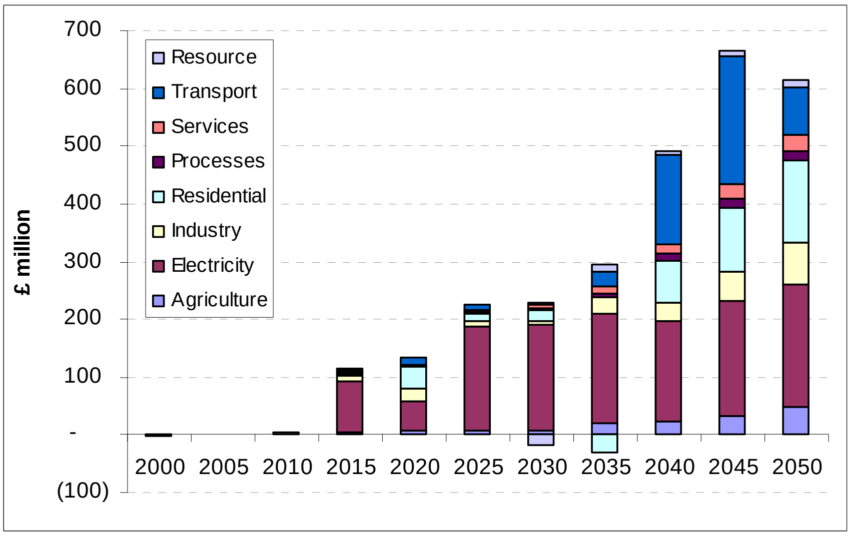
The above emissions can also be expressed in terms of total damage costs, shown in Figure 2.5 below. Under the baseline, total annual damage costs start to rise post-2020, as emission reductions decrease while damage cost values increase (due to the uplift factor applied to cost values). The result is that that the damage costs savings are much larger than the emission savings imply, primarily due to this uplift. Note that these values are annual undiscounted values.

Figure 2.5 Damage costs (£ million) associated with NOx emissions under baseline and 33/80 cases, 2000-2050



The area between the trend lines in Figure 2.5 represent the co-benefits of carbon reduction targets for NOx emissions. The reductions are shown below in Figure 2.6, disaggregated by sector. It shows that reductions from damage costs until 2035 are primarily associated with the electricity generation sector; post-2035, significant contributions come from the transport and residential sectors as constraints become increasingly stringent.

Figure 2.6 Reductions in damage costs (£ million) of NOx due to carbon reduction targets, 2000-2050

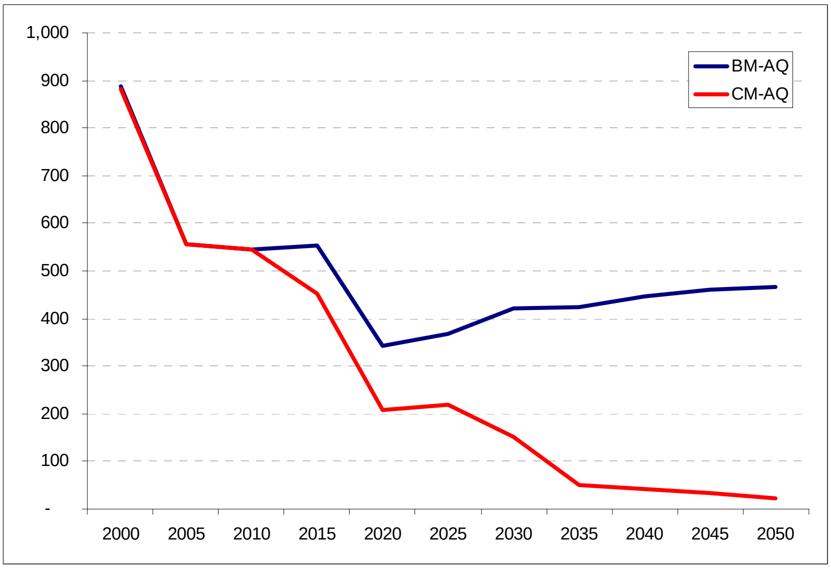


SO_2 emissions

At the UK level, SO_2 emissions are largely driven by the power sector. In the baseline, emissions fall dramatically by 2020, reflecting requirements under the LCPD. Post-2020, the electricity generation sector becomes dominated by coal generation plant, hence the gradually increasing emissions out to 2050 (No additional SO_2 emission factor improvement is considered post 2020, which is consistent with the approach in the NAEI projections).

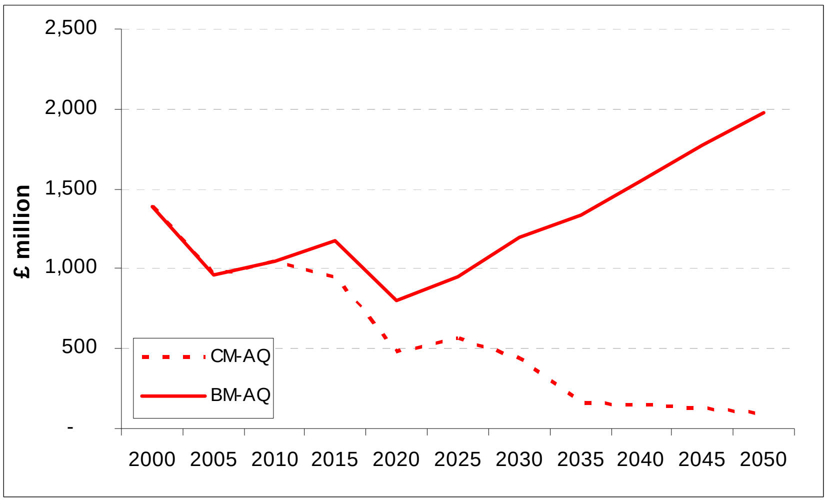
The CO_2 constraint case leads to additional reductions (relative to the baseline) from 2015 (102 ktonnes, or 18%), increasing to 2050 (433 ktonnes, or 95%), as shown in Figure 2.7. The reductions are primarily due to reductions in coal and oil use in industry, and the use of coal in electricity production using CCS technologies, where it is assumed that SO_2 will also be scrubbed out of the flue gases.

Figure 2.7 SO_2 emissions (ktonnes) under baseline and 33/80 cases, 2000-2050



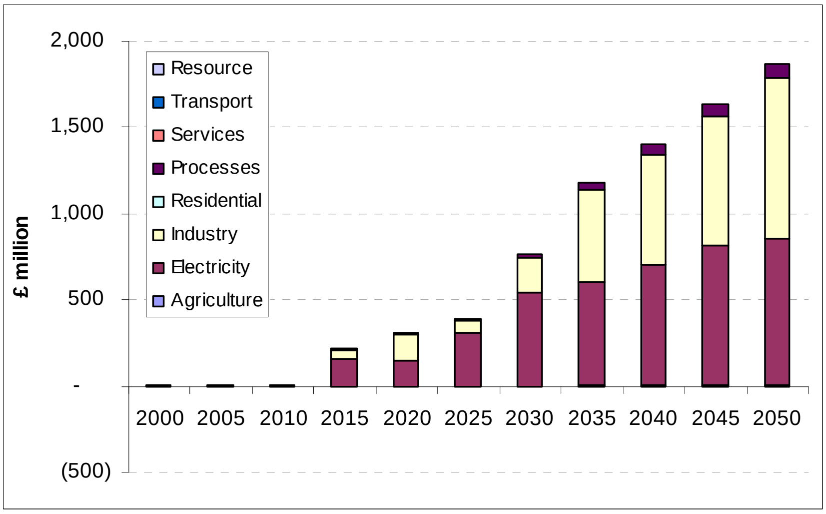
The damage costs associated with SO_2 emissions under both cases is shown in Figure 2.8, reflecting the emission trend above.

Figure 2.8 Damage costs (£ million) associated with SO_2 emissions under baseline and 33/80 cases, 2000-2050



From Figure 2.9, as discussed above, most of the reductions in damage costs are associated with industry and electricity sectors due to reductions in coal use or use of clean coal technology.

Figure 2.9 Reductions in damage costs (£ million) of SO_2 due to carbon reduction targets, 2000-2050

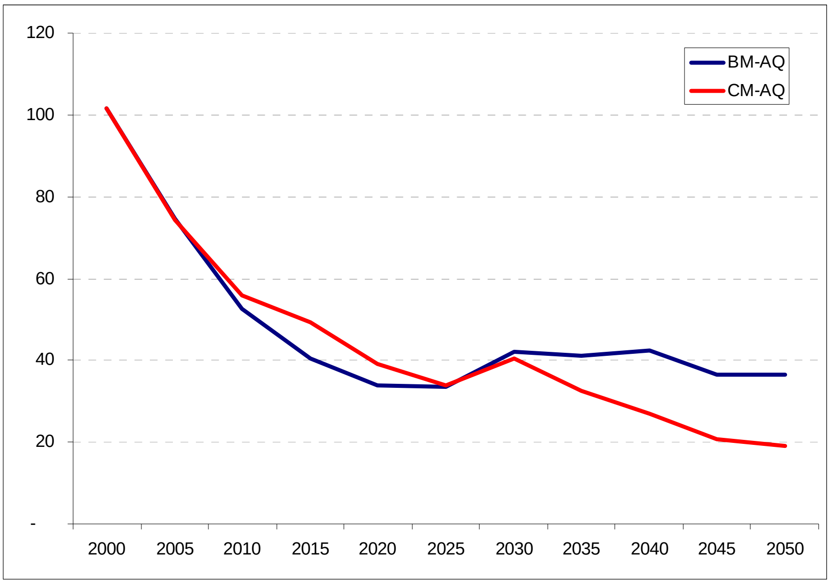


PM_{10} emissions

In the baseline, as for NOx, significant reductions occur in the transport sector and the residential sector out to 2015. Transport sector emission reductions are due to European legislation whilst in the residential sector, this is due to the phase out of solid fuels. In later years, technology evolution in the transport sector leads to smaller reductions e.g. hybrid vehicles, hydrogen. Post-2030, some increases are observed due to increasing coal use in power generation and some increases in biomass use in the residential sector.

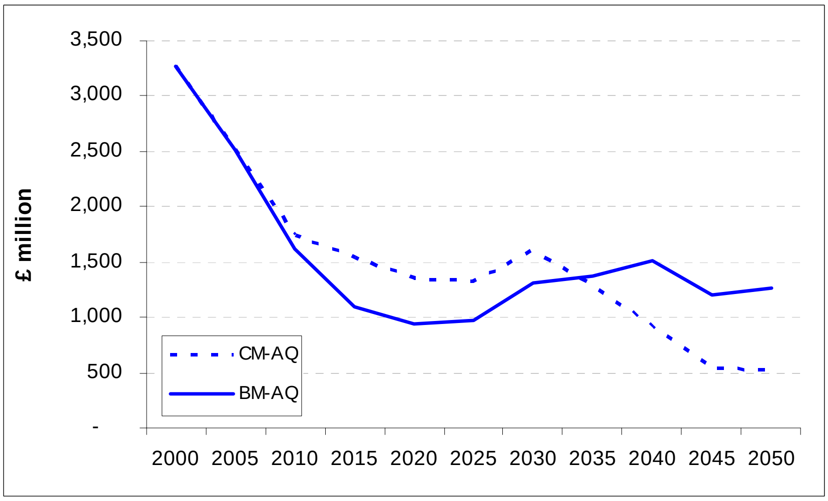
The CO_2 constraint case leads to actual increases (relative to the baseline) between 2010 and 2020, followed by reductions post-2030 (48% by 2050), as shown in Figure 2.10. Increases observed are due to the uptake of biomass in the residential sector. It is important to stress that the emission factors associated with biomass use (sourced from the NAEI) are extremely uncertain, and probably do not reflect emissions from more advanced biomass stove and boiler technologies. The reductions post-2030 are driven by reductions in fossil fuel use (fuel oil and coal) in the electricity generation and industry sectors.

Figure 2.10 PM_{10} emissions (ktonnes) under baseline and 33/80 cases, 2000-2050



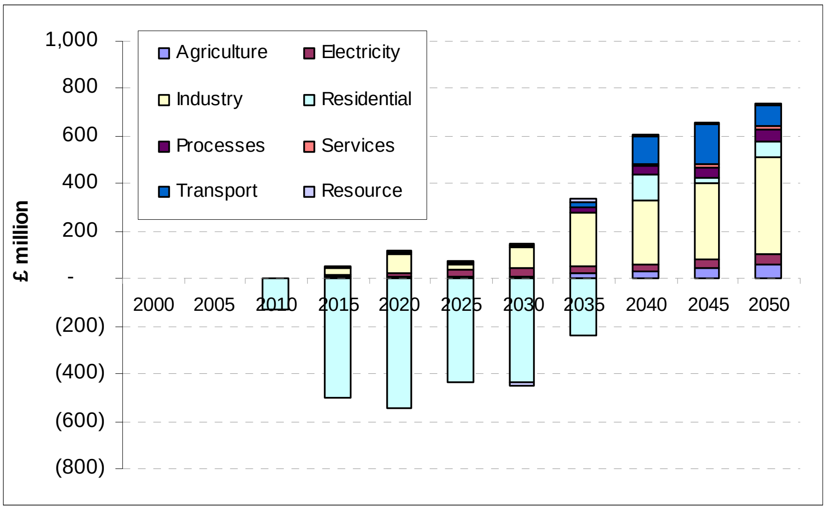
The changes in emissions are also expressed terms of in damage costs in Figure 2.11, with the change in damage costs between the baseline and constrained case shown in Figure 2.12, disaggregated by sector.

Figure 2.11 Damage costs (£ million) associated with PM_{10} emissions under baseline and 33/80 cases, 2000-2050



In Figure 2.12, the increases in damage costs due to uptake of biomass in the residential sector can be observed. However, it is important to stress the large uncertainties in the emission factors used due to a lack of information on biomass using technologies in the NAEI and projection estimates. Reductions in damage costs are mainly from reduction in the use of non-gaseous fossil fuels in industry, and technology changes in the transport sector.

Figure 2.12 Reductions in damage costs (£ million) of PM_{10} due to carbon reduction targets, 2000-2050



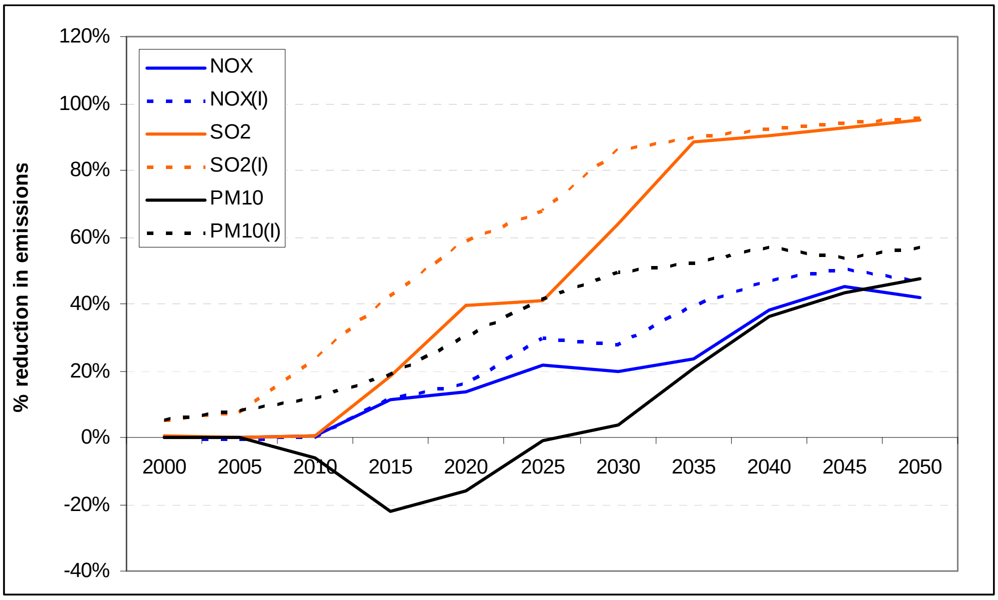
Finally, a more optimistic transport baseline means that PM_{10} reduction associated with efficiency savings in the transport sector in future years is not a co-benefit because it is captured in the baseline.

3 The impact of internalising AQ externalities on the cost of carbon reduction targets

In this second analysis, the damage (or external) costs of air pollution have been internalised, and therefore are considered in the model's optimisation routine. The reason for this analysis is to assess how, when we include the full costs of air pollution, the model decisions change, and what impact this has on overall costs. The additional costs of certain technologies (with damage costs added) may not appear so cost-effective, particularly those with the highest emissions.

The impact on emissions can be seen in Figure 3.1. The dashed lines represent the reduction in emissions in the cases where external costs have been internalised. (Note that the comparison is against the same baseline as used in the non-internalised cases; this is because we are only interested in the impact under a climate reduction case).

Figure 3.1 % reduction in AQ pollutant emissions relative to the baseline with damage costs (central estimates) internalised (dashed line represents internalised 33/80 cases)



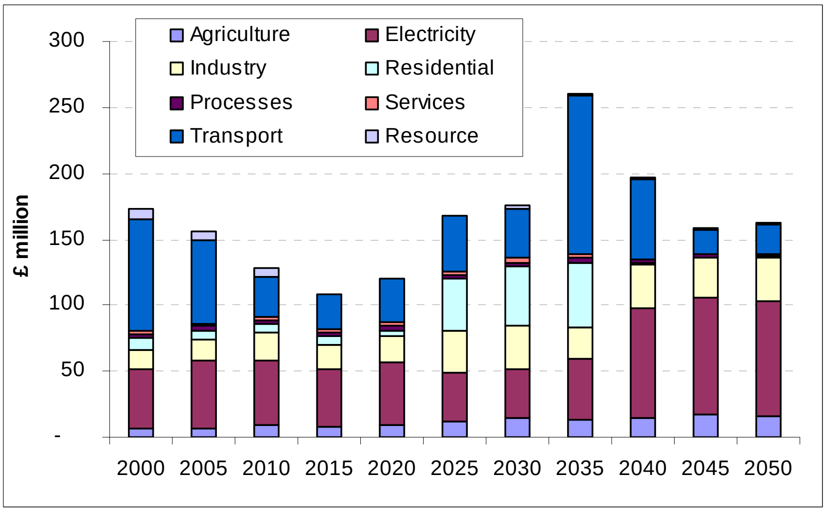
For all three pollutants, additional reductions are observed. In certain years, the differences are quite large in all cases. For SO_2, higher reductions are observed earlier in the time horizon. PM_{10} emissions no longer increase between 2010 and 2025, but actually show large reductions e.g. 40% in 2025. Reductions in NOx emissions are also higher, but not to the same extent as seen for PM_{10}.

3.1 Energy system evolution and AQ pollutant emissions

The additional emission reductions observed in Figure 3.1 are shown for each pollutant below as the additional reduction in damage costs, disaggregated by sector. The reduction in damage costs is a result of the model avoiding external costs (modelled as an emissions tax), and choosing to use different technology-energy combinations whilst still meeting carbon reduction targets.

The reduction in NOx damage costs (see Figure 3.2) are mainly observed in transport and electricity sectors. In transport, this is mainly due to reductions in diesel use; in 2035, there is a big reduction, leading to a large increase in the use of hydrogen. In the electricity sector, a small reduction in the level of coal CCS and increase in gas CCS / nuclear leads to the additional reductions in this sector.

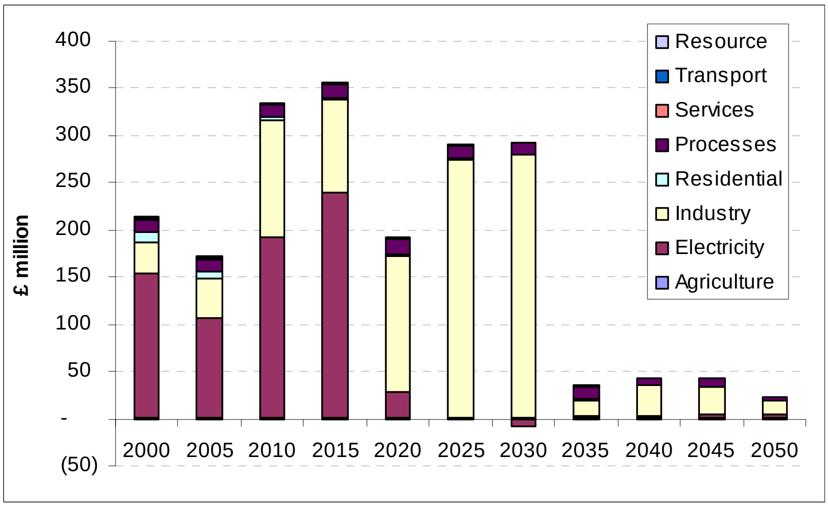
Figure 3.2 Additional reductions in damage costs (£ million) of NOx due to internalisation of AQ damage costs, 2000-2050



For SO_2, a quicker phase out of solid fuels results in more damage cost savings out to 2030. Most of the savings are in the electricity generation sector to 2015, and then in industry between 2015-2030. For electricity generation, the reduction is due to a higher load on existing FGD plant, and a lower load on non-FGD plant. After 2015, all coal plant are expected to have FGD fitted under LCPD.

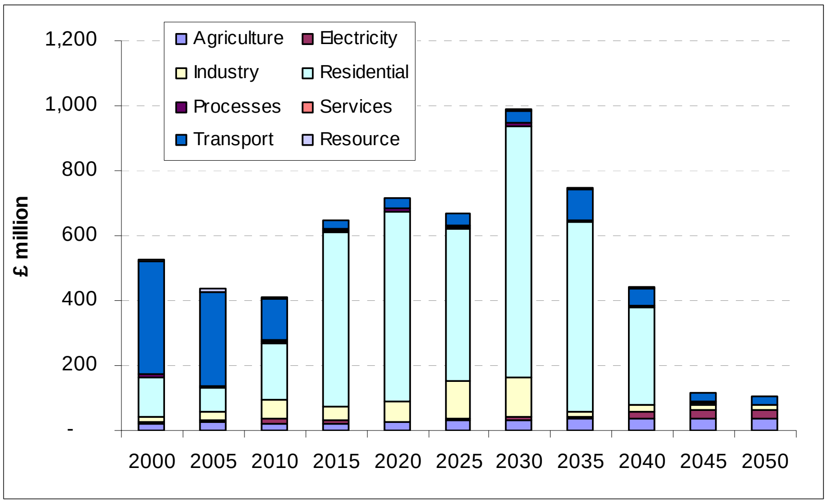
The industry sector essentially does not use coal between 2020-2030 but switches to gas.

Figure 3.3 Additional reductions in damage costs (£ million) of SO_2 due to internalisation of AQ damage costs, 2000-2050



Emissions of PM_{10} are lower from the transport sector in 2000-2005 due to a move away from diesel to petrol. Although the shift is relatively small, the associated damage per tonne results in sizeable additional benefits. Additional savings between 2015 and 2040 are primarily as result of a switch away from biomass. Again, this PM_{10} analysis needs to be carefully interpreted due to the uncertainty associated with the biomass emission factors.

Figure 3.4 Additional reductions in damage costs (£ million) of PM_{10} due to internalisation of AQ damage costs, 2000-2050



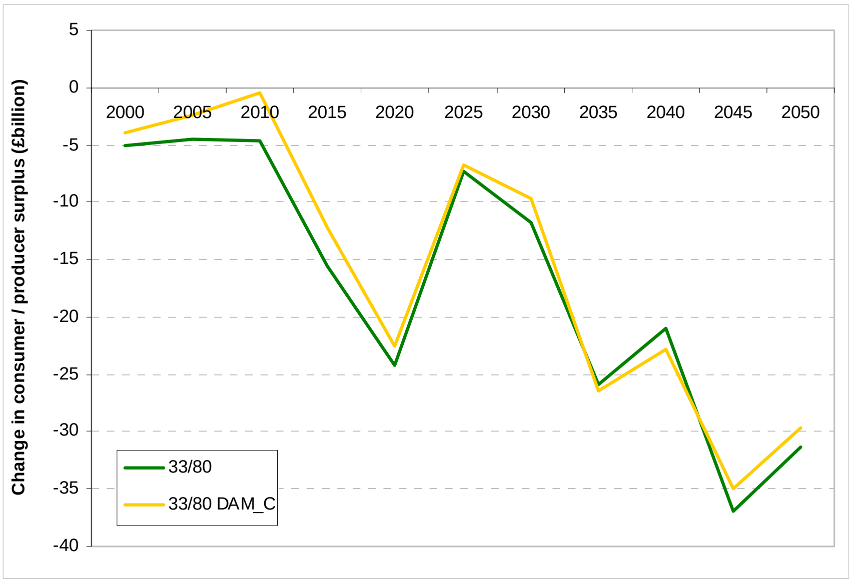
This reduction in the use of biomass shifts abatement primarily to the industry sector, through the use of less coal. Lower coal coal use is also a function of damage costs across all three pollutants.

3.2 Energy system costs

Under the MARKAL analysis, the model optimises to maximise discounted economic surplus over the model lifetime (2000-2070). With the inclusion of AQ damage costs and carbon constraints, some of the decisions change as previously cost-effective opportunities are no longer cost effective in relative terms.

A comparison of the undiscounted losses in economic surplus associated with the two cases is shown in Figure 3.6. The case 33/80 DAM_C includes damage costs in the optimisation. For the 33/80 case (where damage costs have not been included in the optimisation), we have added the undiscounted damage costs to the losses in economic surplus off-model to enable a comparison. It can be observed that across most of the time series, particularly in the early years, damage costs are reduced by the optimisation (accounting for a reduction in the loss of economic surplus). This reflects the model trade offs between high emission taxes that could be incurred (particularly in the early years due to higher fossil fuel use) and higher costs of alternative energy service demand provision, within the carbon constraints imposed.

Figure 3.5 Annual undiscounted losses in economic surplus (£billion), 2000-2050



A key output from this anaysis is that internalising damage costs does result in a reduction in the losses in economic surplus in most time periods, when compared against a case where damage costs are included but not in the optimisation.

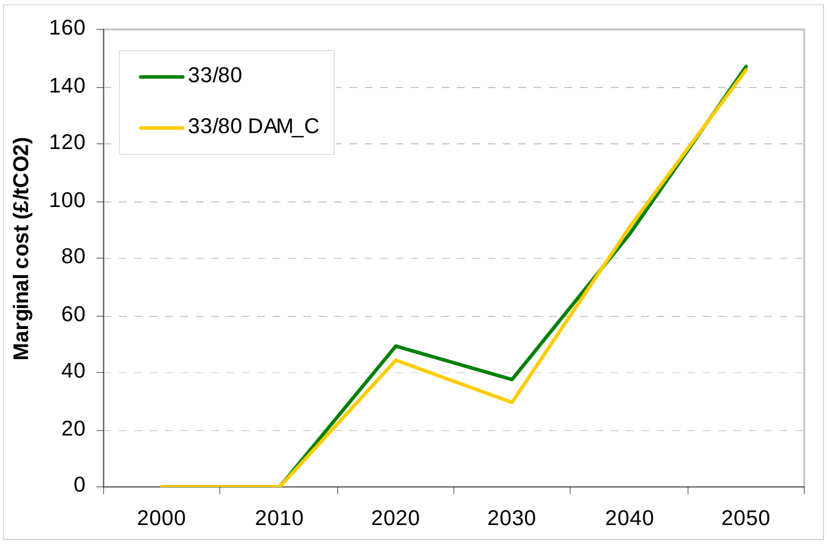
However, the model optimises on the basis of discounted economic surplus. Under the 33/80 trajectory, the loss in discounted economic surplus is £123.6 billion (2000 basis) without damage costs considered. With damage costs internalised, these losses increase as would be expected although are balanced against some reductions in carbon abatement costs (as discussed above and observed in Figure 3.6). Based on central damage cost estimates, the loss rises to £127.7 billion and to £130.2 billion under the high estimates. An important observation from this analysis is that including AQ damage costs doesn't significantly impact on (i.e. increase) overall losses in economic surplus, reflecting the synergies between climate and air quality policy.

Note that this comparison is not equivalent to that shown in Figure 3.5. The results for 33/80 case do not include damage costs, as they have not been factored into the model calculations; they only factor in Figure 3.5 through off-model calculations.

In terms of the marginal costs of carbon abatement, lower marginal costs can be observed in certain time periods (see Figure 3.6). This is because the model has responded to the inclusion of AQ damage costs by deciding not to use specific energy types, many of which are carbon intensive. This results in less cost pressure on carbon mitigation in certain periods, lowering the marginal costs (with the previous marginal technology under the standard 33/80 case no longer needing to be employed).

It is interesting to note that there is very limited change in demand response feedback, despite the internalisation of the external costs.

Figure 3.6 Marginal abatement costs of carbon with and without damage costs internalised (M33/80 C has damage costs internalised)

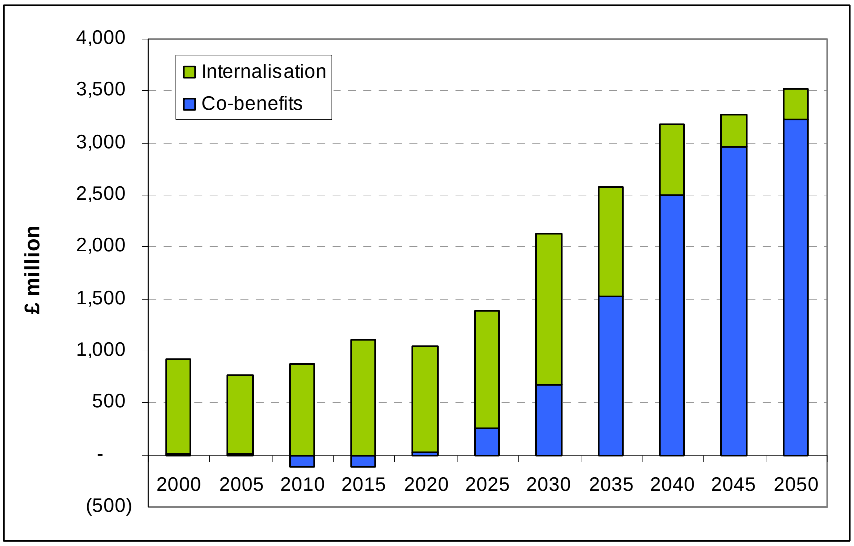

160
140
120
100
80
60
40
20
0
Marginal cost (£/tCO2)
33/80
33/80 DAM_C
2000
2010
2020
2030
2040
2050

4 Summary

The analysis shows that air quality emissions could be significantly reduced as a result of an increasingly decarbonised energy system. This is primarily due to the phase out of fossil fuels, particularly oil and solid fuel, and the reducing energy intensity of the system. The analysis also suggests that technology improvements alongside legislation will reduce AQ pollutant emissions in the absence of climate policy (as shown under the baseline), although not to the same extent.

The co-benefits associated with air quality improvements are shown in Figure 4.1. Co-benefits are associated with the significant changes in the system post-2030, when the system uses limited fossil fuels. Costs are seen in earlier years due to the uncertain assumptions on PM_{10} emissions from biomass use in the residential sector. In 2050, the annual undiscounted reduction in damage costs exceeds £3 billion.

Figure 4.1 Co-benefits of climate policy (under 33/80 trajectory) on AQ pollutant emissions (NOx, PM_{10}, SO_2) with and without damage costs internalised (annual undiscounted, £ million) under 33/80 trajectory



NB. Capital costs annualised based on technology specific discount rate

When the same scenario is run except with damage costs internalised, the co-benefits increase, particularly in the earlier years, with power plant switching to coal generation with FGD and the residential sector not using biomass. Post-2030, the additional co-benefits are smaller as the system is using low levels of fossil fuels anyway, so the damage costs (as emission taxes) have limited impact on the model decisions.

Internalising damage costs leads to lower (undiscounted) losses in economic surplus over the model horizon. This is based on the model balancing the need to meet energy service demands against the cost of emission taxes and the abatement requirements under a stringent carbon constraint.

A similar comparison is difficult to make in terms of discounted costs due to the way the model is set up. However, an important conclusion can be drawn from this analysis; that the inclusion of AQ damage costs on the model results in higher total system costs although these costs are not significantly higher, reflecting the many synergies between AQ damage cost reduction and carbon mitigation.

The results provide some useful insights into the co-benefits of climate policy. However, there are some caveats with this analysis, particularly around the emissions factors that have been used. The analysis is NAEI consistent; however, this is not a technology-based inventory and therefore there is not a consistent match in all cases.

There are a range of AQ emission factors, mainly associated with new forms of energy use / new technologies, which require further research.

1. **Biofuels.** There is ongoing work to better understand the NOx and PM_{10} emissions associated with the use of biomass, including in the transport sector. This work is ongoing; however, it is important that new emission factors for biofuels are incorporated into the UK MARKAL model when the become available.
2. **CCS.** Further research on the impact on NOx / PM_{10} emissions from pre- and post-combustion CCS plant will be necessary

It is also important that account of future developments in the NAEI are considered. This might include additional sectoral dissagregation, for example, which could better match the specific sector structures in MARKAL.

Finally, whilst the UK model now includes marginal damage cost functions, it could be further developed to assess both climate and air quality targets simultaneously. This could be done by including emission ceilings, for example, for air quality pollutants, which the model would factor in, as part of the optimisation process.

For an effective joint optimisation, it would also be important that air quality abatement options were incorporated into the model, to ensure that options were available beyond fuel switching to allow for reductions. In the Belgium national model, and those run by the USEPA, AQ cost curves have been incorporated into the model so that optimisation runs can be undertaken, setting ceilings for pollutants and assessing the costs.

Annexes

Annex 1. Identification of emission coefficients for use in the UK MARKAL model

Annex 2. Model set-up and calibration

Annex 1. Identification of emission coefficients for use in the UK MARKAL model

A1.1 Introduction

This section of the report outlines in more detail the work undertaken to indentify emission factors to be used in the model. It is structured by model sector, describing some of the key issues that have been addressed in developing appropriate emission factors. Sectors include:[10]

- Residential
- Commercial
- Agriculture
- Industry
- Transport
- Electricity generation
- Processes, including refineries, fuel tranformation etc.
- Resources

The general principles of data collection included:

- Consistency with the 2006 NAEI emission factors as far as possible (as the official source of UK emission factors).[11]
- Future year emission factors consistent with the UEP30 (2005) NAEI projections[12]
- Emission factors have been identified at the technology level where AQ abatement opportunities could be foreseen for future inclusion. Where emissions are primarily related to fuel quality or type, or the model has limited disaggregation, emissions factors have been identified at the sector or sub-sector level. For SO_2, emission factors have generally been included at the sector level, except where we are aware of specific abatement technologies e.g. FGD on power stations

Due to time and resource constraints, limited time has been spent reviewing non-NAEI sources, although this has been necessary for some source-fuel combinations. For different sectors, the level of emission factor detail will differ, depending on the sectoral disaggregation in the model. We have worked closely with the NAEI team to discuss what are the most appropriate emission factors for use for the source sector-fuel combinations in the model.

A significant issue that has arisen has been the use of an emission factor database (NAEI) that does not include factors for many of the new and emerging technologies included in MARKAL. This issue is considered in more detail below for each sector.

A1.2 Residential and commercial sector

Meeting **residential** sector energy demand (heating, cooking, appliances) is primarily through the use of electric and gas using technologies, with limited characterisation of solid fuel and wood / biomass technologies. Recent update activities of the UK model have included new biomass based technologies, recognising the potential importance of this energy type in future years. Conservation measures are also important; these lead to a reduction in the requirement for energy, and are often associated with building fabric. A number of renewable technologies are also included for the sector, including heat pumps, solar water heating etc.

[10] Further detail on the model structure and assumptions for different sectors can be found in the documentation on the UKERC website, http://www.ukerc.ac.uk/ResearchProgrammes/EnergySystemsandModelling/ESMMARKALModelDocs.aspx
[11] This information is available for download from the data warehouse section of www.naei.org.uk
[12] These projections are based on the 2005 NAEI and BERR's UEP30 energy forecasts. In April 2008, the projections will be updated to incorporate the 2006 NAEI. It is thought however that this will have little impact on the emission factors presented here.

Electric appliances do not have AQ emission factors allocated, as accounting for emissions is done in the electricity generation sector whilst conservation measures / non-biomass renewable technologies obviously do not need AQ emission factors.

PM_{10} and NOx factors for gas, oil and wood have been identified by fuel use in specific technologies, whilst SO_2 factors are based on fuel used at the sector level. A limiting factor in the NAEI is that specific gas using technologies (e.g. boiler type – condensing etc) are not differentiated. Therefore, reductions in AQ emissions will be a function of improvement in thermal efficiency rather than specific abatement associated with different boiler types.

The **commercial** sector is structured in a similar way to the residential sector, with more detailed depiction of gas using technologies. No biomass using technologies are currently included in this sector.

A1.3 Agriculture sector

The agriculture sector is a relatively small part of the energy system, and therefore CO_2 emissions are relatively low. Consequently, the sector has not been modelled in detail. Average emission factors have been derived for the main fuel inputs - solid biomass, bio agricultural wastes, diesel, coal and natural gas.

A1.4 Industry sector

In the UK MARKAL model, the demand for energy (services) is split into five distinct sectors: iron and steel, non-ferrous metals, chemicals, paper, pulp, and publishing, and other industries. Energy services are needed for the following industrial processes - high temperature processes (HTH), low temperature processes (LTH), drying/separation (DRY), motor (MOT), and other services (OTH). Generic technologies provide sectors with these different services using a range of different fuels.

A generic technology represents, for example, all of the technologies using a specific fuel in the chemical sector that provide high temperature heat. Therefore, the industry sector has been modelled in an aggregated way that is relatively consistent with the NAEI structure.

Emission factors by NAEI sector-fuel categories have been used for the MARKAL industry sub-sectors. Emission factors do not differentiate between industrial processes e.g. HTH and LTH, or account for future abatement controls[13] (consistent with approach used for NAEI projections). AQ emission reductions in future years are due to improvements in efficiency of processes, as modelled in MARKAL.

A1.5 Transport sector

The transport sector in the UK MARKAL model is perhaps the most detailed, with numerous transport mode-technology-fuel combinations. Many of the technologies will only be available or taken as options in future years e.g. 2030 and beyond. This means that deciding on emission factors is often not straightforward.

In this section of the report, we have described the approach used for the different vehicle technologies. SO_2 emission factors have been included at the sector level, as these are based on general fuel quality being used. PM_{10} and NOx emission factors, however, have been included at the technology-fuel level. In general, these factors are consistent with data obtained from tests conducted on vehicles conforming to particular Euro standards. For technologies where the appropriate emission factor to use is uncertain, the euro standard approach provides the maximum emission per vkm. In these circumstances therefore a conservative approach has been taken. In general, most factors are taken from the NAEI and are based on a weighted mix of urban, rural and motorway driving and associated road transport projections work.

Note that there are no AQ emissions associated with hydrogen, fuel cells and electric vehicles, as these are accounted for in the associated energy production processes elsewhere in the model.

[13] Abatement technologies to reduce AQ emissions would be difficult to implement in this sector due to the limited detail of specific technologies

Specific comment on AQ emission factors for fuels used in specific technologies are provided below:

Biodiesel – The NAEI team are are currently reviewing all types of biofuel emission factors for use in the NAEI. This work is not yet complete, but when it is, it will provide scaling factors for biofuels used in different modes (i.e. emission factor relative to conventional diesel). If appropriate, the MARKAL model will be updated when this information becomes available.

An interim conclusion is that running a vehicle on biodiesel is likely to have little impact on AQ emissions. The emissions will however depend on the type of biodiesel and the blend assumed; even for 100% biodiesel, the affect on NOx and PM emissions depends on the biodiesel feedstock. As a conservative estimate, it is currently assumed that vehicles running on biodiesel will emit at the same rate as their corresponding Euro standard applicable to diesel vehicles.[14] SO_2 factors are assumed to be zero because there is almost no sulphur in biodiesel.

CNG – NOx data for heavy duty vehicles running on CNG has been taken from test data provided to AEA by DfT[15]. For light duty vehicles, it is assumed that NOx emissions will be the same as those arising from equivalent age petrol vehicles. PM_{10} and SO_2 emissions are presumed to be zero from all vehicle types.

Flex-ethanol 85 (cars only) – NOx emissions are assumed to be similar to a standard petrol car; PM_{10} is assumed to be 20% lower than an equivalent petrol car and SO_2 is assumed to be 85% less than an equivalent petrol car.[16]

LPG (car and LGV only) - For PM_{10}, we have assumed the same factors as for the equivalent petrol driven vehicles. There is no sulphur in LPG, so SO_2 emission factors are zero. NOx is difficult to generalise about, as much of the evidence shows a mixed picture, with emissions sometimes higher and sometimes lower compared to petrol cars. It appears to depend on whether the vehicles is a dedicated LPG vehicle, a conversion (which most are these days), or bi-fuel (runs on petrol or LPG). For the purpose of this study, we have therefore assumed that the NOx emission factor is the same as a petrol car of the same age.[17]

Methanol (car and LGV only)– In the absence of other data, for NOx and PM_{10}, emission factors have been assumed to be the same as for a diesel powered equivalent vehicle. SO_2 emissions are zero due to methanol being virtually sulphur free.

Hybrid and plug-in hybrid cars and LGVs– Hybrid cars and LGVs are assumed to emit at the same rate as their equivalent conventional vehicles. This is a conservative estimate. For plug-in hybrid cars/LGVs, NOx emissions are estimated to be 80% and 35% lower than conventional diesel and petrol vehicles respectively; PM_{10} emissions from a plug-in hybrid diesel are estimated to be 90% lower than from a conventional diesel equivalent. PM_{10} emissions from petrol plug-in hybrids are assumed to be similar to a petrol vehicle of the same age. SO_2 emissions on the basis of fuel consumed will be the same as for conventional vehicles.

For **rail technologies**, NOx and PM_{10} emission factors have been taken from the 2006 NAEI. Due to the slow turnover in the fleet, no improvements have been incorporated in to the model in future years for these pollutants. For SO_2, it is assumed the requirements of the Sulphur in Liquid Fuels Directive (SCLFD) are met and that sulphur levels in gas oil are reduced to 0.1%.

For **air technologies**, NOx, PM_{10} and SO_2 emission factors have been taken from the 2006 NAEI. No further improvements are expected in future years.

[14] NOx and PM10 emissions are not directly related to a vehicle's fuel consumption. For example, the formation of NOx is extremely dependent on the temperature and the fuel / air ratio. Consuming energy with a lower calorific value does not necessarily mean that AQ emissions will be impacted in terms of grams per kilometre driven
[15] SCANIA test data, March 2001.
[16] Source: Estimating emissions from biofuels used by road transport in the NAEI: A scoping study. Report to Defra. April 2007. AEAT/ENV/R/2431.
[17] It is difficult to say whether EFs should vary due to the high uncertainty; on balance bi-fuel vehicles tend to emit slightly more NOx when running on LPG. However, the uncertainties are very large.

A1.6 Electricity generation sector

Similar to the transport sector, the electricity generation sector is characterised in detail, reflecting its importance in the energy system and the diverse set of options for carbon reductions in future years.

Key technologies include:

- New conventional fossil plant (primarily CCGT (gas), pulversied fuel (coal), and IGCC (coal), with increasing efficiency of plant in future years
- Conventional plant with carbon capture and storage (CCS)
- Nuclear technologies
- Renewable generation technologies – including offshore / onshore wind, marine, solar, biomass
- CHP

Emission factors used for existing and new conventional plant take account of the requirements of the Large Combustion Plant Directive (LCPD), and are consistent with the assumptions made in the NAEI projections.

For CCS based technolgies, we have assumed that most technologies will have almost no SO_2 emissions due to the flue gas scrubbing required. NOx and PM_{10} factors are low in future years, and consistent with new conventional plant; these assumptions would benefit from further research.

Emission factors are not required for nuclear and renewable technologies, with the exception of biomass. For biomass co-fired in power stations, it has been assumed that emissions are the same on an energy basis as for coal. Other types of biomass plant are not particularly prevalent in this sector, apart from energy crop gasification. Emission factors for this type of plant are not known; however, this technology is a very small contributor to generation.

For the many different CHP technologies in this version of the MARKAL database, we use factors for 'gas turbines' taken from the NAEI in the case of gas fired plant, and factors from AP-42[18] for diesel use in engines, in the case of all other CHP plant. Since NOx emissions from gas turbines and stationary engines are generally higher than those from conventional steam-raising boilers, the factors used for CHP will show that, although CHP plant are more efficient and therefore can help to reduce emissions of CO_2, emissions of NOx may increase.

A1.7 Process sector

The process sector includes energy transformation process and energy infrastructure. Key processes included in this sector include:

- Refineries
- Coke and other solid fuel production
- Enrichment of nuclear fuel
- Hydrogen production
- Biofuel production

Emission factors for hydrogen and biomass production constitute a gap in AQ emission factor understanding, as provided by the NAEI EF database. Such processes include biomass pyrolysis and gasification for hydrogen production, 1st and 2nd generation biofuel production, and fermentation to ethanol. We do not think these are significant emitting sectors but nevertheless constitute a gap in understanding. Further literature review would be required to better understand the AQ emissions associated with such process.

Uranium enrichment is also covered by the process sector. Most of the direct energy requirements come from electricity generation; emissions of this will be accounted for in the electricity generation sector.

[18] US EPA, AP42, Volume I, Fifth Edition. http://www.epa.gov/ttn/chief/ap42/

The main sectors of importance with regard to AQ emissions are covered, with factors sourced from the NAEI. This includes refineries and other fuel transformation processes.

A1.8 Resource sector

The resource sector covers the import and export of energy commodities, and the domestic extraction processes including oil, gas and solid fuels.

Emission factors for mining of solid fuels is from the NAEI 'Collieries – Combustion' code. Emission factors for oil and gas are not distinguished but based on an average factor covering all of the associated activities in the NAEI including:

- Gas production
- Offshore oil and gas - own gas combustion
- Gas separation plant - combustion
- Gas separation plant - combustion
- Shipping - coastal
- Shipping - coastal
- Offshore oil and gas - processes
- Offshore oil and gas - well testing
- Offshore oil and gas - flaring

A1.9 Uncertainties in emission factors

Air quality emission factors tend to be more uncertain than carbon factors. This is because carbon factors are based on the carbon content of the fuel and are therefore subject to small uncertainties. The uncertainties arising from the NOx, PM_{10} and SO_2 emission factors are briefly described below.

Sulphur dioxide – emissions of this pollutant can be estimated with most confidence as it largely depends on the sulphur content of the fuel being combusted.

Nitrogen oxides – emission estimates are less accurate than SO_2 because they are calculated using measured emission factors. These emission factors can vary widely with combustion conditions. In the case of road transport emissions, while the inventory methodology takes into account variations in the amount of NOx emitted as a function of speed and vehicle type, significant variations in measured emission factors have been found even when keeping these parameters constant.

Particulate matter – the uncertainty is high for particulate matter. The emission factors are generally based on a few measurements on an emitting source, which is assumed to be representative of the behaviour of all similar sources. Emission estimates for PM_{10} are based whenever possible on measurements of PM_{10} emissions from the source, but sometimes measurements have only been made on the mass of total particulate matter and it has been necessary to convert this to PM_{10} based either on the size distribution of the sample collected or more usually on size distributions given in the literature. Many sources of particulate matter are diffuse or fugitive in nature, for example emissions from coke ovens, metal processing or quarries. These emissions are difficult to measure and in some cases it is likely that no entirely satisfactory measurments have ever been made.

Annex 2. Model set-up and calibration

The emission factors were sourced primarily from the NAEI, as described in the preceding section. They were collated in a spreadsheet prior to entry into the model, ensuring that factors were in units consistent with what was needed in MARKAL (e.g. kt/PJ rather than kt/Mtonnes). This stage also provided a basis for checking.

Emission factors have been incorporated into the UK version of the MARKAL model. They can be tracked at the technology, sectoral or UK level. Naming of emission factors in the model has ensured tracking of emissions can be done at a sectoral level. For example, technologies and fuels in industry have three specific emission factors – INOX, IPM10, and ISO2. They also have the generic emission factors - NOx, PM_{10}, and SO_2. All sectors in the model follow this process.

The main check that has been run on the model is a comparison of 2000 emission levels by sector against the NAEI. Whilst we do not expect these to be exact, this is a useful first check to ensure magnitude of emissions is correct, split between sectors is broadly correct, and the aggregate emission is similar.

NOx – The 2000 total in the model is lower than in the inventory e.g. 1520 (MARKAL) versus 1900 (NAEI). Differences are primarily due to off road vehicles and coastal shipping not be explicitly included in MARKAL, and a lower estimate for agriculture. The core sectors (residential, transport, electricity) are all consistent.

PM_{10} – The 2000 total in the model is much lower than in the inventory e.g. 100 (MARKAL) versus 185 (NAEI). Road transport and residential sectors are broadly consistent, while electricity generation total in MARKAL is a bit lower. The main differences are driven by non-combustion (process) emission sources in agriculture, and more detailed industry depiction. In addition, other high emitting sectors e.g. off road are not seperated in the model so are not allocated the relevant emission factors.

SO_2 - The 2000 total in the model is lower than in the inventory e.g. 890 (MARKAL) versus 1200 (NAEI). The discrepancy is primarily due to a lower estimate of energy use in the MARKAL model from the electricity generation sector.

All of these differences will be further considered, as the model is developed. Issues causing the differences, in summary, are due to:

- Calibration of the model to DUKES not the NAEI
- Less detail of sectors in MARKAL
- Consistency of DUKES issue year (used for calibration) and use of latest NAEI inventory
- No account of process (non-combustion) emissions in MARKAL model

AEA Energy & Environment
From the AEA group

The Gemini Building
Fermi Avenue
Harwell International Business Centre
Didcot
Oxfordshire
OX11 0QR

Tel: 0845 345 3302
Fax: 0870 190 6318

E-mail: info@aeat.co.uk

www.aea-energy-and-environment.co.uk