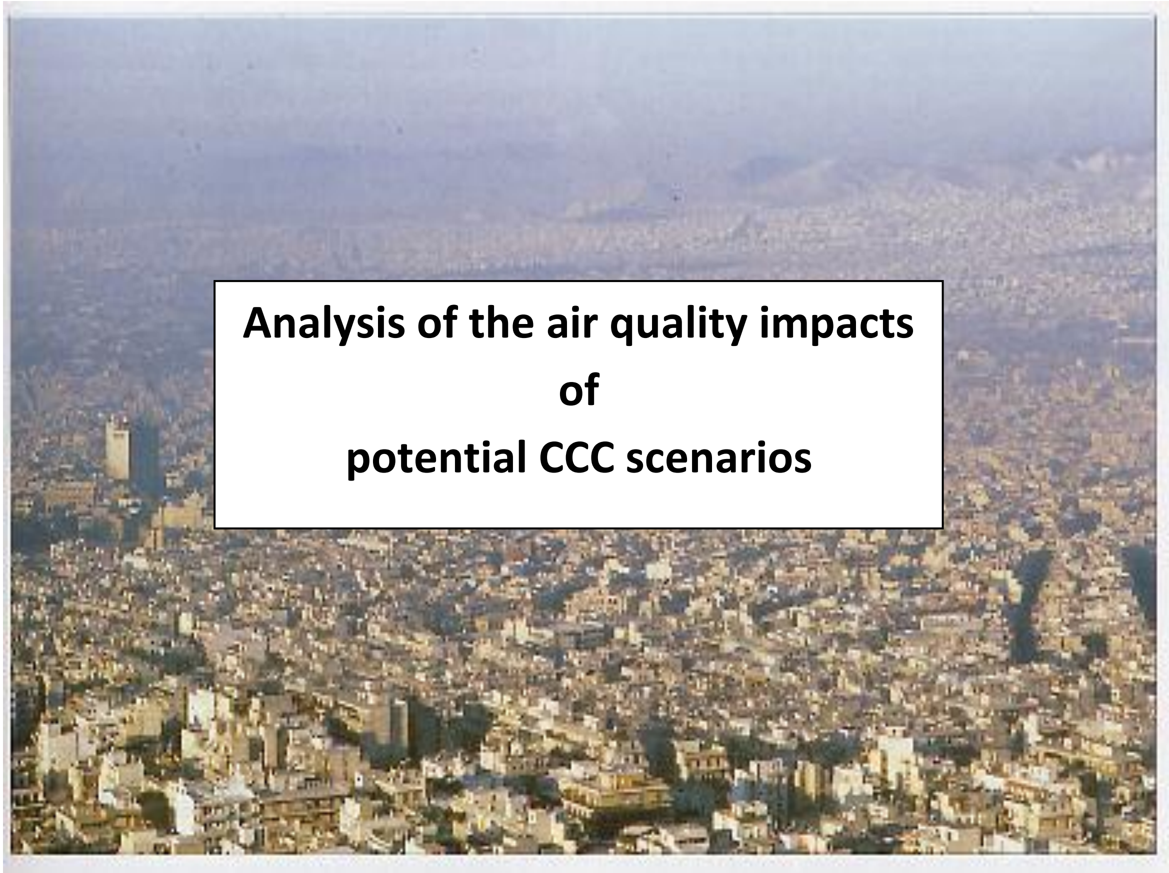

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Executive Summary

Part 1: Analysis of the air quality impacts of potential CCC energy scenarios

Part 1 of this study investigates and compares the air quality impacts of three energy scenarios to 2030 defined by the CCC. These are a "climate action" scenario (CCC.CA) which underpinned the CCC's advice on the fourth carbon budget; a "no climate action" scenario (NO.CA) in which no action is taken to meet the carbon budgets, with rising energy demand met by new conventional coal and gas generation; and a "dash for gas" scenario (D.GAS) in which the UK's renewable energy targets are met, but subsequent demand is met mainly with unabated gas generation. Power generation data for each scenario has been provided by the CCC covering the period 2008 to 2030 (see figure 1.1 of report). The "CCC climate action" and "dash for gas" scenarios are coupled with a number of measures in each of the heat, transport, residential, non-residential and industry sectors, with any associated changes in electricity requirements represented in the power sector. These have been analysed source by source, differentiating fuels and technologies, using the RAPID (Rapid Air Pollution Impacts Diagnostics) tool. Resulting emissions of the air quality pollutants SO_2, NOx, NH_3 and fine particulate matter, PM_{10} and $PM_{2.5}$, have been estimated for each sector and source. These have provided the data required for the current method used by Defra to estimate economic costs of environmental damage attributable to these pollutants (see section 1.4). They are also relevant to compliance with national emission ceilings as legal requirements for the UK.

However, to give a broader picture of environmental impacts, indicator values have also been calculated with respect to contributions to acid deposition, nitrogen deposition and eutrophication of ecosystems, and mean concentrations of NOx, PM_{10} and $PM_{2.5}$ with respect to air quality and human exposure (see section 1.2). This reflects atmospheric dispersion and deposition depending on the characteristics of different sources, as represented by source specific "impact factors" in RAPID. The fine particulate matter includes both primary particles and secondary particles formed from chemistry of SO_2, NOx and NH_3 in the atmosphere. Because of impacts on human health the particulate concentrations tend to dominate damage costs, and hence provide an alternative approach to estimating damage costs.

In the heat sector there are particular concerns in relation to air quality over the use of biomass, and hence the increased deployment of biomass and biogas has been separated out from the large reductions in fossil fuel use for this sector, which include other measures such as heat pumps. This distinguishes the potentially adverse effects from the beneficial measures in this sector, since both are large and uncertain; with the net balance dependent on assumptions about the emissions from biomass use, and the achievability of the very large reductions in fossil fuel use for heating defined in the CCC scenario on top of efficiency measures.

Not all measures can be associated with changes in air quality. For example, in the transport sector, measures which reduce CO_2 emissions do not imply changes in NOx emissions.

Renewables such as wind, pumped storage and solar have been assumed to give zero emissions.

The summary table provides an overview of the results, with negative numbers implying reductions in emissions- that is benefits. The top line provides differences between the " CCC climate action" (CCC. CA) power generation and the "no climate action" (NO.CA) scenario. The second line shows the corresponding differences between the "dash for gas" (D.GAS) scenario and the NO.CA scenario. These are followed by the effect of accompanying measures in other sectors, which are the same for the CCC.CA and D.GAS scenarios. The final lines provide an overall net effect of the combined effect of these measures with the power sector effects in the first 2 lines, to give the overall effect of the CCC.CA and D.GAS scenarios relative to the NO.CA scenario.

The first four columns indicate the effects on annual emissions of the respective pollutants in kt/year at the end of the scenarios in 2030. Additional information on accumulated total emissions over the period 2010 to 2030 is provided in table 1.3a of the report, with comments on assumptions and uncertainties. Columns 5 to 8 provide a corresponding indication of the effects in 2030 on the environmental indicators defined with respect to acidification of ecosystems, nitrogen deposition and biodiversity, and human exposure to NOx and PM. An explanation of these indicators is provided in section 1.2 with the integrated values over the period in table 1.3b. The final two columns indicate the estimated environmental damage costs the first based on emissions in the year 2030 (without any discount factor applied), and the secondly accumulated over the period 2010 to 2030 including discount factors to give net present value, NPV as of 2010. The costs are based on emissions following the Defra methodology (see section 1.4), and are summarised broken down for each sector in table 1.2. Negative values indicate a reduction in environmental damage, and hence a benefit. In addition histograms in figures 1.1 to 1.11 of the report give a visual picture of the trends over time broken down by different source components in each sector for all the components in the table.

<u>The power sector</u> (see figure 1.1 for comparison of scenarios)

The "no climate action" (NO.CA) scenario, with increasing use of both coal and gas and declining nuclear and small renewable component, gives a worsening effect over time in all respects with increasing emissions of SO_2, NOx and PM. Power demand is a little different in both the "dash for gas" and "CCC climate action" scenarios, because they include the effects of efficiency and electrification measures in other sectors. The "dash for gas" (D.GAS) scenario reduces the use of coal, and hence SO_2 emissions, but the increased use of gas plus some biomass compensates for this with respect to NO_x emissions, which are almost the same in 2030 as in 2010. The "CCC climate action" (CCC.CA) power sector scenario also phases out conventional coal fired power stations, hence reducing SO_2; but also reduces conventional gas plants, with replacement by CCS coal and gas plants plus increased nuclear and renewables- resulting in some further reduction of NOx.

Compared with the “no climate action” scenario both the “CCC climate action” and the “dash for gas” scenarios imply a very big reduction in both SO_2 emissions (~116 kt in 2030) and NOx emissions (127 and 82 kt respectively), with associated improvements in acid deposition and nitrogen deposition, and also in secondary PM_{10} exposure. The corresponding relative benefits in reduced environmental damage costs over the 20 year period are large, and similar for both scenarios, with net present values of £2.3 billion and £2.2billion. However, with the final mix of energy generation by the end of the period in 2030, the “CCC climate action” achieves a slightly bigger improvement than the “dash for gas” power scenarios, mainly due to the greater reduction in NOx.

The heat sector

The biggest effects on air quality arise from measures in the heating sector, with contrasting adverse impacts from use of biomass/biogas and benefits from the savings in fossil fuel use specified in the CCC climate action scenario. There are large uncertainties in both, and hence in the net effect.

Of particular importance is the emission of primary particulate matter from the use of biomass. Even with the conservative assumption of strict compliance with emission factors defined for the renewable heat incentive (RHI), annual emissions of $PM_{2.5}$ in 2030 are estimated at ~7kt. However the emissions from wood burning stoves are very variable and uncertain, generally giving much higher emissions. The figures in brackets in the table are for a sensitivity study assuming the use of eco-label Swan Stoves as an alternative “strict standard” for just the residential heating component of biomass use. Despite the modest energy contribution this doubles total emissions of $PM_{2.5}$ from biomass heating measures in 2030 to almost 13kt. The associated health impacts are reflected in adverse environmental damage costs. Because biomass use in the residential sector only grows in the final years of the scenario the overall increase in NPV over the 20 year is limited to an increase from £2 billion with the strict RHI emission factors to £2.7 billion with the eco-label Swan Stoves. However the (undiscounted) costs in the final year, 2030, increase from £0.4 billion to £0.7 billion, larger than the power sector savings and eradicating any overall benefits from savings in fossil fuel for heating (see below). The high emissions of $PM_{2.5}$ also raise serious concerns with respect to compliance with the national ceiling for total UK emissions of this pollutant (~57kt per year).

The estimates of exposure reflect the spatial distribution of sources relative to urban populations. Thus it has been assumed, for example, that residential biomass will replace oil and coal more concentrated in rural areas as opposed to gas, which is not represented in such detail in the Defra costs based on emissions. Even so there are large increments overall in exposure to both NOx and PM due to the use of biomass and biogas in the heat sector.

The savings in fossil fuel use defined by the CCC for the heat sector are very large, totalling over 300 TWh in 2030, which is nearly 3 times the energy for biomass and biogas, and reflects additional measures such as heat pumps. This is on top of efficiency savings treated below. Although these savings counteract the biomass/biogas use, with additional bonuses of reduction in SO_2 emissions and acid deposition from less coal combustion, this is dependent on these reductions in fossil fuel use being achievable. The reduction in damage costs is reflected in the NPV of -£3.1 billion as compared with the increase of at least £2 billion from biomass/biogas use assuming the RHI emission factors. However any net benefit in 2030 is dependent on the attainment of the fossil fuels savings in the CCC scenario, and the achievability of such strict limits for biomass emissions.

Transport

Road transport measures covered include electric cars and vans, hydrogen buses, HGV logistics and "smart choices" to reduce car use. There is a moderate reduction in NOx emissions although this does not include additional emissions from electricity generation in the power sector. Taking this into account the "smart choices" is the most effective measure (although this has not included the potential for any increased emissions from public transport as a result of reduced car use). There is a modest environmental benefit for the transport sector represented by the NPV of £0.6 billion over the 20 year period, and a damage cost saving in the year 2030 of ~£100 million.

Efficiency measures

The benefits of efficiency measures for residential, industrial and non-residential energy use have been combined. The corresponding savings in fossil fuel use are less than half of those in the heat sector, with correspondingly smaller effects on pollutant emissions and environmental impacts. But there is still a significant effect on SO_2 and PM emissions, and a substantial reduction in damage costs with a NPV of £1.6 billion, and a contribution of £226 million to cost savings in the final year- about a third of those for reduced use of fossil fuels in the heat sector.

Overall impact of CCC climate action scenario

Both the "CCC climate action" and "dash for gas" scenarios imply substantial air quality benefits compared with the "no climate action" scenario. There are large reductions by 2030 of over 200 kt in SO_2 emissions, and also in NOx (almost 200 kt for the climate action, and ~150 kt for the dash for gas scenario). Changes in PM emissions are very dependent on biomass use. There is an overall improvement in all the environmental indicators for acidification, nitrogen deposition and eutrophication, and in human exposure.

Assessment of environmental damage costs using the Defra methodology based on emission indicates substantial benefits, with an estimated NPV over the period 2010 to 2030 of around £5.5 billion relative to the no climate action scenario for both the CCC climate action scenario and the dash for gas. Of this a similar amount of around £2billion is due to the power sector in both cases, with the remainder due to the measures in other sectors. However these sums are critically dependent on the scenarios defined by the CCC and underlying assumptions, and on uncertainties in the environmental assessment and damage costs. Of particular importance is particulate matter in the heat sector. Further work is recommended to consider the heat sector in more detail both with respect to the use of biomass, and the reductions in fossil fuel usage: and also to extending preliminary comparisons of alternative approaches to environmental damage costs

Executive summary table

	<				2030			>	Costs[#]	NPV
	SO2	NOx	PM10	PM2.5	acid dep	Ndep	NOx	PM10	year 2030	2010-2030
	kt/yr	kt/yr	kt/yr	kt/yr	Meq	kt N	ng/m3	ng/m3	£bn	£bn
Power: CCC.CA-NO.CA	-116	-127	-3.35*	-0.94	-1303	-4.80	-333	-267	-.467	-2.27
Power: D.GAS-NO.CA	-116	-82.6	-2.06*	-1.03	-1201	-3.79	-131	-219	-.403	-2.18
Heat/biomass[+]	2.0	48.3	8.45(16.1)	6.8(12.9)	434	5.81	2593	257(363)	.396(.718)	2.0(2.7)
Heat /energy saved	-83.6	-72.0	-9.73	-5.5	-1381	-7.20	-2193	-355	-.693	-3.13
Transport	0	-23.7	-1.00	-0.65	-138	-1.94	-494	-64	-.106	-0.60
Efficiency	-30.2	-22.5	-3.06	-1.75	-473	-1.67	-655	-80	-.226	-1.65
Overall:CCC.CA-NO.CA[+]	**-228**	**-197**	**-8.7**	**-2.0**	**-2860**	**-9.8**	**-1080**	**-510**	**-1.1**	**-5.6**
Overall: D.GAS-NO.CA	**-228**	**-152**	**-7.4**	**-2.1**	**-2759**	**-8.8**	**-880**	**-461**	**-1.0**	**-5.5**

* There is a difference in the calculation of PM10 emissions and PM2.5 emissions for natural gas, with the former based on NAEI emission factors (pessimistic) and the latter assuming no emissions from natural gas.

[#] Costs in 2030 are not discounted to 2010 as in the final column for the NPV. With such discounting they would be half these values.

+ Figures in brackets correspond to the sensitivity study to emission factors for residential use of biomass for heating.

Part 2: Exploration of air quality impacts of changes in the agricultural sector

Part 2 of this report investigates some hypothetical scenarios to explore the air quality impacts of changes in agricultural demand and production, which also affect greenhouse gas emissions. These scenarios are not part of the CCC climate action scenario, but have been taken from a study for the CCC by Cranfield University. The main effect on air quality is from emissions of ammonia, NH_3, for which agricultural manures and fertiliser use are the dominant sources.

The analysis has been undertaken using the full UKIAM model to look at ecosystem protection in more detail, and in particular SSSIs. The current baseline scenario in UKIAM has been used based on NAEI UK emissions, including agriculture, projected to 2020, together with associated imported contributions from other countries and shipping. This enables mapping of total deposition (including both oxidised and reduced nitrogen) for comparison with critical loads for ecosystem protection (figure 2.1), and particulate concentrations from all sources with respect to human exposure and health impacts. Separate runs have then been undertaken reducing the agricultural NH_3 to explore the scenarios.

The first scenario involves large changes in agriculture with a 40% reduction in dairy and eggs and a 64% reduction in meat production. The correspondingly large reduction of 100 kt in NH_3, or 45% of the baseline agricultural emissions, leads to a substantial improvement in ecosystem protection with a reduction from 27% to 21% of UK ecosystems at risk with respect to acidification, and from 47% to 28% with respect to eutrophication. Such an improvement is difficult to achieve, and these changes are considerably larger than could be achieved by conventional abatement measures targeted at NH_3 emission reduction. A more detailed analysis with respect to SSSIs (figure 2.2) shows a similar picture with a large improvement in the statistical distribution of sites across 5 classes of increasing severity of risk according to exceedance of critical loads (figure 2. 3).

The second scenario depicts a switch from red to white meat consumption (75% reduction in beef and lamb, and 45% increase in pig and poultry meat); whereas the third scenario represents a 50 reduction in white meat. Both scenarios involve more modest changes than scenario 1 in annual emissions of $NH_{3,}$ of 30 and 20 kt respectively. Mapping of exceedance of critical loads indicates improvements to 35% and 40% of ecosystems still at risk with respect to eutrophication for the two scenarios. For acidification scenario 2 shows a small improvement of 2% relative to the baseline, or 25% of ecosystems unprotected: however for scenario 3 there is a very slight increase in ecosystems at risk despite the overall decrease in emissions. This illustrates the importance of spatial aspects with different geographical distributions of emissions for different livestock categories. Although reduction of ammonia emissions reduces deposition more locally it can enhance deposition, including SO_4 and NO_3, further away over sensitive areas. Analysis of SSSIs gives a similar overall picture of improvements.

With respect to human health the first scenario has the greatest effect on secondary PM_{10}, with a population weighted reduction in mean concentration of $0.16\mu g.m^{-3}$ which is comparable with reductions in some sectors in part 1 of this report. The other scenarios generate smaller reductions, with scenario 3 implying a bigger improvement than scenario 2, again reflecting the different spatial distribution of white meat production.

Since the temporal development of these agricultural scenarios was not specified in the data provided by the CCC it has not been possible to assign damage costs in the same way as for the energy scenarios in part 1. However, using the Defra damage costs of £2 million per kilotonne of NH_3 emitted, indicates an approximate benefit of £200 million per year for the reduction of 100kt in annual emissions for scenario 1. Corresponding values for scenarios 2 and 3 are £60 million per year and £40 million per year respectively. These are very much order of magnitude estimates with large uncertainties, and are for purely hypothetical agricultural scenarios which are not related to the CCC climate action energy scenarios in part 1. Moreover they do not include any valuation of the benefits of improved protection of natural ecosystems in the UK.

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Part 2

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Appendix A: The UKIAM model

Analysis of the air quality impacts of potential CCC scenarios

Introduction to study

The purpose of this contract has been to investigate and compare the implications for air quality of future UK energy scenarios defined by the Committee on Climate Change (part 1 of this report); and also to undertake preliminary exploration of the effects of changes in the agricultural sector (part 2 of this report) . The energy scenarios apply to the period from 2008 to 2030, and cover the power sector together with heat from biomass and biogas, transport, and energy use by industry, residential and non-residential sectors. Using the RAPID (Rapid Air Pollution Impact Diagnostics) tool described below, annual emissions of air quality pollutants (SO_2, NOx, NH_3, and fine particles PM_{10} and $PM_{2.5}$) have been estimated, and indicators of environmental impacts assessed with respect to protection of natural ecosystems and human exposure and health impacts. Data used by Defra for environmental damage cost per ton of pollutant emitted have been applied to the emissions data to assess the economic benefits.

In part 1 the methodology used is described, followed by results showing the breakdown of emissions on a sector-by-sector basis, and environmental impact indicators with respect to acid deposition, eutrophication of ecosystems and biodiversity, and population exposure to NOx and fine particulate matter. These are set in the context of air quality policy and legal obligations, to complement the economic assessment of environmental damage/benefit; and to give a more overall summary of the synergies between energy policies for climate change and air quality, and aspects where there are potential conflicts.

In part 2 the pollutant of particular concern is ammonia, NH_3, which comes predominantly from agriculture and is a major contributor to nitrogen deposition and ecosystem impacts, as well as playing a role in secondary production of small particles with respect to human health. Here the full UK Integrated Assessment Model, UKIAM (from which the RAPID tool is derived) has been used to produce a baseline scenario for 2020 based on current projections for agriculture and other emissions in and outside the UK. This baseline has been compared with three other scenarios in which agricultural production of meat and dairy products has been varied as specified by the CCC. The results illustrate how changes in the agricultural sector have air quality implications as well as affecting greenhouse gas emissions.

Part 1:

Analysis of the air quality impacts of potential CCC energy scenarios

1.1 Introduction

The energy scenarios provided by the CCC comprise three scenarios for the power sector, of which the "CCC climate action" and "dash for gas" power sector scenarios are coupled with a number of measures in each of the "heat", "transport", "industry", "residential" and "non-residential" sectors. The baseline scenario for the power sector is a "no climate action" business as usual scenario. The sectors have been analysed source by source, differentiating fuels and technologies, and the RAPID tool applied to derive emissions of air quality pollutants (SO_2, NOx, NH_3 and fine particles as PM_{10} and $PM_{2.5}$) on an annual basis from 2008 to 2030. This provides the basis for the current method used by Defra for estimating economic costs of environmental damage attributable to these pollutants (see section 1.4).

However, to give a broader picture of environmental impacts, indicator values have also been calculated with respect to contributions to acid deposition, nitrogen deposition and eutrophication of ecosystems; and mean concentrations of NOx, PM_{10} and $PM_{2.5}$ with respect to population exposure, providing an alternative approach to health impacts. This reflects atmospheric dispersion and deposition depending on the characteristics of different sources (see section 1.2). The fine particulate matter includes both primary particles and secondary particles formed from chemistry of SO_2, NOx and NH_3 in the atmosphere. Because of impacts on human health the particulate concentrations tend to dominate damage costs, and hence provide an alternative approach to estimating damage costs.

1.2Methodology- the RAPID tool, emissions and impacts

The RAPID (Rapid Air Pollution Impact Diagnostics) tool is an off-shoot from the UK Integrated Assessment Model, UKIAM, developed with funding from Defra for analysis of future scenarios with respect to air pollution in the UK, and cost effective strategies for improvement (Defra contract AQ0902). Thus UKIAM (Oxley et al 2003and 2012) brings together projected pollutant emissions, source footprints from atmospheric modelling of dispersion and deposition, criteria for protection of ecosystems and limit values for protection of human health, together with potential abatement measures and their costs[1]. UKIAM covers imported contributions from Europe and shipping to represent trans-boundary contributions, as well as detailed treatment of UK emissions based on NAEI (National Atmospheric Emission Inventory) projections: and maps concentrations and deposition on a 1x1 and 5x5 km grid scale respectively, with major roads superimposed in relation to compliance with limit values for road-side concentrations in urban areas. It has been extensively compared with measured data, and with other modelling through Defra inter-comparison exercises. More details may be found in Appendix A.

[1] It also includes some greenhouse gas emissions to reflect synergies between measures for air quality pollutants and for GHG reduction, and it is hoped to extend this in future.

The sources treated in UKIAM include major point sources such as power stations, plus gridded source distributions for smaller and area sources such as domestic gas and off-road emissions. Road transport emissions are built up across the UK road network on a road by road basis, and assembled on the same 1x1 km grid. Release characteristics and spatial distributions play a significant role in the deposition patterns and exposure of the population. For use in the RAPID tool, sources may be grouped and treated collectively, for example coal fired power stations. In this study emissions have been based on emission projections to 2020, assuming the power stations expected to be in operation then, and reflecting the technologies and abatement of air quality pollutants anticipated under current legislation.

RAPID is a simple spread-sheet tool, drawing on data bases of firstly emission factors to define emissions for a wide range of sources and technologies, and secondly on impact factors for pollutant deposition and concentrations for a range of different sources. The emission factors are the same as those used in the NAEI and UKIAM, supplemented for additional sources and technologies that are not directly represented in the NAEI such as different types of CCS. Emission factors for biomass sources are those specified for the Renewable Heat Incentive, RHI: but which, as discussed, could be very much larger. Emissions are then calculated by combining emission factors with activity data such as Mtherms of gas or Mtons of coal used, derived from the energy projection spread-sheets supplied by the CCC and energy contents of fuels and conversion factors as defined in DUKES. (Note that the NAEI uses gross emission factors and adjustment has been made where the CCC data specifies net efficiencies.)

The impact factors, IFs, have been calculated for each source in UKIAM by estimating the change in respective deposition or population weighted concentrations across the UK per unit change in emissions of each pollutant. Combined with pollutant emissions these then give an indication of the contribution of a source to different environmental impacts. Thus

i) SO_2, NOx and NH_3 emissions combined with respective IFs contribute to acid deposition. The units used here are acid equivalents, Meq: and because of the continental scale transport of these pollutants, emissions outside the UK are also important. In the full UKIAM model acid deposition is mapped and compared with critical loads as criteria for protection of ecosystems (see part 2 of this report), distinguishing different habitats and sensitivities. But as an approximate indication using RAPID, the significance of a source contribution in Meq can be compared with the total acid deposition across the UK projected to be around 23,000 Meq in 2020, of which approximately 60% is due to UK sources.

ii) NOx and NH_3 emissions generate nitrogen deposition contributing to eutrophication of ecosystems and loss of biodiversity. Again there are transboundary imported contributions, and in the full UKIAM model nitrogen deposition is mapped and compared with critical loads for eutrophication of ecosystems. Whereas there have been big improvements with respect to acidification, protection of natural ecosystems with respect to eutrophication remains a more difficult problem. In RAPID the deposition of nitrogen in kilotonnes is used as an indicator. To put this in perspective the total projected deposition of N in the UK in 2020 is around 260 kt, of which approximately 40kt is due to UK NOx emissions and 120 kt to UK emissions of NH3 (which come mainly from agriculture), and the rest from imported contributions from shipping and other countries.

iii) NOx, a combination of NO and NO_2, is a key pollutant with respect to urban air quality where the UK, in common with many other European countries, has difficulties in meeting limits specified in EC legislation for NO_2. The limit value of 40 $\mu g.m^{-3}$ for annual mean NO_2 applies to the most polluted sites where the public can be exposed, predominantly road-side sites. The fraction of NOx as NO_2 is complex and non-linear depending on chemical reactions and ozone. UKIAM attempts to model this and to consider the most polluted roads, but the simpler RAPID approach estimates the contribution of a source to the population weighted average exposure to NOx. This is very dependent on the proximity of emissions and high population densities, with orders of magnitude difference between urban traffic and remote power stations with tall stacks. To put the NOx indicator values in perspective, average NOx concentration at background monitoring stations in London in 2009 was around 70 $\mu g.m^{-3}$, (or 70,000 $ng.m^{-3}$ in the units used for the indicator values.)

iv) Exposure to fine particulate matter either as PM_{10} (less than 10 microns in diameter), or the finer fraction $PM_{2.5}$ (with greater penetration into the lungs and thought to be more responsible for health effects). As for NOx there are limits on PM_{10} concentrations set in EC legislation, but the main focus here is on health impacts where it is the total exposure of the population to fine particulates that tends to dominate damage costs in the economic assessment. The RAPID model therefore estimates contributions to population weighted mean concentrations from a source, combining secondary contributions due to chemical formation of SO_4, NO_3 and NH_4 aerosol from SO_2, NOx and NH_3, and those directly from primary PM emissions. In the RAPID model we only consider exposure of the UK population, but long-range transport across Europe leads to further trans-boundary exposure, especially of the secondary inorganic aerosol. Calculations with UKIAM have indicated an approximate doubling of the UK exposure and health impacts for the total UK plus European exposure when this is taken into account. UKIAM estimates of population weighted mean SIA concentrations in 2020 are ~3700 ng/m3 as PM_{10} and ~3300 ng/m3 as $PM_{2.5}$, allowing for the coarser NO_3 fraction. About half of this is due to UK emissions and half attributable to shipping and other countries. The primary contribution to UK exposure is smaller at around 1500 and 900 ng/m3 for PM_{10} and $PM_{2.5}$ respectively.

There are also other considerations directly related to emissions, with recent revision of the Gothenburg protocol setting national emission ceilings for 2020 for SO_2, NOx, NH_3, $PM_{2.5}$ and VOCs for countries within the UNECE. Indicative values for the UK are for SO_2 290 kt, for NOx 710 kt, for NH_3 282 kt, and for $PM_{2.5}$ 57 kt. These may be tightened for EC countries in the current review of the EC's Thematic Strategy on Air Pollution and revision of the Air Quality Directive.

Note that we have not included VOCs in this analysis as they are not yet in UKIAM and RAPID[2], and nor have we included the combined contribution of NOx and VOCs to tropospheric ozone. This is because of the complex non-linear chemistry and trans-boundary context. But ozone reduction through control of NOx and VOCs is another factor with both air quality benefits and radiative forcing effects. Similarly we have not differentiated between black carbon and other particulate components in relation to radiative forcing, although this is another aspect that could be considered in future.

1.3 Results: emissions and impacts

The power sector

The energy mix for the “CCC climate action” and “dash for gas” power sector scenarios addressed in this study are shown in figure 1.1, together with the “no climate action” scenario for comparison. The “CCC climate action” and “dash for gas” scenarios include adjustments for electricity savings and additional electricity requirements in other sectors, which balance out to give an overall energy requirement in 2030 of 460 TWh , very slightly less than the “no climate action” scenario (465 TWh in 2030). The “renewables” shown in blue, include hydro, wind, pumped storage and other renewables, which do not lead to air pollutant emissions when generating energy, and are hence ignored in this study: but does not include biomass combustion, which does generate pollution and is an important aspect of this study. Similarly the nuclear component is assumed to give rise to negligible air pollutant emissions, and together with the renewables leads to very much less power generation from combustion.

The dash for gas scenario effectively removes coal combustion, whereas the CCC climate action scenario retains a modest amount of coal with carbon capture and storage, CCS. The use of CCS with coal is assumed to be half a post-combustion amine process, and half Integrated Gasification Combined Cycle, IGCC. A feature of the former is that it can generate emissions of ammonia. The CCS applied to combined cycle gas turbines, CCGT, is also assumed to be a post capture amine process although no ammonia emissions have been quantified for this. Emission factors for these CCS technologies as compared with equivalent plants without CCS, have been taken from a TNO study (TNO, 2009) as these technologies are not covered in the NAEI.

These data represent the net energy output from the power sector, whereas emissions of pollutants depend on amounts of fuel consumed and the application of gross emission factors per unit consumption (e.g. Mtherms of gas, or Mtons of coal). The CCC therefore provided data on the efficiencies to be assumed for the different types of plant, and emissions are very sensitive to these. For example the emissions of NOx from coal plant with and without CCS depend on the difference in efficiency: which, in the CCC climate action scenario, has been set at 36% for standard pulverised coal plants effectively phased out in this scenario, and 35%

[2] Work is currently in progress on incorporating VOCs.

with CCS assuming this is fitted to more efficient plants- i.e. just a 1% difference. In the no climate action scenario where there is no CCS fitted, pulverised coal plant efficiencies are assumed to improve from 35% to 41 % by 2030, and CCGT plants from 49% for current plants to 53% by 2030.

Pollutant emissions from the power sector.

The emissions of SO_2, NOx, and PM_{10} are shown in figures 1.2a to 1.2c, again broken down by the mode of generation and with comparison between the scenarios. The SO_2 emissions clearly reflect the amount of coal used, and are very much greater in the "no climate action" scenario rising to almost 120 kt/yr, while falling to negligible values in the other scenarios. As shown later this has environmental benefits, while an increase in emissions as in the "no climate action" scenario would make attainment of the SO_2 emission ceiling for the UK difficult.

The emissions of NOx are also reduced more in the "CCC climate action" scenario, where the emissions in 2030 are dependent on new technologies of CCS with associated uncertainties, and on biomass. Here it has been assumed that wood would be used in power stations co-fired with coal, with corresponding emission factors projected to 2020; as opposed to smaller installations which might not be subject to the same controls.

A similar picture emerges for $PM_{10,}$ where we have included emissions for CCGT burning natural gas based on the emission factors used in the NAEI, although there has been discussion on whether these are pessimistic recognising that this source is generally ignored as negligible[3]. To retain authenticity with the NAEI we have retained them in the PM_{10} estimates making the contribution clear, and omitted emissions from natural gas in the $PM_{2.5}$ emission estimates as a sensitivity study. However the main uncertainties in the PM emissions in 2030 relate to emissions from the new technologies of CCS and biomass. The latter could potentially be much higher if used in smaller plants with less stringent control.

With regard to ammonia emissions these are normally dominated by the agricultural sector (see part 2), and emissions from the power sector are small. However there have been concerns about emission of ammonia from post combustion CCS using the amine process. Using the emission factors from the TNO report on CCS (TNO Bolk report) leads to an indicative value of 2.6 kt of NH3 for the 27 TWh of generation in 2030 from coal plus post combustion CCS in the CCC climate action scenario. This is a relatively small amount but could be significant with larger proportions of this technology.

Impacts from the power sector

The different impact indicators have been described above in section 1.2. The first two, acidification and eutrophication, are dependent on pollutant deposition and relate to protection of natural ecosystems. The trends over time for the CCC climate action power sector scenario are shown in figure 1.3a, indicating a much larger reduction in acid deposition

[3] Discussion with Ricardo-AEA has explained that the NAEI emission factor for PM_{10} from natural gas is based on US-EPA data.

than in nitrogen deposition and eutrophication. This reflects the large reduction in SO_2 in this scenario. To put these numbers for the power sector in perspective please refer to section 1.2 where recent predictions are given to 2020 from UKIAM for these indicators due to all sources both within and outside the UK. Table 1.1 provides comparison with the two other scenarios with impact indicator values for 2030, when there is the maximum divergence.

The other three impact indicators reflect contributions to exposure of the UK population, firstly with respect to NOx and urban air pollution, and the second and third to PM_{10} and $PM_{2.5}$ in relation to health impacts. Again section 1.2 gives indicative concentrations due to all sources to put these contributions in perspective. Note that the PM includes both secondary inorganic aerosol (SO_4, NO_3 and NH_4) and primary contributions, with the former larger than the primary part, especially for more remote sources like power stations with tall stacks. Figure 1.3b shows the trends in these three indicators for the CCC climate action scenario, and comparison with the other scenarios for the year 2030 is also given in table 1.1. These again show a consistent pattern of divergence with greater improvements in the CCC climate action case than in the dash for gas, and a deterioration in the no climate action case as expected in view of increased emissions of SO_2 and NOx.

Table 1.1: Comparison of environmental indicators in 2030 for 3 power scenarios

Scenario	CCC climate action	Dash for gas	No climate action
Acidification (Meq)	246	348	1549
Eutrophication (kt N dep)	3.14	4.15	7.94
NOx exposure (ng/m^3)	148	350	481
PM_{10} exposure “	68.0	116	335
$PM_{2.5}$ exposure “	59.2	95.2	305

The following sections cover the measures in other sectors coupled to the power sector for the CCC climate action and dash for gas scenarios. (The implications of these measures for electricity generation have already been allowed for by the CCC in the power sector).

Heat sector

Changes in generation of heat include deployment of heat pumps and solar energy plus use of biomass and biogas. These affect emissions of air quality pollutants in two ways. First there are additional emissions from combustion of the biomass and biogas: and secondly there are emissions savings due to reduced use of gas, coal and oil. These two aspects have been treated separately as they result in large opposing effects, where uncertainties critically affect the net balance.

Emission factors for NOx from biogas have been taken as equivalent to those for natural gas. The emissions from biomass combustion have been based on emission factors used for RHI

(Renewable Heat Incentive) assessments- that is 150 g/GJ of NOx and 30g/GJ of PM_{10}. It should be noted that these values only apply to very clean technologies when properly operated, and there are large variations in these emissions with the technology and control measures used. This is especially important for PM emissions which can be very much larger. For example for domestic combustion a recent study in Denmark (Press-Kristensen 2013) indicates that the RHI is met by the cleanest stoves burning wood pellets, but for other types of stove can be up to 30 times higher. By comparison with the RHI values, emissions of $PM_{2.5}$ given for Swan label stoves (an eco-label established by the Nordic Council of Ministers) are an order of magnitude higher at 250 g/GJ. This is a suggested Danish limit for new stoves by 2016, which is less than a suggested EU limit by 2019 of 310 g/GJ. An emission factor of 30g/GJ could be very optimistic, since wood stoves may be deployed outside the RHI scheme. The assumption of the Swan stove value provides a suitable sensitivity study, with emissions of PM ten times higher than the RHI values.

Figure 1.4a shows the heat energy generation from biomass and biogas and the corresponding emissions of NOx and PM_{10} (emissions of SO_2 are negligible). Emissions of primary $PM_{2.5}$ are a large proportion of primary PM_{10} rising to 6.75 kt in 2030 (as compared with 8.4 kt of PM10). Apart from health impacts this is a considerable amount with respect to attainment of the $PM_{2.5}$ emission ceiling (~57kt), especially in view of uncertainties if emissions are not strictly regulated and controlled. For example, assuming the Swan stove standard, the tenfold higher emission from residential biomass combustion than the LHI value would effectively double the total PM_{10} and $PM_{2.5}$ emissions in 2030 from biomass/biogas use in the heat sector shown in figure 1.4a , emphasizing the need for very careful regulation of biomass use. Note that this results from a relatively small amount of biomass combustion introduced towards the end of the scenario period. Similar considerations may apply to a proportion of the non-residential use of biomass in offices and commercial premises. The non-residential use of biomass is introduced earlier in the scenario, and cumulatively is considerably greater than the residential use. Hence uncertainties in emission factors are even more important for these non-residential sources and need further investigation. This is illustrated further in section 1.4 on environmental damage costs.

Counteracting these emissions are fuel savings of gas, oil and coal for heating, replaced not only by biogas and biomass use above, but also by heat pumps and solar energy. The CCC estimates indicate very large energy savings in this respect, equivalent to about 3 times the biomass plus biogas energy input considered above, and implying a very large energy saving from heat pumps and solar energy. For example in the residential sector, the saving in natural gas for heat generation of 147 TWh by 2030, combined with a subsequent saving of 58 TWh in 2030 for efficiency measures (see later), represents a large proportion of total gas use in the residential sector.

Figure 1.4b gives a break-down of the fuel savings assumed in the heat section in the CCC climate action scenario by fuel type and source sector. The emission reductions implied by these energy savings are correspondingly large. The reduction of SO_2 emissions by ~80 kt in 2030 results from reduced use of coal, especially in the industrial sector. An implied reduction in NOx of 72 kt in 2030 would more than compensate the additional emissions from biogas and biomass above by 23kt. Emission reductions of PM_{10} and $PM_{2.5}$ would approximately balance those from biogas and biomass, subject to these energy savings being achievable and the caveat about potentially higher emissions from biomass than implied by the emission factors defined for the RHI.

The impact indicators (see figure 1.5) show a net improvement in acid deposition (~1000 Meq in 2030) largely due to the reduced coal and SO_2; and a small improvement in nitrogen deposition and eutrophication of ecosystems (1.4 kt of N deposition). Despite the overall reduction in NOx there is a small increase in population weighted mean exposure to NOx of 400ng/m^3, affected by spatial distributions and dispersion relative to urban populations. Net effect on PM_{10} and $PM_{2.5}$ exposure is small with a net decrease of -97 and -66 ng/m3 respectively. However these net figures are subject to big uncertainties in the balance between biomass emissions and in the emission reductions due to energy savings.

Transport

The measures that have been assessed for this sector are :-

i) Electric cars with a percentage of cars switched from petrol/diesel to electric rising to 10% by 2030. The forecast petrol/diesel mix of the km driven was provided by the CCC in consultation with DfT (rising from 36% diesel in 2008 to 56% in 2020, and then falling off slightly to 53% by 2030) . Electricity use for this measure is included in the power sector so only the reduction in exhaust emissions is considered here.

ii) Electric vans with a percentage of vans, assumed to be all diesel, rising to 7% by 2030. Again exhaust emission reductions have been estimated.

iii) Hydrogen buses with the fraction of the fleet increasing to 23% between 2020 and 2030. Again it is assumed that the hydrogen generation is allowed for elsewhere and the reduction in exhaust emissions is estimated.

iv) Smart choices with a change of travel mode to public transport, cycling, car sharing or avoided journeys rising to 5% in 2030. This avoids the corresponding % of car emissions completely, including both non-exhaust and exhaust emissions[4] . Note that no allowance has been made for increased capacity of public transport to accommodate extra journeys. (In this context average bus emissions of NOx are roughly 10 times those of a car assuming a 50/50 split of diesel and petrol cars, and around 5 times those of a car for total $PM_{10}/PM_{2.5}$ emissions. Bus occupancy is thus a factor in providing improvements in public transport to encourage a switch from car journeys.)

v) Improved HGV logistics giving up to a 7% reduction in HGV km by 2030. Again total exhaust plus non-exhaust emission savings have been estimated.

[4] As exhaust emissions become increasingly strictly controlled the non-exhaust emissions become relatively more important. Note that emission factors for 2020 are used in this study reflecting expected improvements from air quality legislation.

Other measures which have not been assessed include CO2 and fuel efficiency savings, plug-in hybrids, eco-driving, biofuels, and enforced speed limits of 70 mph for cars and vans, as none of these can be associated with a definite reduction of air quality pollutants. For example setting lower CO_2 emissions does not necessarily lead to lower NOx emissions. NOx is independently regulated through the setting of Euro standards, and there is no correlation between NOx and CO_2. There is no conclusive evidence for changes in emissions resulting from biofuels, with different results for different fuel mixes. Speed dependent emission factors for modern vehicles exhibit very modest sensitivity to speed limits, and although the mode of driving can be important it is difficult to quantify in relation to eco-driving .

Emissions for the measures considered have been based on projected emissions to 2020 provided by Ricardo-AEA (Tim Murrells –private communication), reflecting recent revision of emission factors for road transport for the NAEI. Usually in modelling the road transport sector we differentiate between urban roads, rural roads and motorways allowing for the speed dependence of emissions, and also because measures to reduce emissions in populated areas have a greater effect on population exposure. In the CCC scenarios there is no specific differentiation between urban and rural areas, although some of the measures are likely to have more influence in urban areas: hence country average emissions per km for each vehicle class have been used in assessing the effects of measures, and similarly for impact factors in estimating mean concentrations for population exposure.

The resulting emission savings of NOx, PM_{10} and $PM_{2.5}$ are shown in figure 1.6. The "electric cars" measure shows the biggest reduction in NOx, although this will be partially offset by emissions included in power production. The second most effective measure is the "smart choices", which is also by far the most effective measure in the reduction of PM_{10} and $PM_{2.5}$. This is influenced by the non-exhaust contribution to PM emissions, which is reduced as well as the exhaust emissions for the "smart choices" and "HGV logistics" measures, but not for the other measures.

Figure 1.7 shows the resulting impact indicators, implying relatively modest improvements; and with "smart choices" and electric cars contributing most, in keeping with the emission reductions.

Residential, industry and non-residential fuel use

For the residential, industry and non-residential sectors, efficiency measures result in reduced use of coal, oil, and gas. These are treated collectively here. Figure 1.8 shows the energy savings by sector and fuel (there is a very small saving from use of coal in the non-residential sector so this has been ignored as negligible). This again shows considerable energy reduction of gas use in the residential sector of up to nearly 60 TWh in 2030. Also shown alongside the fuel savings are the corresponding reductions in SO_2, NOx and PM_{10} emissions.

It is clear that different sectors and fuels are important for the three pollutants; with reduction in residential gas use as the largest energy reduction just playing a modest role in NOx emissions. Overall reductions of SO_2 of up to 30kt in 2030 are dominated by reduced coal use in industry: and coal use by both industry and the residential sector feature in PM_{10}

emission reductions. The reduction in NOx of up to 22.5 kt in 2030 is more evenly distributed across different fuels and sectors.

The impact indicators for the energy savings in these three sectors are shown in figure 1.9, but are more modest than for the very large energy savings indicated by the CCC for the heat sector. The reduction in SO_2 from less industrial coal use shows up clearly in the benefits with respect to acidification.

1.4 Environmental damage costs and economic assessment

Corresponding environmental damage costs have been estimated as specified by Roald Dickens of Defra. As the full air quality modelling process is relatively resource and time intensive, damage costs were developed as a simpler methodology to estimate average values for the impacts of changes in emissions. The marginal values approximate the social costs of the emission of one tonne of particulate matter (PM), oxides of nitrogen (NOx), sulphur dioxide (SO2) and ammonia (NH3). The impacts included vary between the different pollutants with all including chronic mortality and hospital admissions, PM including building soiling and SO2 reflecting impact on materials. More information on the estimation of damage costs is available from https://www.gov.uk/air-quality-economic-analysis

and the original research report is available from:

http://archive.defra.gov.uk/environment/quality/air/airquality/panels/igcb/documents/dcs-report2006.pdf.

Table 1.2 summarises the damage costs estimated on this basis broken down by measures in the individual sectors, and discussed in more detail below. The three columns give the costs for emissions in the final year, 2030, and the accumulated costs over the 20 year period 2010 to 2030, with the final column including discounting to give the overall net present values.

Damage costs are not, however, considered a replacement for detailed modelling and where policies have an air quality impact of over £50 million consideration must be given to undertaking more detailed bespoke analysis. In this study the effects are significantly above this threshold and so a more tailored approach has also been applied using the estimated exposure of the UK population to estimate and value the impact on chronic mortality (the most significant monetised impact). This approach is based on IOMLIFET modelling produced by the Institute of Occupational Medicine to estimate life years lost. More information on these tables are available from http://www.iom-world.org/research/research-expertise/statistical-services/iomlifet/.

This approach is still in development and so the results of this analysis have been presented in this paper as a sensitivity on the central damage cost analysis. Hence a comparison test with the simpler methodology has been undertaken for the power sector, using the modelled population exposure from RAPID (which gives much more detailed differentiation between population exposure to PM_{10} from different sources) and the more complex approach based on life tables. The closeness of these results to the damage cost results and the time required for a further analysis mean that it has been decided that a more in depth analysis is not required at this stage. The scale of the impacts on specific areas does however suggest that a more detailed consideration will be necessary when different options are considered to realise a number of the major changes.

Table 1.2 Summary of environmental damage costs: (£ millions) Negative numbers indicate benefits.

	2030	2010-2030	
	No discounting	No discount	NPV
Power sector:			
CCC.CA	90	3145	2439
Dash for gas	154	3377	2532
NO.CA	556	6913	4714
Heat sector:			
Residential biomass	42 (364)	170 (1458)	95 (814)
Non-residential biomass	37 (313)	450 (3795)	282 (2384)
Industrial	227	1886	1140
Biogas	7	50	29
District heating biomass	83	775	474
TOTAL	396	3331	2020
Heat sector: fuel savings			
Residential sector	-264	-2283	-1416
Non-residential	- 52	- 512	- 321
Industry	-377	-2392	-1397
TOTAL	-693	-5187	-3134
Transport sector			
Electric cars	- 26	- 152	- 88
Electric vans	- 6	- 44	- 26
Hydrogen buses	- 6	- 23	- 12
Smarter choices	- 52	- 663	- 427
HGV logistics	- 16	- 84	- 47
TOTAL	-106	- 965	- 600
Efficiency measures			
Residential	- 78	- 986	- 642
Non-residential	- 14	- 208	- 138
Industry	-134	-1348	- 869
TOTAL	-226	-2542	-1649

Values in brackets refer to sensitivity studies assuming alternative emission factors equivalent to eco-label Swan stoves for residential heating using biomass

Power sector

Figure 1.10 gives a comparison of estimated damage costs to show time trends without discounting for the three power scenarios. As expected there are much higher damage costs (total £6.9 billion, NPV £4.7 billion) for the no climate action scenario emitting more SO_2 and NOx. The dash for gas and the CCC climate action power sector scenario give rise to similar costs, showing clearly the air quality benefit of reduced coal use (see figure 1.10b). However the costs drop off more by 2030 in the CCC climate action scenario with a smaller contribution from natural gas, and dependence on CCS and biomass sources. Note that NH_3 contributes a third of the costs for the coal+ CCS post combustion. This is an uncertain source but could be important if there was more reliance on an amine post combustion CCS process.

Figure 1.10b shows the overall net saving (as a negative cost) of the CCC climate action scenario compared with the dash for gas. This shows the reversal over time, with the CCC climate action scenario giving very slightly higher costs until 2020 when new sources of energy take over and the costs become lower. The total net difference is £232 million with an equivalent NPV of £93 million.

Comparison of different methods for environmental costs

A comparison of the approach used by Defra based on emissions, and the alternative approach based on PM_{10} exposure and life tables expressing risk, has been undertaken for net savings in the power sector shown in figure 1.10b. The alternative approach produces discounted costs routinely, and hence comparison is made with costs in figure 1.10 discounted correspondingly to net present values for 2010. The comparison of damage costs is shown in table 1.3. In this case the life-tables approach generally gives higher costs even though it considers human health effects only, and illustrates how such estimates based on different methods can quite easily differ by a factor two.

Table 1.3: Comparison of discounted costs using emissions and damage costs, and usingPM_{10} and lifetables approach

	Damage cost	**Life tables**
Coal	£158m	£146m
CCGT	-£362m	-£542m
Coal CCS post combustion	£54m	£124m
CCGT CCS	£21m	£30m
Biomass	£23m	£27m
Total	**-£106m***	**-£198m**

* Note that this table omits IGCC+CCS for coal and hence the total differs from the NPV of -£93 million in the section above.

Heat sector

The heat sector has the greatest influence on damage costs and is also the most uncertain. Here the estimated damage costs (£3.3 billion or £2billion discounted to give NPV) from use of biomass and biogas, are comparable with the net savings from the power sector for the CCC.CA and D.GAS scenarios relative to the NO.CA scenarios, even with the optimistic assumptions about emission factors for biomass combustion conforming to the RHI limits. These emissions could well be much higher. If, for example, the emission factors for Swan stoves were assumed for the residential biomass emissions (as proposed in Denmark and still tighter than suggested limits by the European Commission) then this would add another £320 million to the undiscounted damage costs for the year 2030, although as biomass is only introduced into the residential sector towards the final years the overall effect on the total NPV is limited to an additional £720 million. Similar concerns about achieving the RHI emission factors apply in other uses of biomass. (If the same sensitivity test for emission factors was undertaken for the whole of the non-residential sector, this would have a similar effect on damage costs in 2030-an extra £280 million, but the earlier introduction of biomass would lead to a much greater effect on the overall NPV adding an extra £2.1 billion). This illustrates the importance of both the biomass usage scenarios and uncertainties in emission factors, which can have very large effects on the environmental damage costs and the overall benefit of the CCC climate action and dash for gas scenarios. Further work is recommended on these aspects.

Against this the CCC climate action scenario indicates very high reductions in use of gas, oil and coal for heating, with corresponding very large benefits implied with an NPV of £3.1 billion. This energy saving is about 3 times the energy input to biomass/biogas heating, implying huge savings from the heat pumps and solar measures in the CCC scenario. If these energy savings were not achieved then the £3.1 billion would be correspondingly reduced.

Hence the net effect of the heat sector is the difference between two large and uncertain quantities resulting from biomass/biogas use and fuel savings, and needs very careful consideration.

Transport sector; and energy efficiency measures

The effects of measures in the transport sector are smaller, with an NPV for environmental benefits of £0.6 billion, with the smarter choices option accounting for two thirds of this benefit. Finally the estimated NPV for the benefits from energy savings from efficiency measures is £1.6 billion, about half those from the fuel savings postulated for the heat sector.

Overall it is the combined energy savings from the heat sector and energy efficiency measures that dominate the estimated economic benefits from air quality improvements; and biomass/biogas use in the heat sector that lead to costs of environmental deterioration in air quality. Although overall the assumptions made imply a large net benefit this could be greatly reduced if, for example, the RHI limits on biomass emissions are not met, or the energy savings specified in the CCC climate action scenario are not achieved.

Summary and conclusions

The preceding sections have described the approach taken in analysing the potential effects on air quality of scenarios specified by the CCC. These comprise three different scenarios for the power sector, plus measures in the heat, transport, residential, non-residential and industry sectors. Considering different technologies, fuels, and measures in each sector, corresponding emissions of SO_2, NOx, PM_{10} and $PM_{2.5}$ have been assessed. These have been related to different environmental impacts through indicator values for acidification and eutrophication of ecosystems, and human exposure to NOx, PM_{10} and $PM_{2.5}$ in relation to urban air pollution and human health effects. Increases in emissions of some pollutants, e.g. $PM_{2.5}$, are also relevant to UK obligations to meet national emission ceilings.

Damage costs, which tend to be dominated by health impacts of fine PM, have been estimated using the Defra methodology based on pollutant emissions, with comparison with a new approach based on life-tables and population exposure to PM_{10} to illustrate the influence of different approaches to environmental costs and benefits.

Tables 1.3a, 1.3b and 1.3c summarise the overall results by sector for emissions, environmental impacts and damage costs respectively. To give an overall picture for each sector, emissions, impacts and costs have been summarised over the years 2010 to 2030 as well as in the final year. As in figures 1.10 and 1.11 the total undiscounted costs are provided in table 1.3c, in which costs for the later years are not reduced relative to the early years of the period. Alongside these are the "net present values", NPVs, with discounting included in the usual manner to values in 2010.

The values reported reflect the scenarios defined by the CCC and underlying assumptions. Independently of this there are uncertainties in the emission factors used, and in the estimation of environmental costs and benefits. It has not been within the scope of this study to look at uncertainties in any detail. Instead we have tried to illustrate how important such uncertainties can be, for example by the comparison of different approaches to damage costs, and by the example of residential heating by biomass with respect to emissions of PM. This is a source with particular concerns, and supplementary values are indicated in the tables, representing the effect of using a different emission standard based on Swan eco-labelling of stoves instead of RHI values for this source. Also comments in the table indicate where particular assumptions or data are significant, and also some additional points to be considered for specific sectors.

For the power sector the tables give values for the difference between the" CCC climate action" scenario and the "no climate action" scenario; and similarly for the difference between the "dash for gas" and "no climate action" scenario. A negative number indicates a lower value for the former than for the latter, and implies improvements both in emissions and environmental indicators, and costs savings with respect to environmental damage costs.

The heat sector is particularly important, with separation retained between the use of biomass and biogas for heating, and fuel savings for this sector. The latter as specified by the CCC scenario are very large (equivalent to about 3 times the energy of the biomass and biogas fuels) and include heat pumps and solar energy as completely independent measures. The air quality benefits are correspondingly large. However the effects of biomass combustion and PM emissions are also potentially large and adverse, and dependent on very variable emission factors depending on technology and how it is operated. The overall effect of the two aspects of the heat sector then depends on the difference between two large opposing and uncertain components of the benefit analysis.

Overall the estimated damage costs imply similar possible benefits for the “CCC climate action” and “dash for gas” scenarios relative to the “no climate action” scenario with an estimated NPV of £5.6 and £5.5 billion respectively. Of this just over £2 billion comes from the power sector, and the remaining larger part from the additional measures. Reduced fossil fuel use plays a large part, but there are also potentially large adverse effects from biomass use. It is clear that there could be substantial air quality benefits from both the CCC climate action and the dash for gas scenarios, but the magnitude of this is very dependent on the mix of sectors and measures introduced, and the attainability of the reductions in fossil fuel use defined. More work is recommended to look into uncertainties, especially relating to biomass use and emissions; and also on different approaches for estimating environmental damage costs.

Table 1.3a: Summary of emissions (kt) summed over 2010 to 2030, with emissions in 2030 in Italics below. Negative numbers indicate a reduction in emissions.

Sector	SO_2	NOx	PM_{10}	$PM_{2.5}$	Comments
Power sector: CCC.CA-NO.CA	-1144 *-116*	-978 *-127*	-24.3 *-3.35*	-7.76 *-0.94*	High emissions from coal and gas in "no climate action". PM_{10} based on NAEI emission factor for gas; PM2.5 assumes negligible emission from gas.
Power sector: D.GAS-NO.CA	-1210 *-116*	-709 *-82.6*	-17.2 *-2.05*	-9.5 *-1.03*	Depends on efficiencies specified by CCC for CCS plants. NB Can be NH3 emissions from amine post-capture process
Heat: use of biomass/biogas	18.7 *1.97*	449 *48.3*	79.5 *8.45*	64(90) *6.8 (12.9)*	Figure in brackets for PM2.5 is for emissions from eco-label Swan stoves for residential biomass instead of RHI assumptions. Biomass also a source of VOCs. **NB importance for UK emission ceiling for PM2.5**
Heat: energy saved in CCC scenario	-613 *-83.6*	-612 *-72*	-83.6 *-9.73*	-44.5 *-5.5*	Corresponds to very large energy savings defined in CCC" with measures" scenario for heat sector
Transport	- -	-197 *-23.7*	-11.2 *-1.0*	-7.02 *-.65*	Depends on diesel/petrol car split defined by CCC. Split between measures for urban and rural areas also needs to be defined, and affects exposure and health impacts.
Efficiency measures	-353 *-30.2*	-321 *-22.5*	-40.6 *-3.1*	-22.2 *-1.75*	Superimposed on fuel energy savings for heat sector, and treated independently as specified by CCC scenario
Overall CCC.CA-NO.CA	**-2091** ***-228***	**-1659** ***-197***	**-80** ***-8.7***	**-17.5** ***-2.0***	Main difference between CCC.CA and D.GAS scenarios is in lower NOx emissions for the former.
Overall D.GAS-NO.CA	**-2157** ***-228***	**-1390** ***-152***	**-78** ***-7.4***	**-19.2** ***-2.1***	

Table 1.3b: Summary of environmental indicators summed over 2010 to 2030, with values for 2030 in italics. A negative value indicates an improvement. Figures in brackets are for sensitivity study assuming eco-label Swan Stoves for domestic biomass.

Sector	Acid dep (Meq)	N dep (kt)	NOx (ng/m3)	PM_{10} (ng/m3)	Comments
Power sector: CCC.CA-NO.CA	-12000 *-1300*	-35 *-4.8*	-2450 *-333*	-2321 *-268*	The indicator values are explained in section 1.2 and give a broader overview of environmental impacts than the economic estimates of damage costs. The acid deposition in Meq can be compared with projected annual deposition across the UK in 2020 of ~23000 Meq The N deposition can be compared with projected annual deposition in 2020 of around 260kt of which ~40kt is due to UK NOx The population weighted NOx concentrations can be compared with background NOx in London of ~70,000 ng/m3 The population weighted PM concentrations can be compared with annual average projected values across the UK due to secondary SO4, NO4 and NH4 aerosol plus primary PM_{10} of around 5000 to 6000 ng/m3 in 2020 as modelled in UKIAM.
Power sector: D.GAS-NO.CA	-12000 *-1200*	-33 *-3.8*	-1020 *-131*	-2124 *-219*	
Heat: use of biomass/biogas	4013 *434*	53.5 *5.8*	24090 *2593*	2420 (2873) *257(363*)	
Heat: energy saved in CCC scenario	-11000 *-1382*	-63.1 *-7.2*	-21440 *-2193*	-3055 *-355*	
Transport	-1142 *-138*	-16.1 *-1.94*	-5353 *-494*	-620 *-64.2*	
Efficiency measures	-5912 *-473*	-24.5 *-1.67*	-9968 *-656*	-1189 *-79.7*	
Overall CCC.CA-NO.CA	**-26040** ***- 2859***	**-85.2** ***-9.8***	**-15120** ***-1082***	**-4765** ***-510***	
Overall D.GAS-NO.CA	**-26040** ***-2759***	**-83.2** ***-8.8***	**-13690** ***881***	**-4568** ***-461***	

Table 1.3c. Summary of environmental damage costs. Negative values indicate a benefit. Values in brackets are for sensitivity study based on eco-label Swan stoves for residential biomass

Sector	Damage costs £ billion			Comments
	Annual in 2030 undiscounted	Total 2010-2030 undiscounted	NPV	
Power sector: CCC.CA-NO.CA	-.467	-3.8	-2.3	Reflects high fossil fuel use in "no climate action"
Power sector: D.GAS-NO.CA	-.403	- 3.6	-2.2	Similarity reflects modest differences in emissions between "CCC climate action" and "dash for gas".
Heat: use of biomass/biogas	.396 (.718)	3.3 (4.6)	2.0 (2.7)	Critically dependent on primary PM emissions from biomass use, illustrated by case study comparing RHI emission factors with alternative standard of eco-label Swan stoves in residential sector. Important for health impacts.
Heat: fossil fuel saved in CCC scenario	-.693	-5.2	-3.13	Energy savings specified by the CCC for heat sector are very large, depending on heat pumps etc. If not achieved this benefit would be correspondingly less.
Transport	-.106	-1.0	-0.60	Depends on take up of measures, especially "Smarter choices" which accounts for a large proportion of this
Efficiency measures	-.226	-2.5	-1.65	This is in addition to large fossil fuel savings defined by CCC for the heat sector
Overall CCC.CA-NO.CA	**-1.10**	**-9.2**	**-5.6**	
Overall D.GAS-NO.CA	**-1.03**	**-9.0**	**-5.5**	

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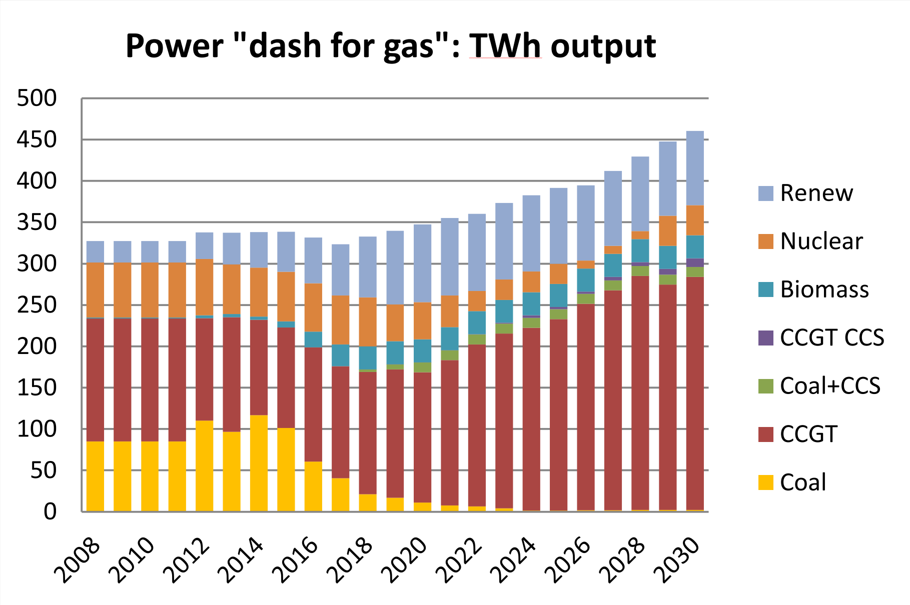
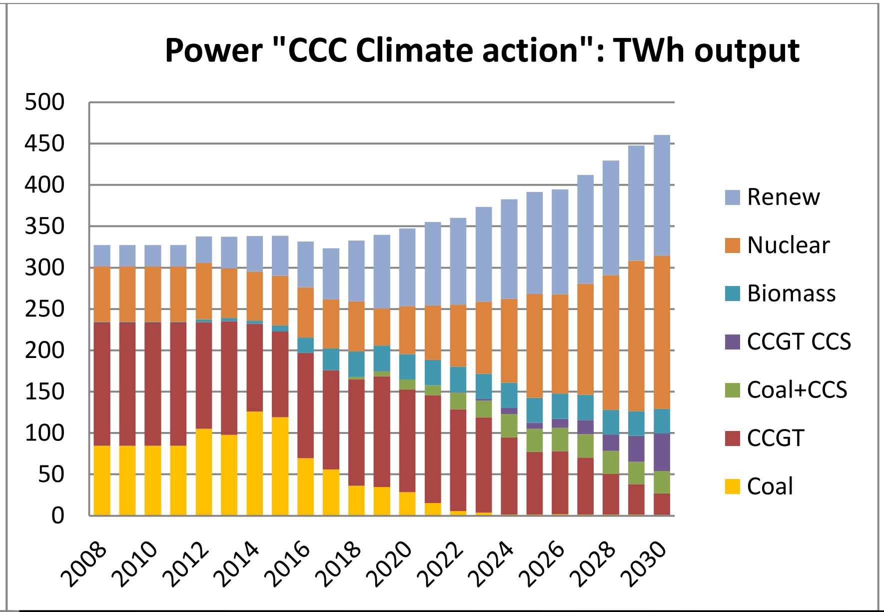




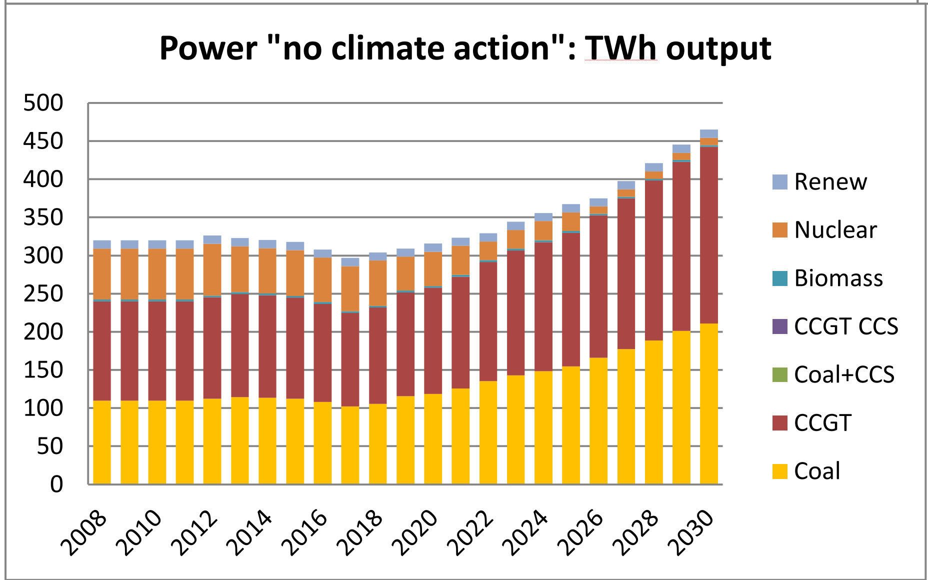
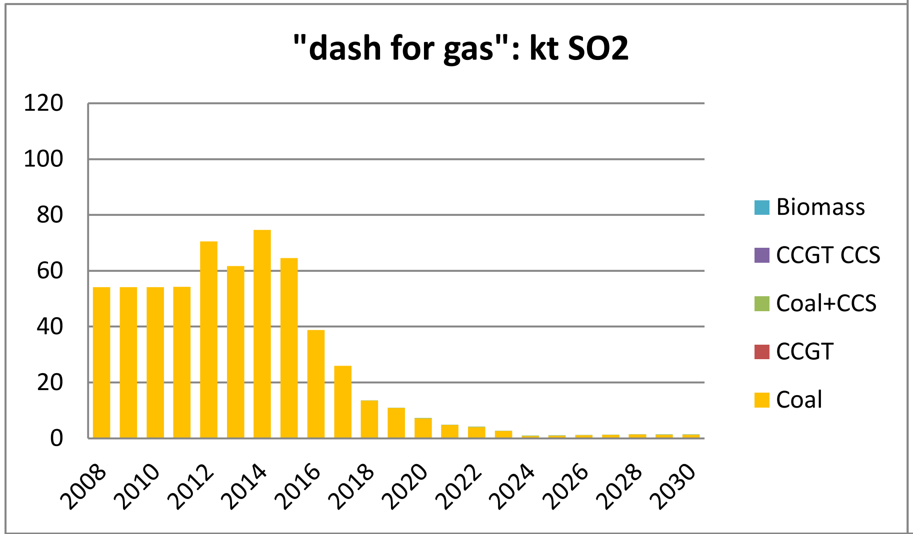
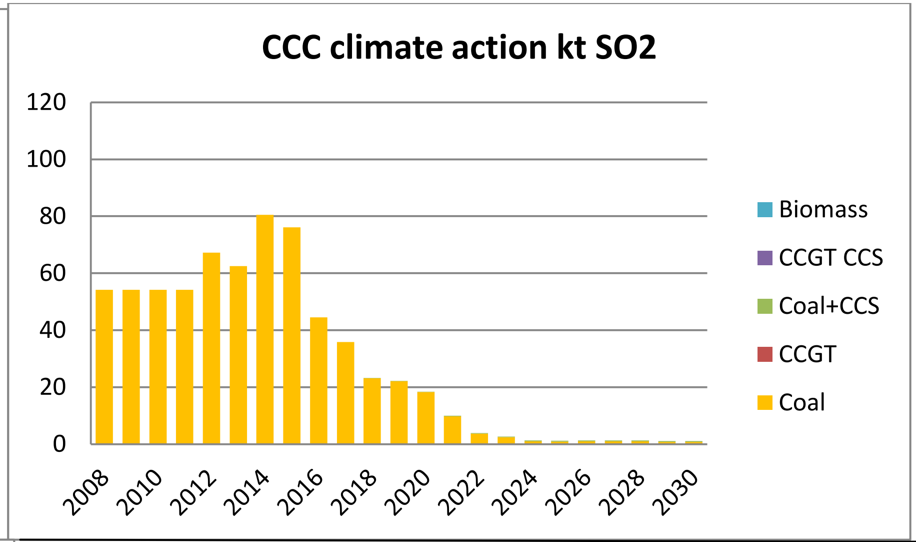


Figure 1.1. Comparison of power sector energy mix for "CCC climate action" scenario with scenarios "dash for gas" and "no climate action"





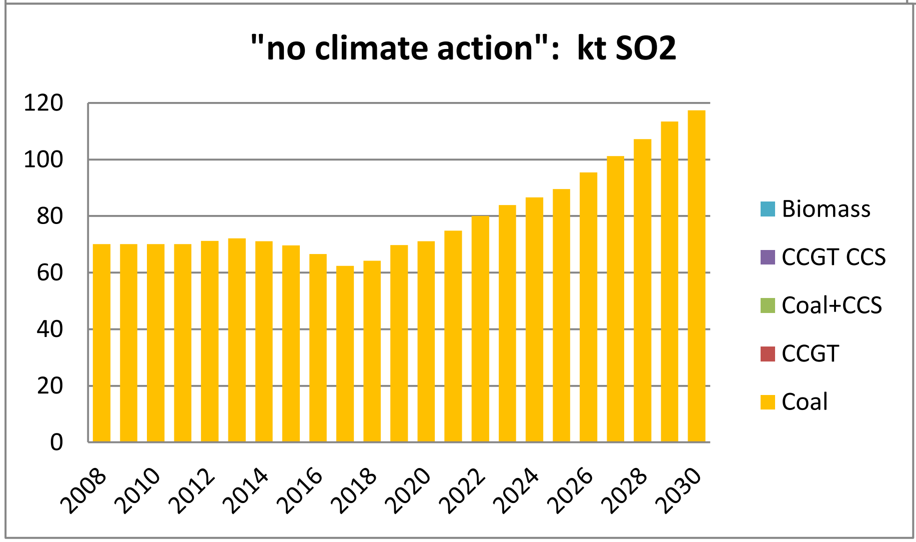
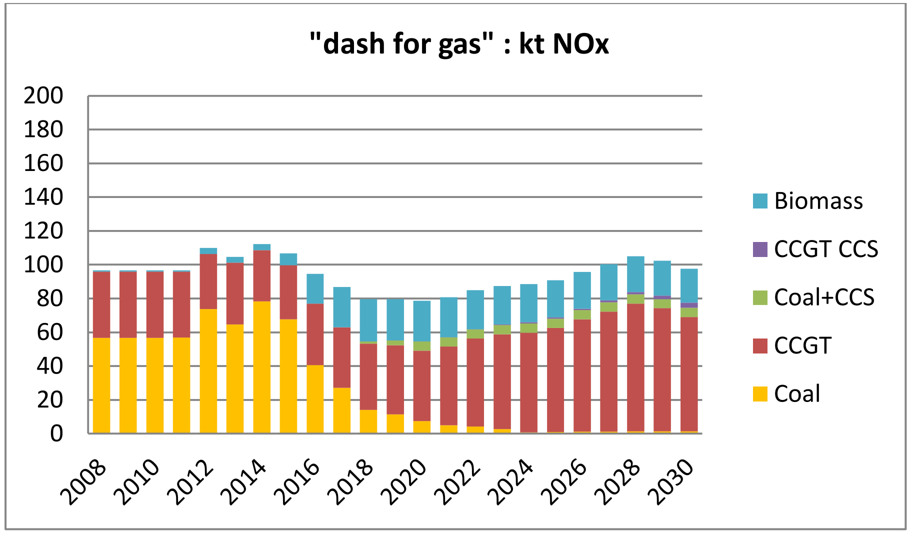
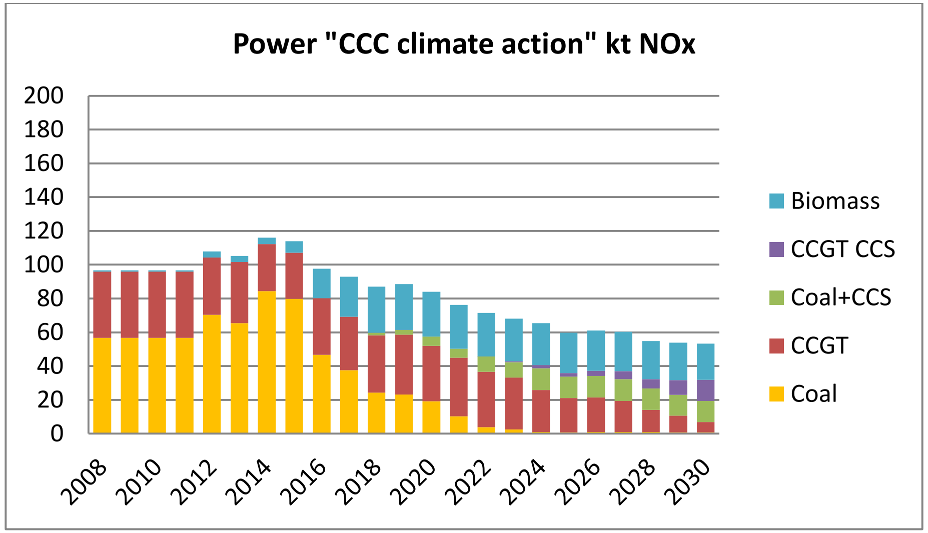


Figure 1.2a: Emissions of SO_2 for the three power sector scenarios





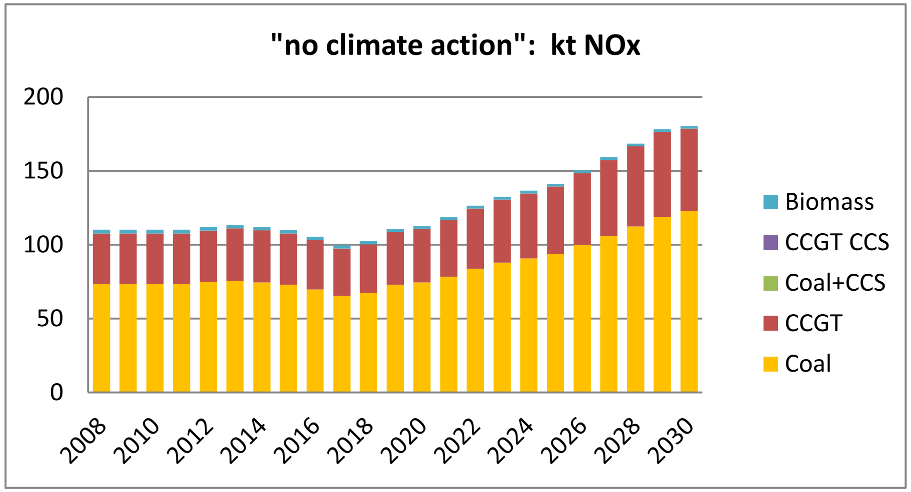


Figure 1.2b: Emissions of NOx for the three power sector scenarios

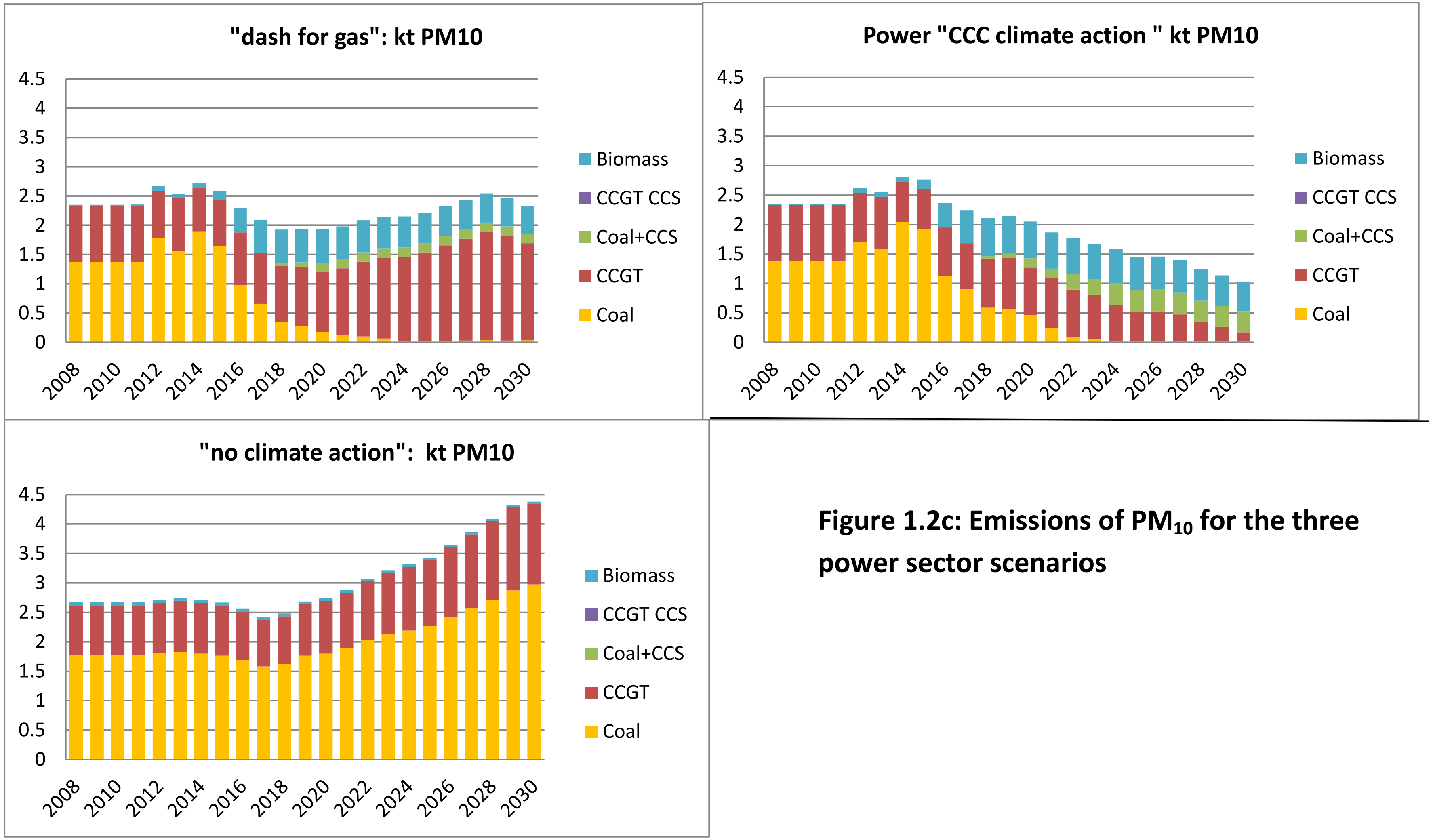
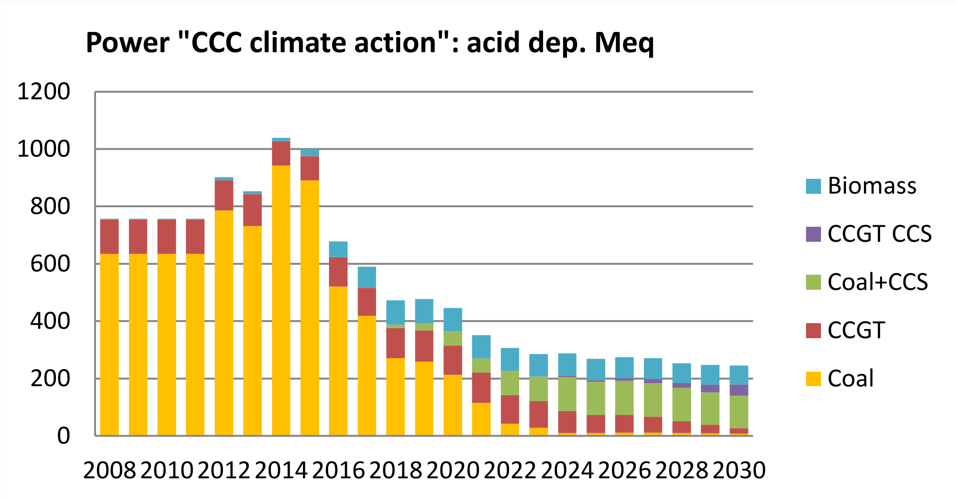


Figure 1.2c: Emissions of PM_{10} for the three power sector scenarios



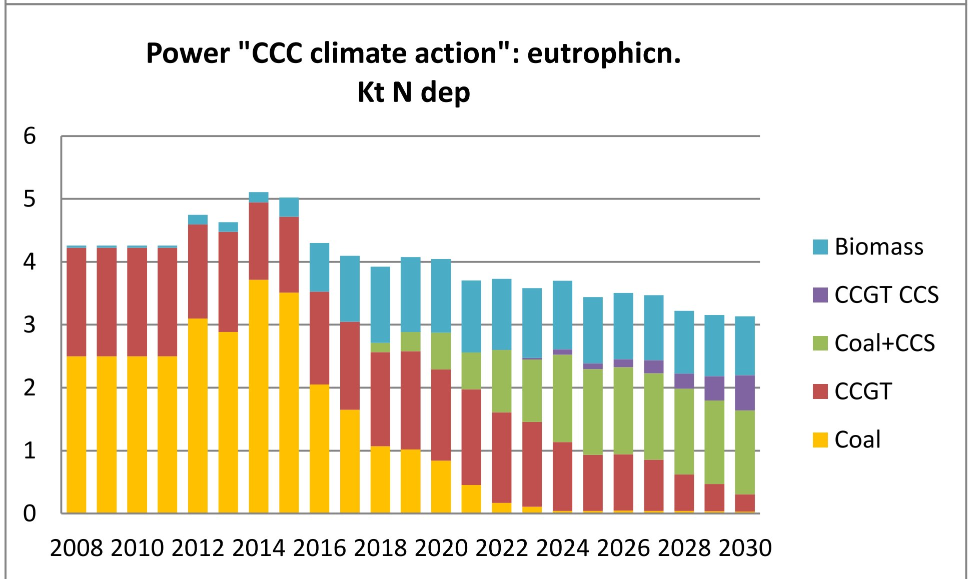
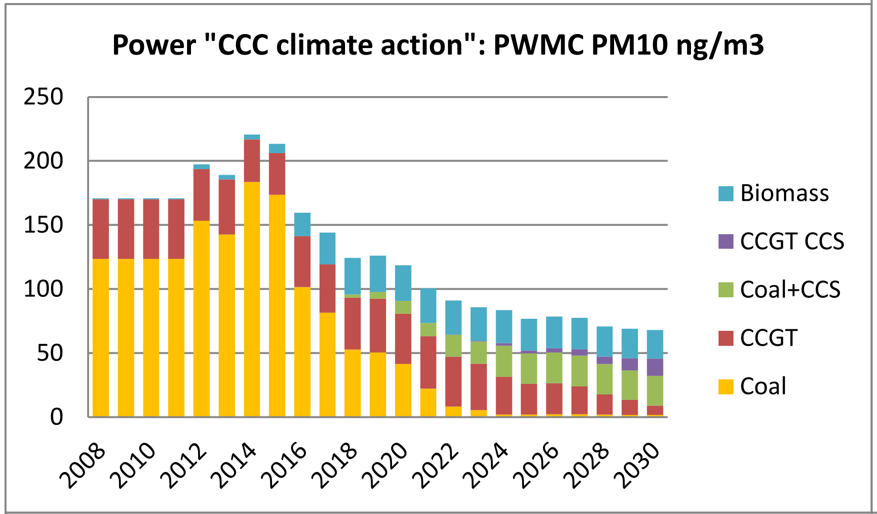


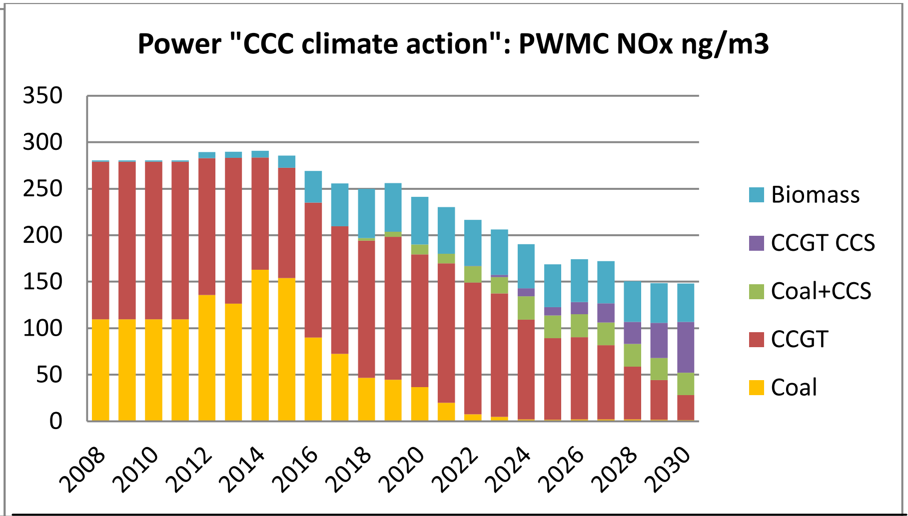
Figure 1.3a: Impact indicators for ecosystems

See section 1.2 to put these values in perspective

i)acid deposition

ii) nitrogen deposition and eutrophication





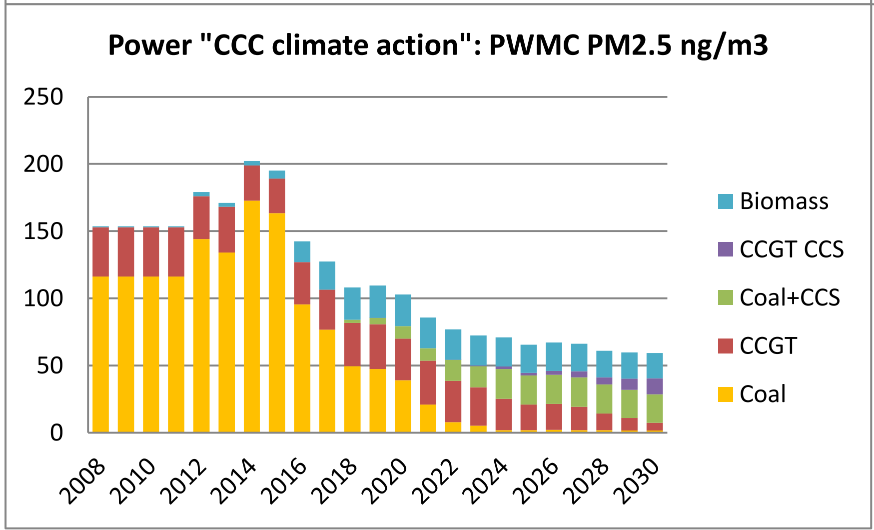
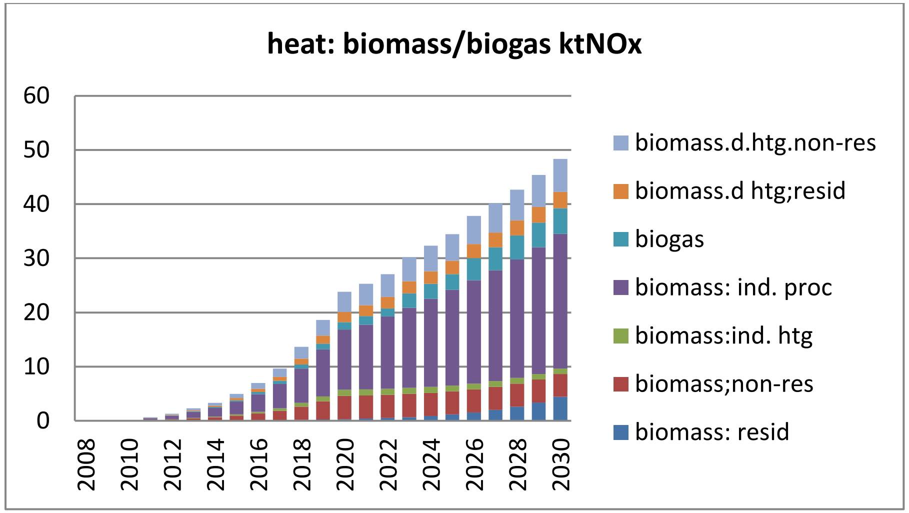
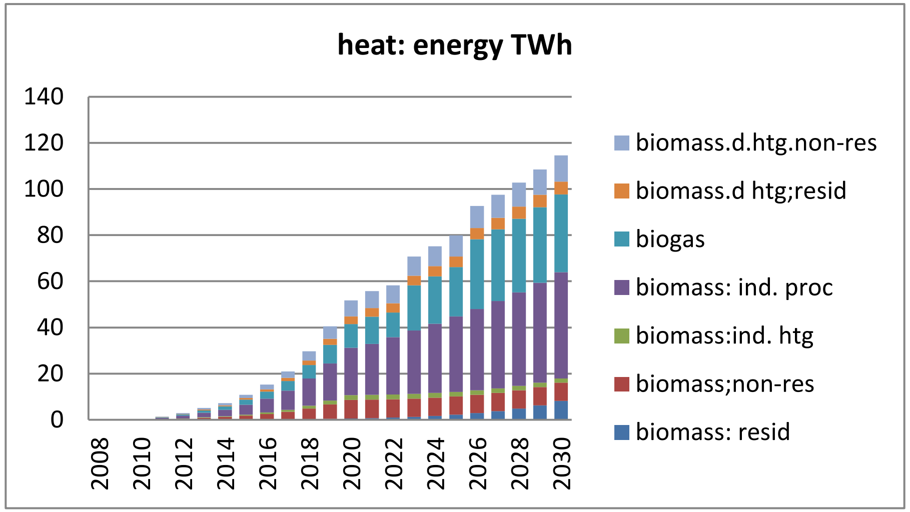


Figure 1.3b: Exposure of UK population

See section 1.2 to put these values in perspective





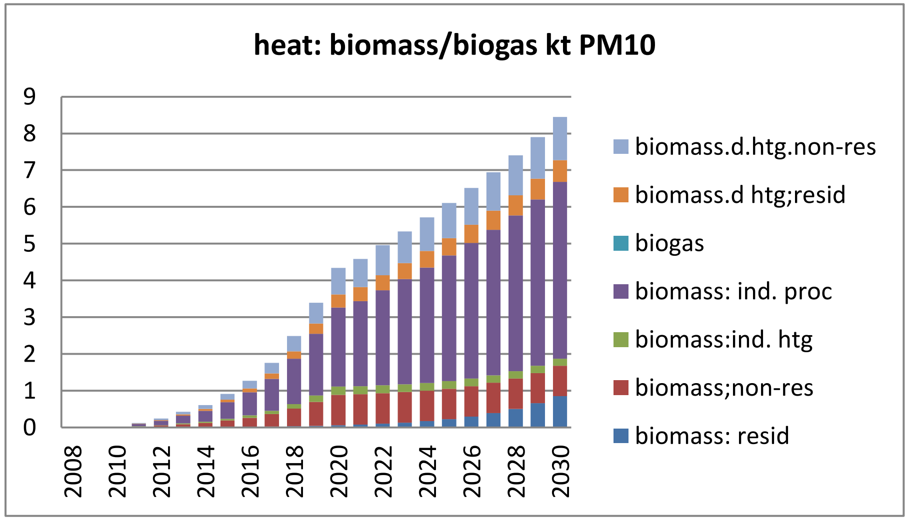


Figure 1.4a: heat energy from biogas and biomass and emissions of NOx and PM_{10}

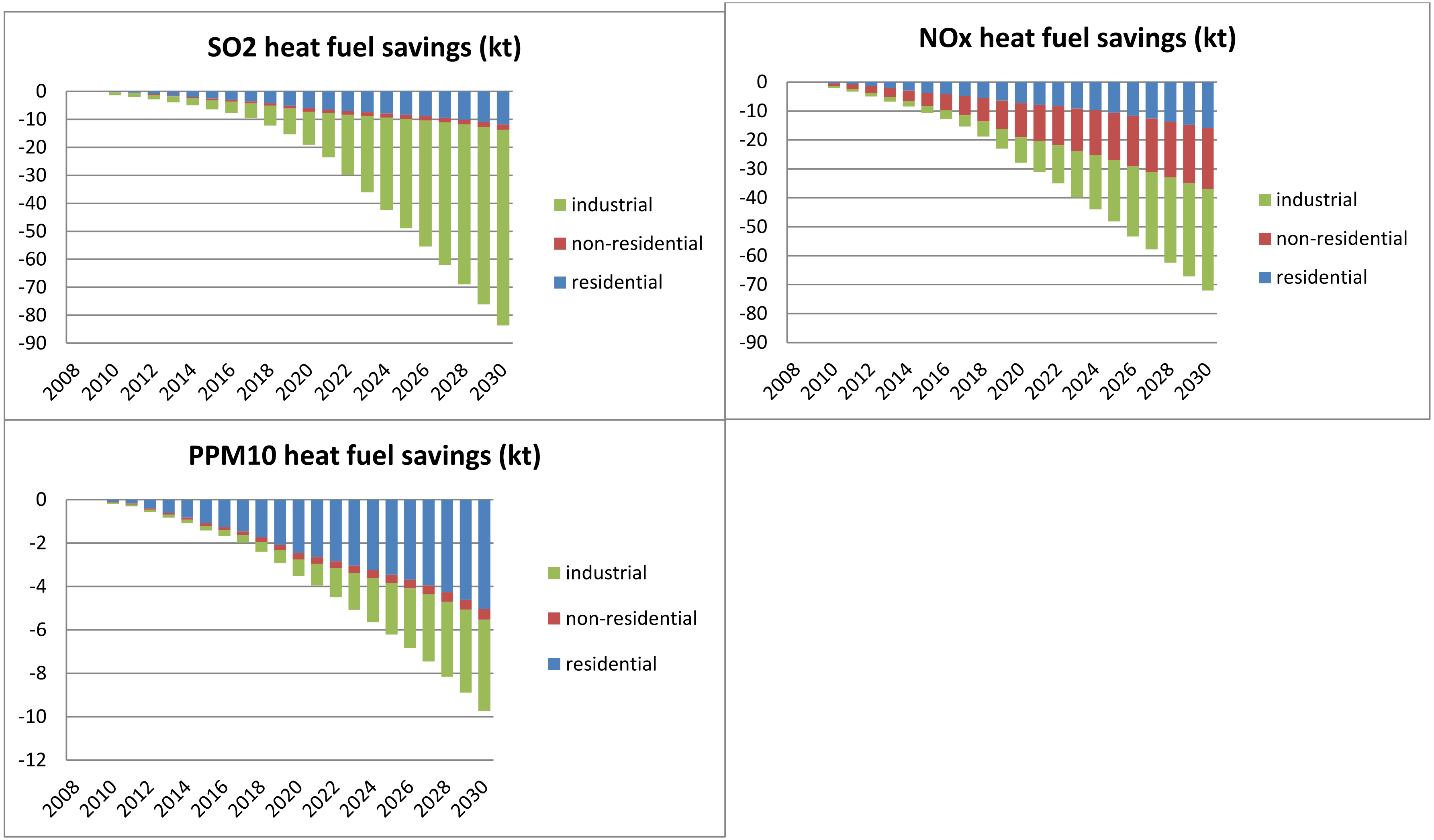


Figure 1.4b. Energy savings in the heat sector and corresponding emission reductions

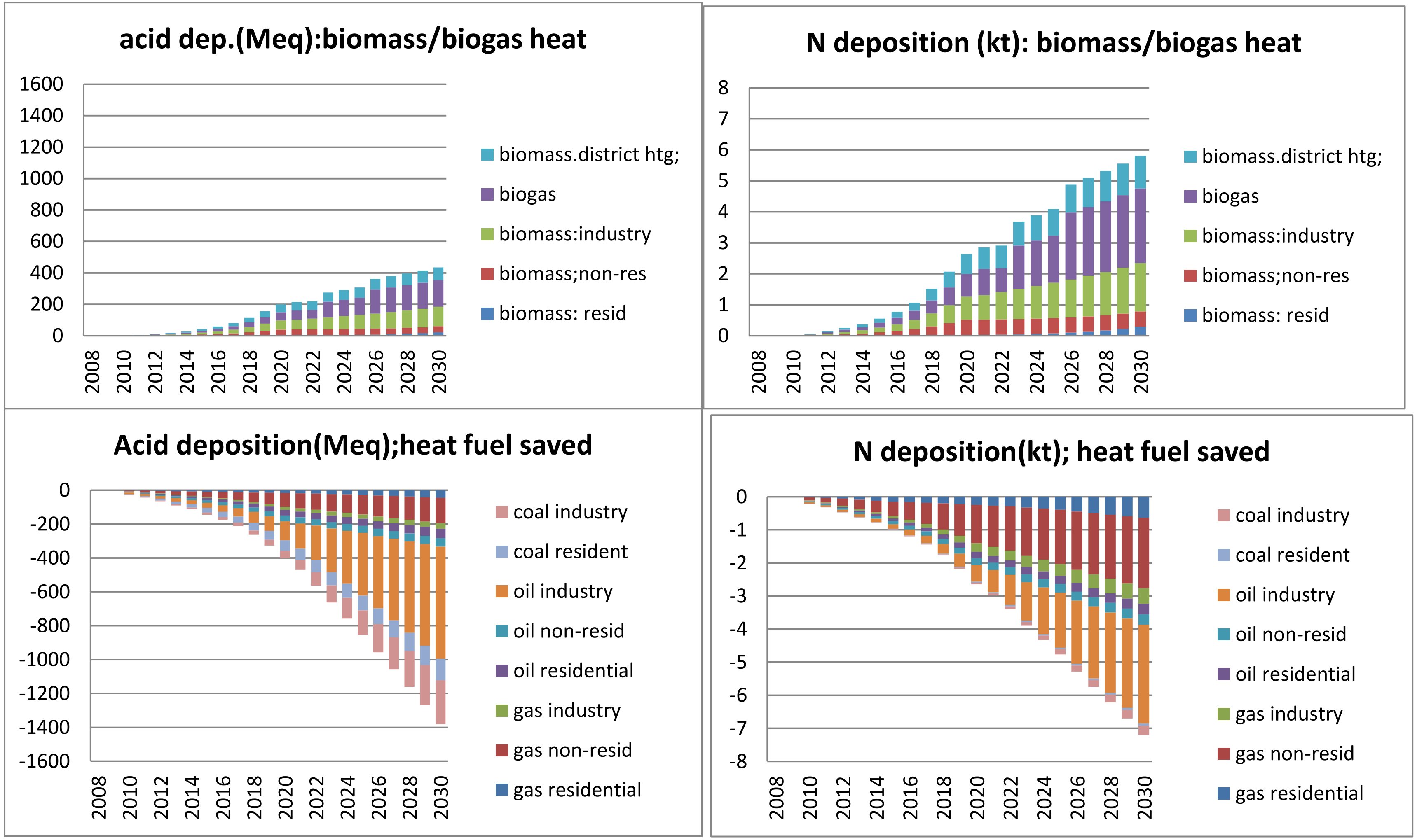


Figure 1.5a Indicator values for ecosystem protection from biomass/biogas and energy savings: heat sector

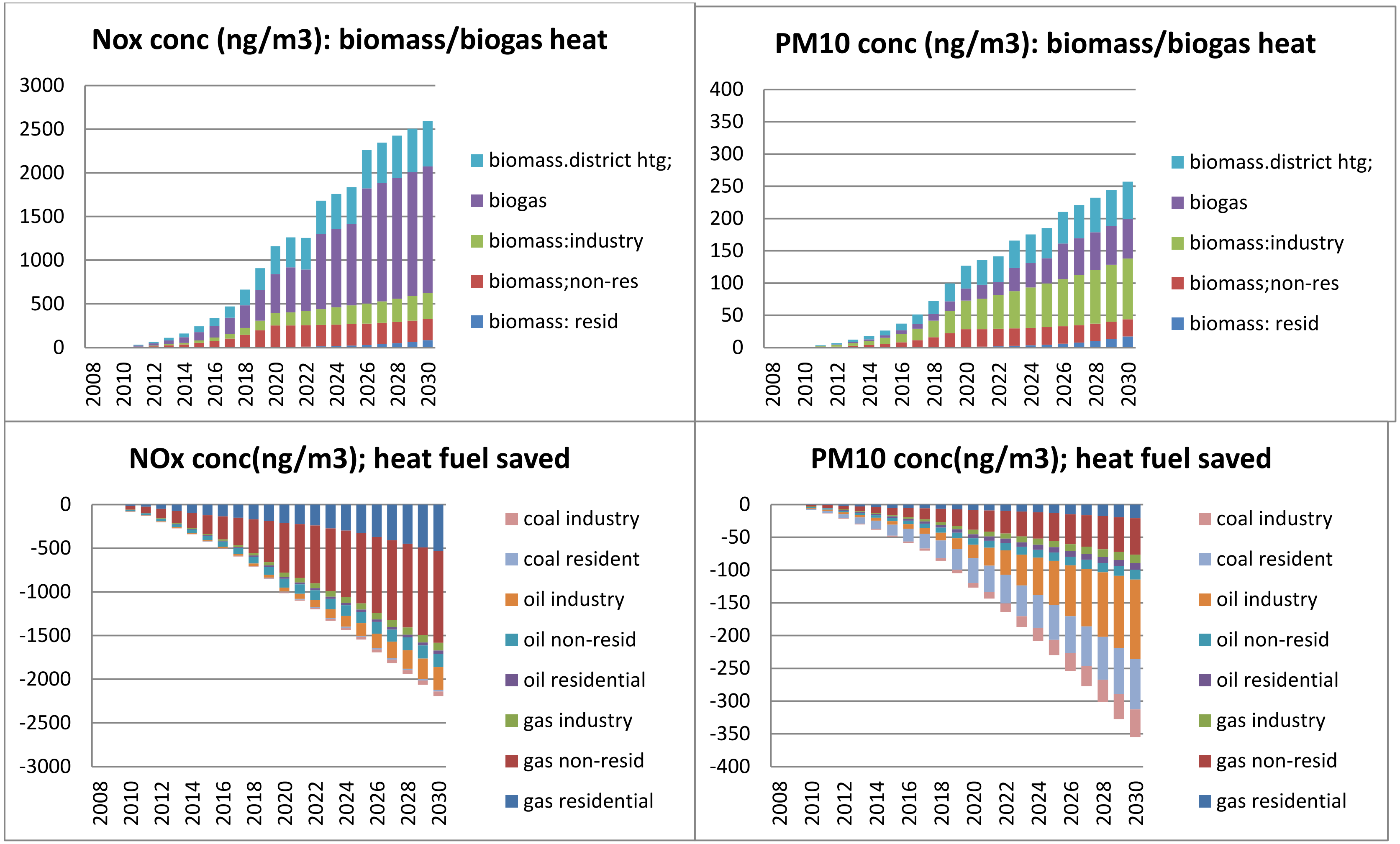
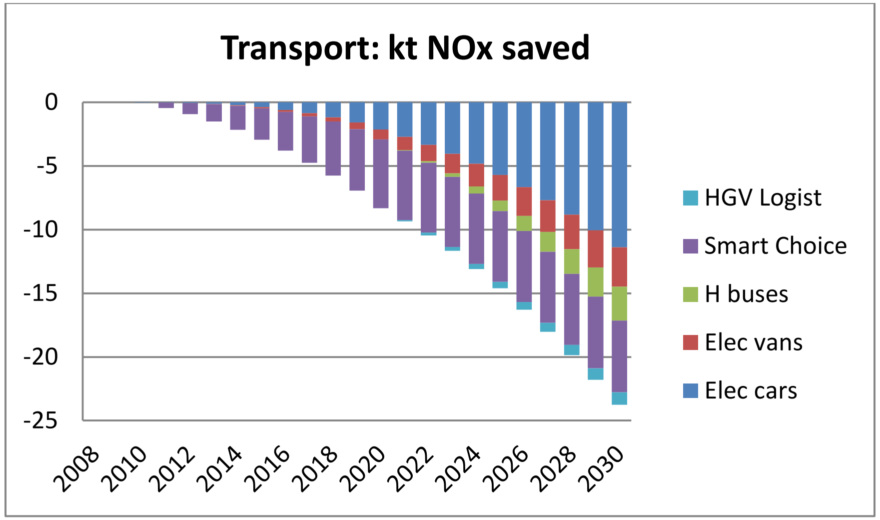
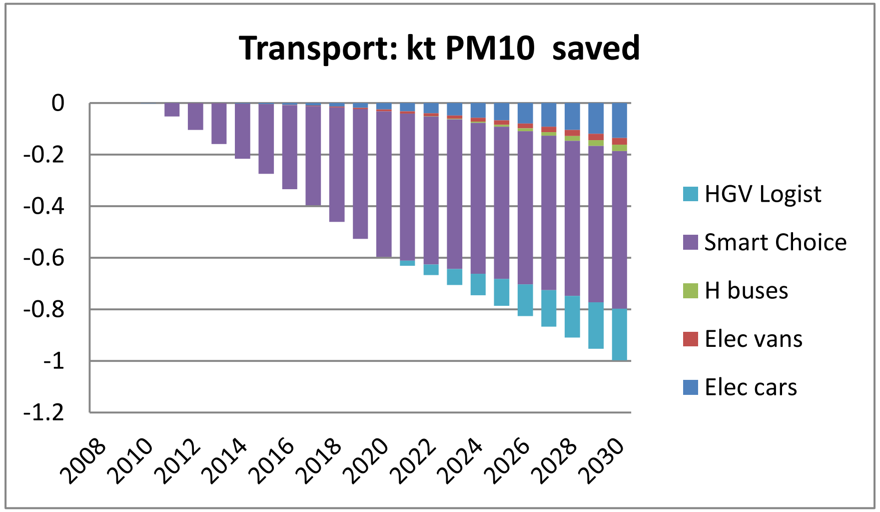
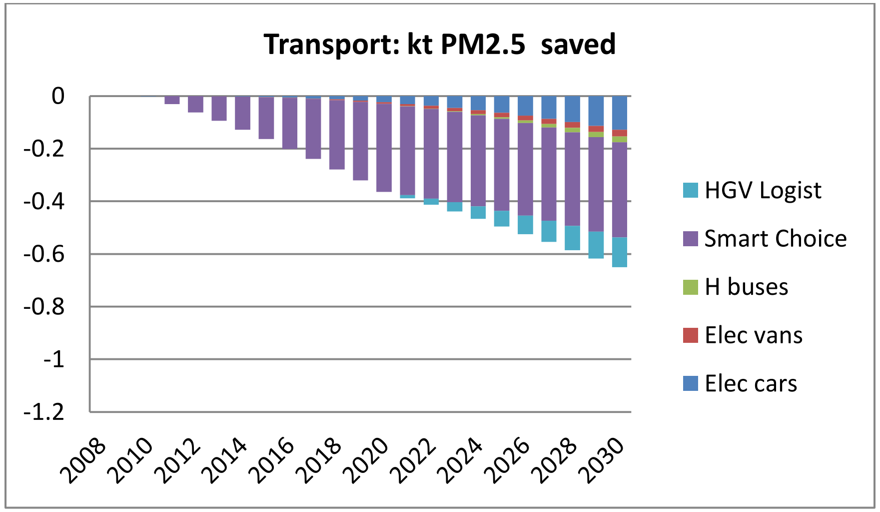


Figure 1.5b Indicators for NOx and PM_{10} exposure for biomass/biogas and fuel savings in heat sector

Figure 1.6. Emission savings of NOx, PM_{10} and $PM_{2.5}$ for road transport measures







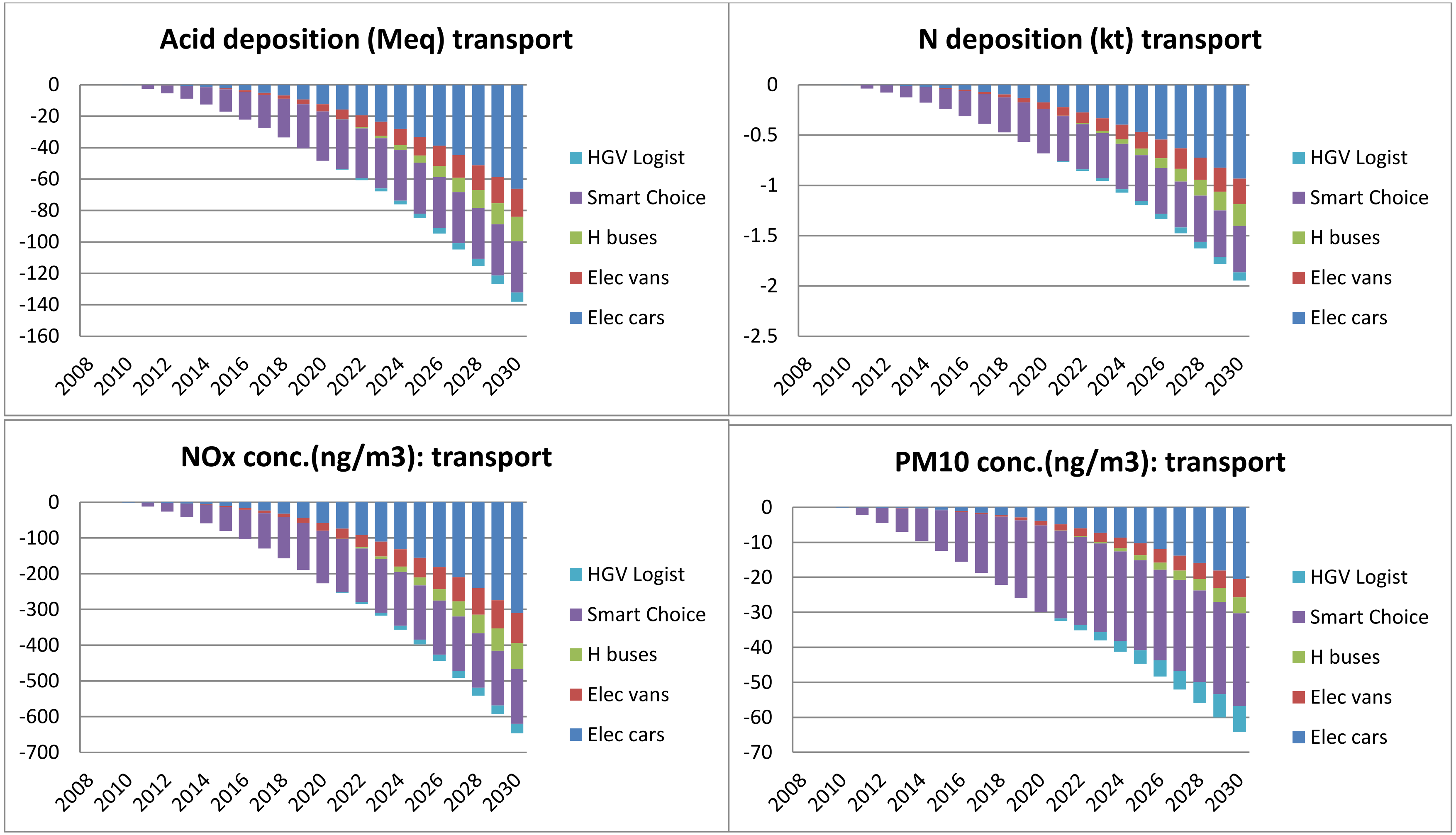


Figure 1.7. Impact indicators for road transport sector

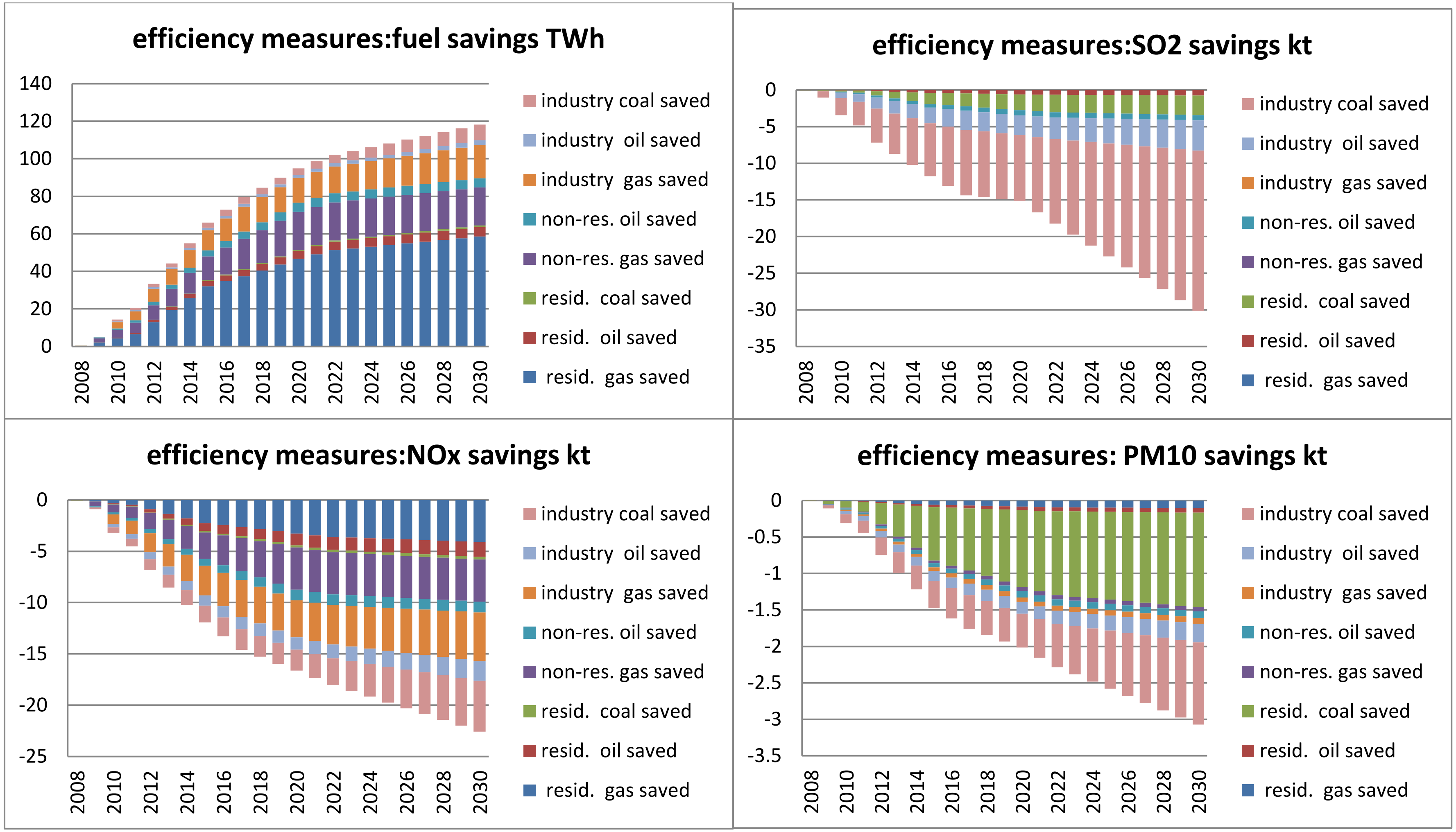


Figure 1.8: Energy savings and emission reductions of SO_2, NOx and PM_{10} for efficiency measures in the residential, non-residential and industry sectors

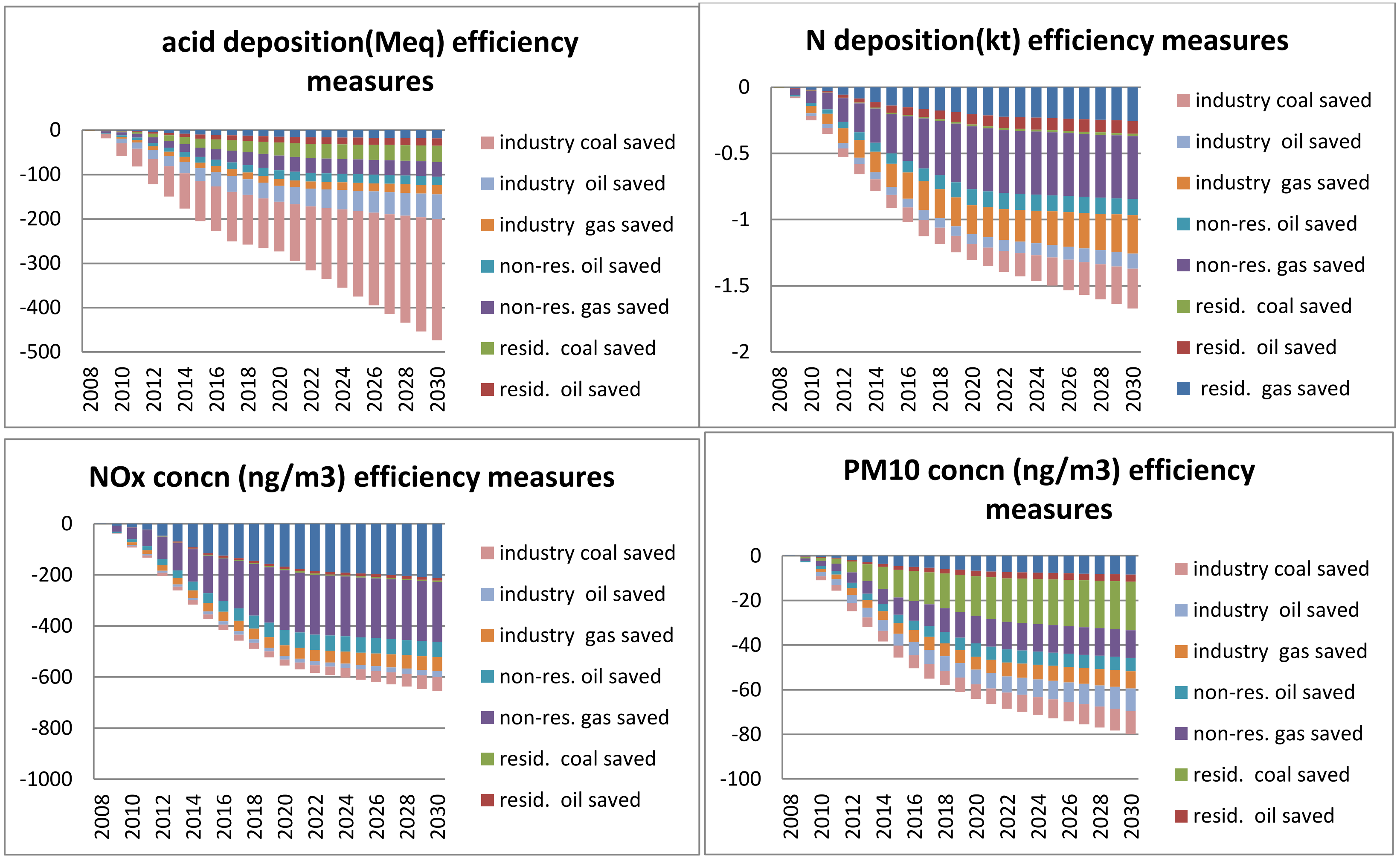


Figure 1.9 Impact indicators for energy efficiency measures

Figure 1.10 a. Environmental damage costs for the three power scenarios

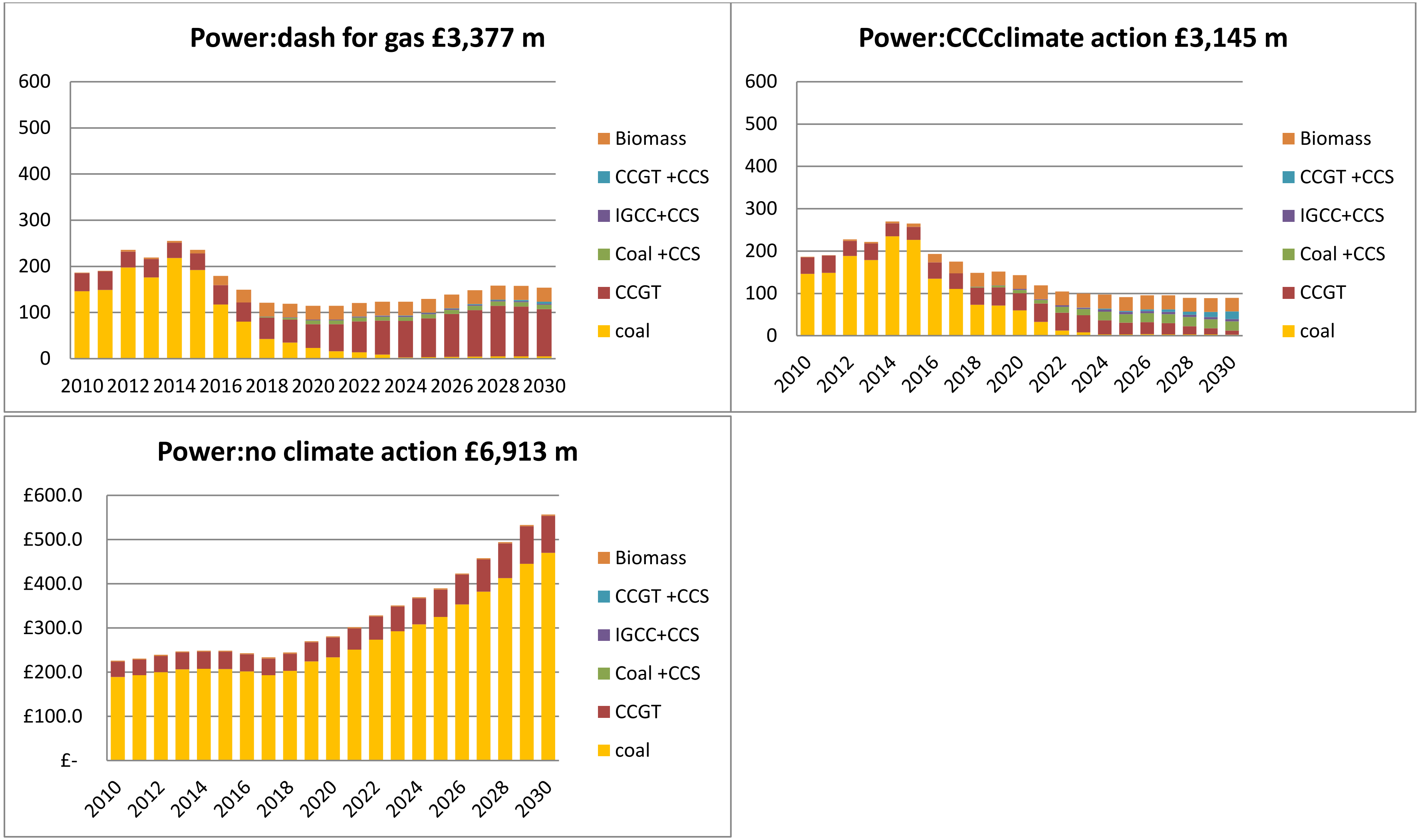


Figure 1.10 b Differential costs between CCC.CA scenario, D.GAS and NO.CA scenarios

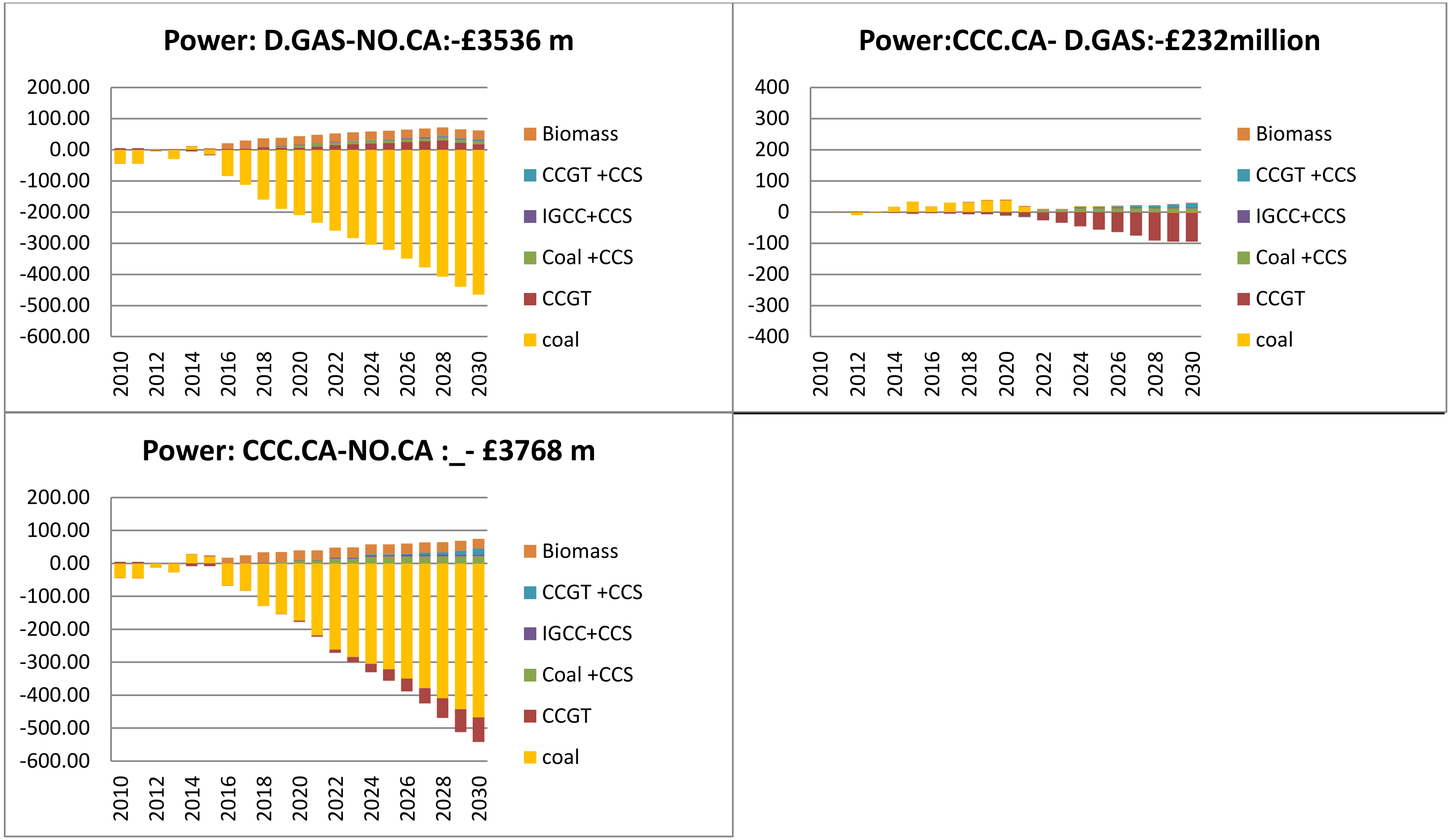
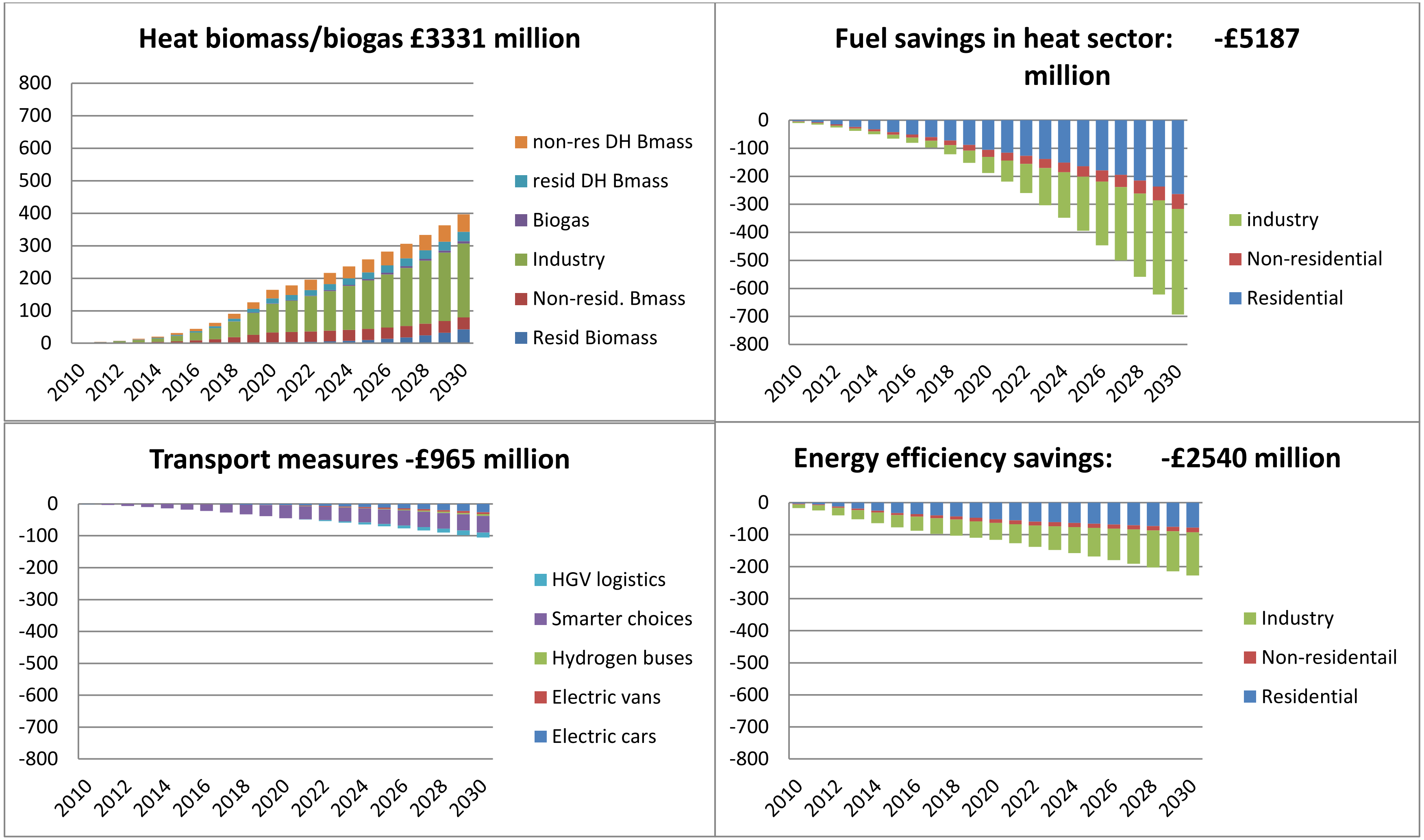


Figure 1.11. Environmental damage costs for additional measures



Part 2:

Exploration of air quality impacts of changes in the agricultural sector

2.1 Introduction

Part 2 of this report addresses some hypothetical scenarios to explore the air quality impacts of changes in agricultural demand and production. These scenarios for changes in the agricultural sector are taken from a study for the CCC by Cranfield University (Audsley E. et al 2011), investigating the effect of changes in UK food consumption on land requirements and land availability for other uses such as biofuel and biomass production, and on greenhouse gas emissions.

In addition to changes in greenhouse gas emissions, for example CH_4 from cattle and N_2O emissions from soils and fertiliser use, the agricultural sector is also the dominant source of ammonia, NH_3, as an air quality pollutant. Ammonia plays an important part in the nitrogen cycle, being a major factor in eutrophication of ecosystems and loss of biodiversity as well as contributing to acidification. It also plays an important role in the chemistry of the atmosphere and the formation of secondary inorganic aerosol, SIA, contributing to human exposure to fine PM_{10} and the finer fraction $PM_{2.5}$ with associated health impacts. It is these aspects that are considered here.

For this part of the study we have used the full UK integrated assessment model, UKIAM, instead of the simpler RAPID tool in order to map the ecosystem impacts in more detail, in particular for SSSIs ; and give more insight into the effects on different habitats. In order to do this we have taken a baseline scenario corresponding to current projections to 2020 used in UKIAM, based on UEP43 energy projections from DECC and agricultural projections used in the National Atmospheric Emission Inventory, NAEI. This baseline has been used to map exceedance of critical loads for ecosystem protection with respect to acidification and eutrophication; and to assess human exposure to secondary inorganic aerosol, SIA. The changes in agricultural production for the Cranfield scenarios have then been superimposed and the calculations repeated for comparison. More details of the UKIAM model are given in appendix A.

The three Cranfield scenarios are:

Scenario 1: a 50% reduction in animal products involving a 40% reduction in consumption of dairy products and eggs, and a 64% reduction in meat consumption

Scenario 2: a switch from red to white meat consumption involving a 75% reduction in beef and lamb, and a 45% increase in pig and poultry meat

Scenario 3: a 50% reduction in white meat (pig and poultry)

These scenarios have been specified with accompanying changes in plant products and other dietary components to provide a calorific balance. Table 2.1 reproduces table 4 from the Cranfield report with the resulting production of livestock commodities.

Table 2.1. The production of livestock commodities (thousand tonnes/year) in the UK as affected by consumption scenarios (based on FAOSTAT data for 2005).
(reproduced from p 18 of Cranfield report)

Consumption scenario	Pig	Chicken	Turkey	Beef	Sheep	Milk	Eggs
Base consumption	674	1,281	207	762	317	14,442	498
50% reduction in livestock	243	461	75	274	114	8,665	299
Red to white meat	977	1,857	300	191	79	14,442	498
50% reduction in white meat	337	641	104	762	317	14,442	498

2.2 Scenario analysis and ammonia emissions

The main effect on air quality of these hypothetical scenarios would result from changes in ammonia emissions, which arise mainly from agricultural manures and fertiliser use. Baseline projections based on the NAEI are given in the first column of table 2.1 broken down by livestock category, and amounting to 227 kt in total from agricultural sources. The geographical distributions of these emissions for each category are represented in the UKIAM database. For the analysis of scenarios 1 to 3 the emissions have been scaled in proportion to the corresponding production figures in table 2.1, as shown in table 2.2 compared with the baseline emissions. This ignores variants in the Cranfield scenarios which, for example, result in greater changes in upland sheep as compared with lowland sheep, and hence in the geographical distributions of livestock.

Table 2.2: Agricultural NH_3 emissions (Tons/yr)

	Baseline	Scenario1	Scenario2	Scenario3
Dairy	70,520	42,311	70,520	70,520
Beef	57,070	20,521	14,305	57,070
Pigs	21,360	7,701	30,962	10,680
Layers	7,530	4,521	7,530	7,530
Other Poultry	20,950	7,539	30,370	10,483
Sheep	9,720	3,496	2,422	9,720
Other Livestock	4,810	4,810	4,810	4,810
Fertiliser	35,200	35,200	35,200	35,200
Total	227,160	126,099	196,120	206,013

Scenario 1 in particular implies very large reductions in UK agricultural ammonia emissions of 45%, with scenarios 2 and 3 giving more modest reductions of around 14 % and 10% respectively. The emission reduction in scenario 1 is much greater than can be achieved by technical measures to abate ammonia emissions from agriculture. Since the baseline agricultural ammonia emissions account for 40% of the total nitrogen deposition across the

UK including deposition from NOx emissions and from imported contributions, such reductions could have significant effects on ecosystem protection.

2.3 Environmental impacts

Impacts on natural ecosystems

Assessment of protection of natural ecosystems is based on “critical loads” as the maximum rates of annual deposition sustainable without adverse effects. These have been defined and mapped in detail across the UK by the Centre for Ecology and Hydrology (CEH) for both acidification and eutrophication using established methods (http://critloads.ceh.ac.uk).Where deposition exceeds critical loads, ecosystems are deemed to be at risk and unprotected. The amount by which deposition exceeds the critical load is the “exceedance”. Critical loads for acidification represent equilibrium between acid inputs and soil processes and uptake, and hence depend critically on soil characteristics. For eutrophication, where excess nitrogen leads to changes in plant species (such as replacement of heather by coarse grass) and effects on biodiversity, critical loads are more empirical based on observation.

Figure 2.1 shows maps of projected exceedance of critical loads for both acidification and eutrophication in 2020 for the baseline scenario. For direct comparability both maps are plotted in keq/ha/yr, the units used for acidity where both sulphur and nitrogen contribute (1 keq/ha/yr is equivalent to 14 kg N/ha/yr and 16 kg S/ha/yr). It is clear that there is a greater exceedance of critical loads for eutrophication, and that the problem of excess nutrient nitrogen is more widespread than acidification. Thus nearly half (46.7%) of the area of habitats sensitive to nitrogen are at risk from eutrophication as compared with 27% at risk from acidification.

Table 2.3: percentage of ecosystem areas at risk with respect to acidification and eutrophication for the different agricultural scenarios

Scenario	% acidification	% eutrophication
Baseline	27.16	46.67
Scenario 1	21.35	28.24
Scenario 2	25.06	34.90
Scenario 3	28.34	39.81

Table 2.3 provides a comparison with the baseline of corresponding areas at risk for scenarios 1 to 3. As expected the large reductions in ammonia emissions in scenario 1imply a big improvement in the ecosystems at risk from eutrophication from 47% to 28%. The improvement with respect to acidification is more moderate; because there is a hard core of sensitive ecosystems, such as acid grassland, where critical loads are very low and difficult to achieve. Scenario 2 gives more modest improvements. But in the case of scenario 3 there is

even a slight deterioration with respect to acidification. It may seem surprising that a modest reduction in emissions can lead to an increase in exceedance, but this is because of the spatial behaviour and interaction with other pollutants. Reductions in NH_3 emission lead to local reductions in deposition, but can also lead to longer range transport of SO_4 and NO_3 and their deposition further away. This is the case for acidification in scenario 3 where the reductions in pig and poultry emissions, concentrated in areas like East Anglia, reduce deposition there where there are fewer ecosystems at risk of acidification, but increase deposition of sulphate and nitrate in rain further away over sensitive areas in Wales. Nevertheless there is still an improvement in scenario 3 with respect to eutrophication where sulphur deposition does not contribute.

The results given above follow the standard format for assessing ecosystem protection. However they do not distinguish ecosystem areas of particular value such as Natura 2000 sites. Also "protection" is dependent on critical loads for each habitat, which are themselves subject to uncertainty. Moreover the nitrogen comes from other sources apart from UK agriculture, and the indication of above or below the critical load does not show the reduction in exceedance. For these reasons a second approach using UKIAM has been devised as an alternative, focussed on the SSSIs (Sites of Special Scientific Interest) in the UK and risks with respect to eutrophication.

This depends on five "protectability bands" depending on the ratio of the deposition to minimum and maximum critical loads indicating a range of uncertainty for a given habitat. Where there is more than one habitat in a particular SSSI this is taken as the most sensitive habitat. The five bands are as follows:

1. Habitats with deposition not exceeding their minimum critical load, and hence most likely to be undamaged
2. Habitats with deposition exceeding their minimum critical load but less than their maximum critical load; these habitats lie in the uncertainty range
3. Habitats with deposition exceeding their maximum critical load by up to 50% (i.e. 1.5xCLmax) where additional measures to reduce deposition are more likely to help protection
4. Habitats with deposition exceeding their maximum critical load by between 50 and 100%; these habitats are more difficult to protect unless local sources are responsible and local measures can be applied
5. Habitats with deposition exceeding twice their maximum critical load which are likely to be unprotectable.

Figure 2.2 shows a map of SSSIs classified in this way for the baseline case by comparison with a corresponding map for scenario 1, which has the largest emission reductions. It is evident that there is a big improvement with more green and blue areas indicating protection, and less red severely exceeded sites. Note that the data on the SSSIs does not make it clear where in the SSSI area the particular habitats of interest are located, and the mapping of deposition is on a 5x5 km grid with allowance for differential deposition rates to different types of vegetation (grass, forest etc) within each grid square. So where a large SSSI overlaps more than one grid square the whole site is classified for the most sensitive habitat in the worst square, and hence may err on the side of pessimism. Also the effects of any local sources close to the habitat area are not resolved at this scale. Hence this mapping gives a statistical picture, and individual sites would need more detailed assessment with more information on the habitat areas within the SSSIs.

Figure 2.3 gives a comparison of the base case with scenarios 1 to 3 in terms of the number of sites in each of the 5 categories corresponding to the five bands related to exceedance. This is broken down into the different regions of England, Wales, Scotland and Northern Ireland. It is clear that scenario 1 shifts the distribution of sites from the right-hand more exceeded bands into the protected bands on the left, leaving relatively few severely exceeded sites. This signifies a dramatic improvement. Scenario 2 also indicates significant improvement though less than scenario 1. Scenario 3 with reduction in white meat shows a more modest but definite improvement, more comparable with studies we have undertaken of the potential effects of technical abatement measures aimed specifically at reduction of ammonia emissions from livestock housing, and storage and spreading of manures and slurries.

Impacts on human health

Ammonia emissions contribute to formation of secondary inorganic aerosol, SIA, and hence to human exposure to fine particulate matter, PM_{10}. The mean exposure to SIA has been estimated as the concentration averaged over the UK population distribution for the baseline scenario and scenarios 1 to 3.

Table 2.4.

Scenario	SIA conc (μg/m3)	Delta SIA conc (ng/m3)
Baseline (UEP43 ccc)	3.563	
Agricultural scenario 1	3.399	-163
Agricultural scenario 2	3.535	-28
Agricultural scenario 3	3.521	-42

This is shown in table 2.4, together with the reductions for the scenarios compared with the baseline. The largest reduction is for scenario 1 as expected, and represents a change comparable with those estimated in part 1 for sectoral changes. Hence this is a potentially important contribution although for a very hypothetical scenario implying very major changes in agriculture. Scenarios 2 and 3 show smaller reductions. The slightly larger effect of scenario 3 compared with scenario 2 despite the smaller reduction in overall emissions of

NH_3, again reflects the spatial distribution of the pig and poultry sectors and the spatial pattern of SIA concentrations which are higher in the south and east part of England.

2.4 Damage costs

Since these agricultural scenarios have not been specified as a development over time in the data provided by the CCC, it is not possible to assign damage costs in the same way as for the energy scenarios in Part 1 of this report. However as an approximate indication the Defra damage cost used in those calculations was £2million per kilo-tonne of NH_3 emission, indicating an approximate benefit of £200 million per year for the reduction of 100 kt in annual emissions for scenario1.This is very much an order of magnitude estimate with large uncertainties. Corresponding values for the other scenarios are £60 million per year for scenario 2 and £40 million per year for scenario 3. However these benefits do not include improvements in protection of natural ecosystems in the UK.

2.5 Summary

In part 2 of this report some hypothetical scenarios have been investigated to illustrate the air quality impacts of changes in agricultural production. Three scenarios have been compared with a baseline scenario currently used in UKIAM based on UEP43 energy projections from DECC and current agricultural projections to 2020 as used in the NAEI for the UK. The three hypothetical scenarios have been taken from the Cranfield report with scenario 1 implying a major reduction in consumption of animal products, scenario 2 corresponding to a large switch from red meat (beef and lamb) to white meat (pork and poultry), and scenario 3 with a halving of white meat consumption. The most significant air quality impacts of these changes arise from changes in emissions of ammonia, for which these scenarios imply reductions of 100, 30 and 20 kilto-tonnes per year respectively relative to the 227 kt emitted in the base case.

The effect of these scenarios on protection of ecosystems with respect to acidification and eutrophication has been investigated using the full UKIAM model. This indicates significant improvements in ecosystem protection with a reduction from 47% for the baseline to 28%for scenario 1 in ecosystems unprotected with respect to eutrophication, and from 27% to 21% with respect to acidification. A more detailed assessment for SSSIs in relation to eutrophication shows a broad shift across the spectrum of damage classes for scenario 1, with a much bigger proportion of sites either protected, or close to protection, based on critical loads (see figures 2.2 and 2. 3). Scenario 1 also implies significant reductions in population exposure in the UK to secondary particulate matter, averaging around 0.16 $\mu g/m^3$. Given the uncertainties in atmospheric chemistry and interaction with other pollutants this is a very approximate estimate, but is comparable with changes in exposure to PM_{10} for sectoral changes in the first part of this report. Based on Defra damage costs for NH_3 emissions the reduction of 100 kt in annual emissions for scenario 1 would imply environmental benefit of the order £200 million per year.

Scenario 2, with a smaller reduction in NH3 emissions of around 30 kt shows clear but correspondingly smaller benefits with more modest improvements in ecosystem protection (see figure 2.3), and in secondary particulate exposure. (.03μg/m^3). Based on Defra damage costs per ton this implies an environmental benefit of the order of £60 million per year. However comparison with scenario 3 illustrates some of the uncertainties which arise due to spatial patterns and atmospheric chemistry. Thus for scenario 3, with a smaller reduction in NH_3 emissions of 20 kt but more concentrated in the south eastern part of the country, the UKIAM model indicates a small improvement for eutrophication but a slight deterioration in protection with respect to acidification due to changing patterns of deposition. Also scenario 3 gives a slightly bigger change in population exposure than scenario 2, again due to spatial factors. This illustrates that other factors in addition to the magnitude of emission changes affect the environmental impacts, and also the damage costs.

This report has made no attempt to look at the other environmental impacts in terms of greenhouse gas emissions, or effects on water and land-use. Nor has there been any comparison with scenarios based on technical abatement measures focused on reduction of ammonia emissions, although this is a task UKIAM has been designed to investigate if required.

Reference:

Audsley E et al (2011) Food, land and greenhouse gases: the effect of changes in UK food consumption on land requirements and greenhouse gas emissions. Cranfield University report for the CCC . April 2011

Figure 2.1: Ecosystem exceedance of critical loads in 2020 with respect to acidification and eutrophication for baseline scenario

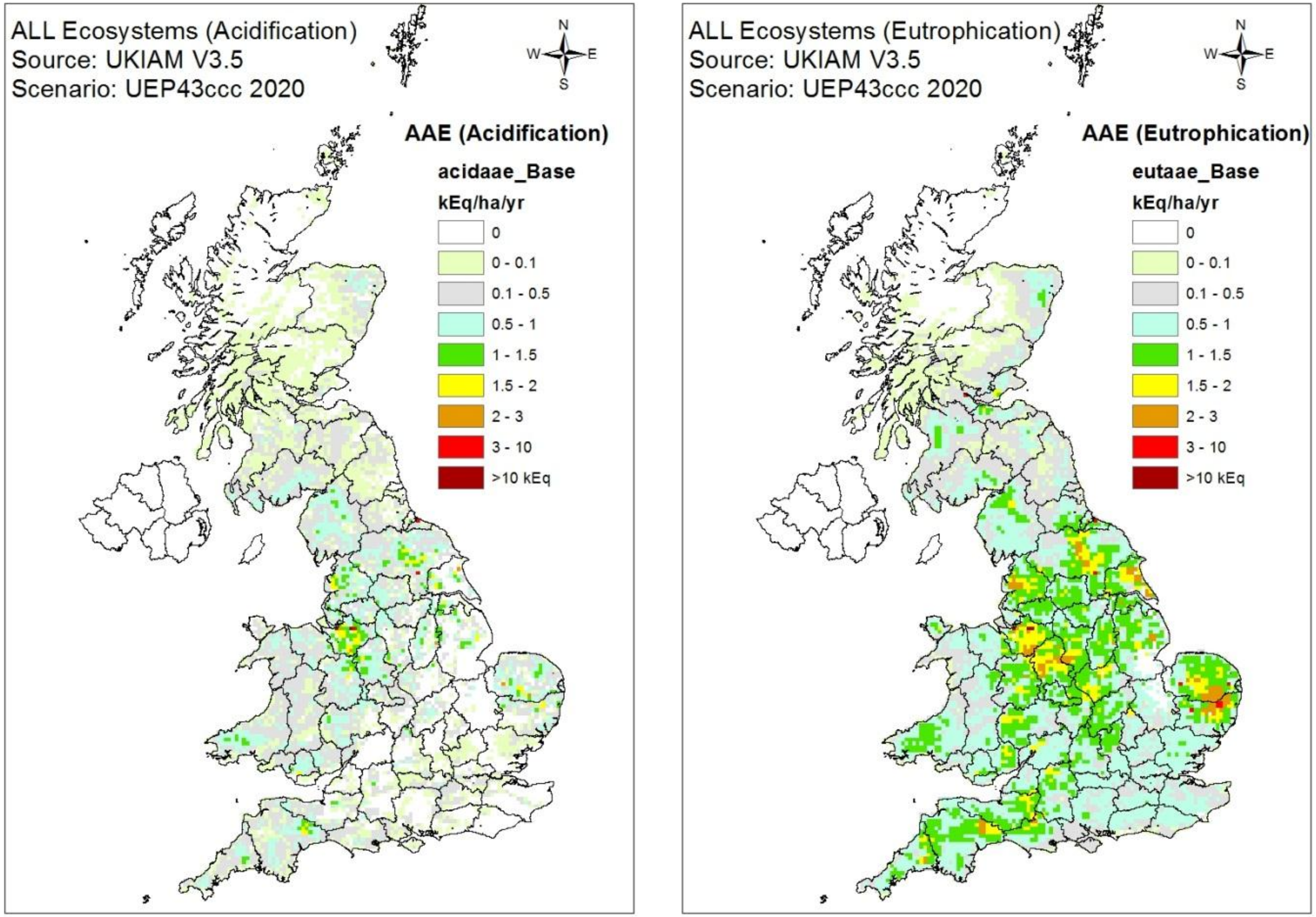


Figure 2.2. Mapping of SSSI protectability for baseline scenario and scenario 1

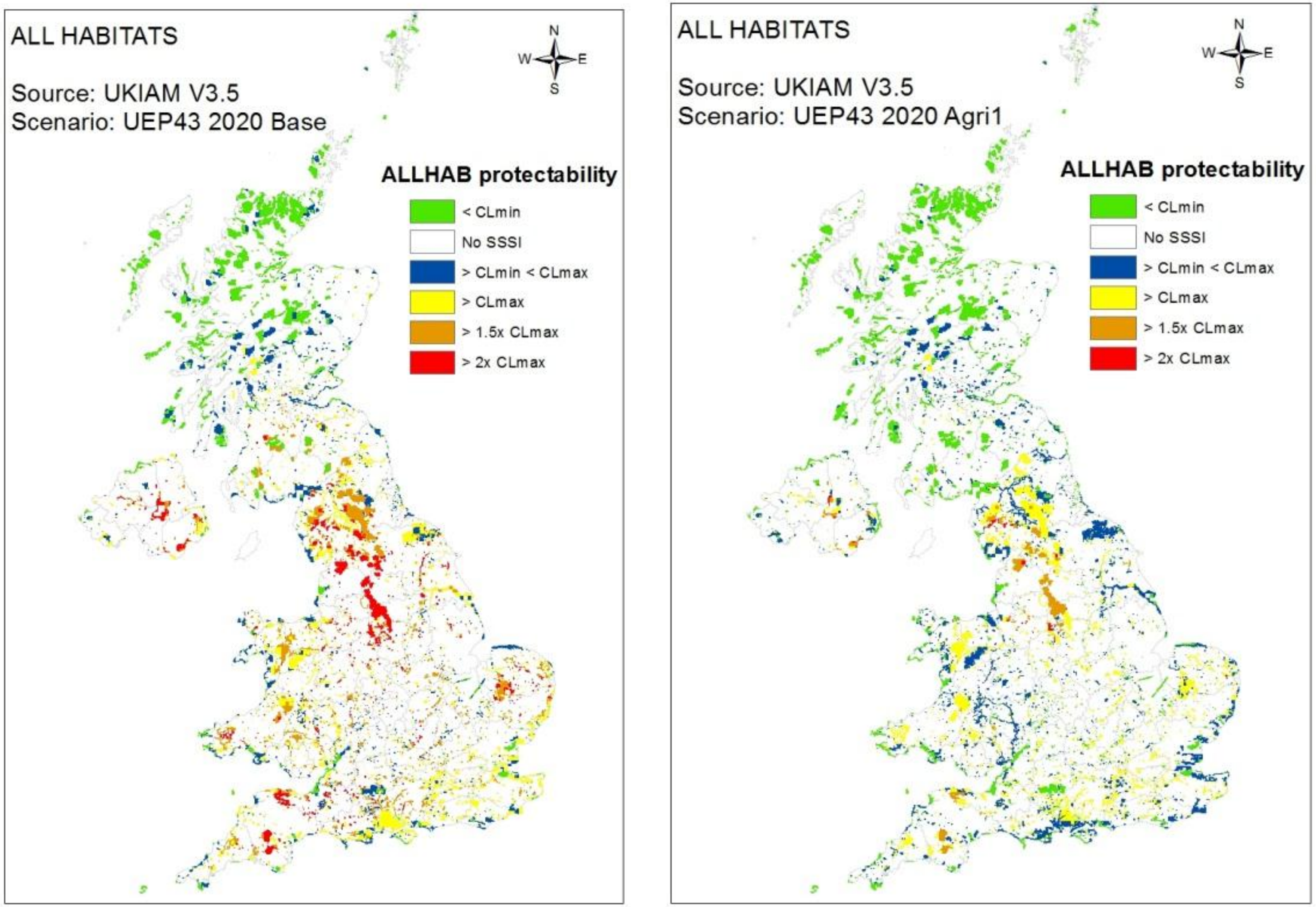
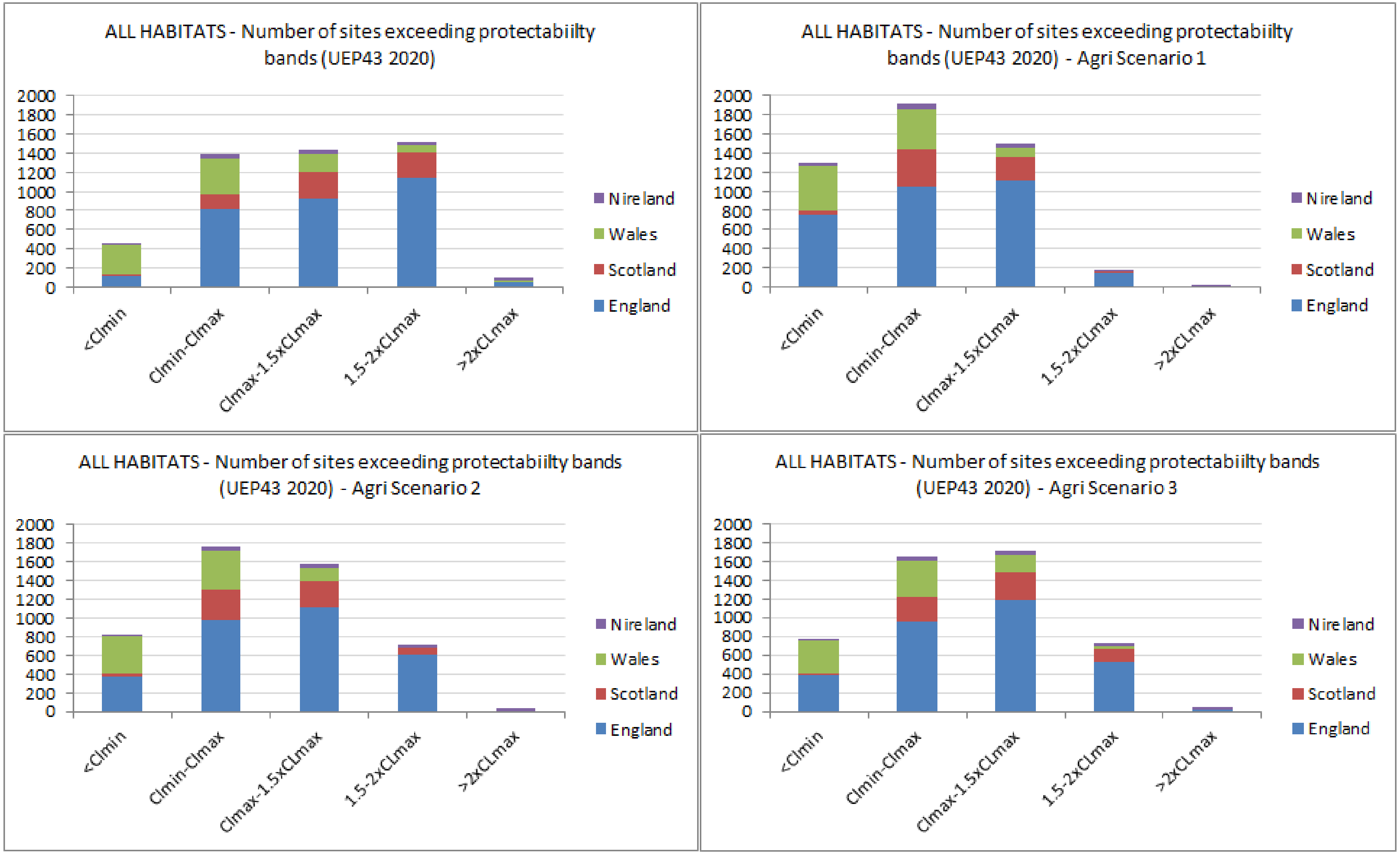


Figure 2. 3:


ALL HABITATS - Number of sites exceeding protectabiilty bands (UEP43 2020)
ALL HABITATS - Number of sites exceeding protectabiilty bands (UEP43 2020) - Agri Scenario 1
ALL HABITATS - Number of sites exceeding protectabiilty bands (UEP43 2020) - Agri Scenario 2
ALL HABITATS - Number of sites exceeding protectabiilty bands (UEP43 2020) - Agri Scenario 3
2000
1800
1600
1400
1200
1000
800
600
400
200
0
<Clmin
Clmin-Clmax
Clmax-1.5xCLmax
1.5-2xCLmax
>2xCLmax
N ire land
Wales
Scotland
England

APPENDIX A

The UKIAM model

This appendix provides a brief description of the UK Integrated Assessment Model, UKIAM, applied directly in part 2 of this report for analysis of the agricultural scenarios. The simpler spread-sheet model, RAPID, used in part 1, has also used data derived from UKIAM.

The UKIAM model

Introduction

The UK integrated assessment model, UKIAM, has been developed at Imperial College with funding from Defra to investigate future scenarios for air pollution, bringing together work from several other Defra contractors. The aim is to derive cost effective strategies for reducing UK emissions, which maximise improvements in environmental protection in the UK, while complying with future UK emission ceilings imposed to reduce trans-boundary air pollution in Europe. It brings together information on projected UK emissions of SO_2, NO_X, NH_3, PM_{10} and $PM_{2.5}$; atmospheric modelling of concentrations and deposition including imported contributions; criteria for protection of UK ecosystems, urban air quality and human health; and data on potential abatement measures to reduce emissions and their costs. UKIAM was one of the first national scale integrated assessment models to be developed after the Gothenburg protocol to investigate compliance with the ceilings for 2010, and has built on experience gained by Imperial College working in parallel with modelling by IIASA at the European scale with the RAINS and GAINS models. UKIAM has since been significantly revised and extended at Imperial College, and now includes greenhouse gas emissions for major combustion sources, and other environmental indicators to give a wider view of the policy implications of different control strategies, including interactions between air quality and climate policy.

UKIAM needs to be able to analyse a wide range of scenarios very quickly, covering a range of scales from European and transboundary air pollution down to roadside concentrations in urban streets with respect to air quality legislation. It is not possible to incorporate complex atmospheric dispersion models directly. Instead UKIAM uses pre-calculated source- receptor relationships derived from a range of atmospheric models at different scales and representing the effect of changes in concentration or deposition at a matrix of locations due to unit changes in source strength for a wide range of sources both within and outside the UK. A pseudo-linear response to emission changes is then assumed for each source; which is a valid approximation, despite chemical interactions between pollutants, providing the emission changes made are not too large. Sensitivity studies have been undertaken to support this, combined with using data derived from different models in relation to model uncertainties. Atmospheric models used to derive the source-receptor matrices include the European scale EMEP model, the UK scale FRAME model of CEH, and the local scale PPM model at Imperial. These have been run externally to develop the baseline and source-footprints used within UKIAM and the BRUTAL sub-model for transport and urban air quality, supported by comparison with measurements for present day emission estimates. This facilitates very rapid assessment of a wide range of future scenarios from which to select the most promising for more detailed evaluation.

Figure A1 provides an overview of the context of the UKIAM, highlighting the sources of data contributing to the representation of impacts across the UK:

- Emissions projections are taken from the NAEI based upon Updated Energy Projections (UEP) from DECC, road transport projections from DfT, and agricultural projections provided by Rothamsted (IGER);
- Abatement measures and associated costs have been developed by AMEC in a Multi-Pollutant Measures Database (MPMD), and by NARSES and IGER in relation to agricultural measures; specific studies have been undertaken of other scenarios including behavioural change and cross-sectoral measures such as electric vehicles
- Spatial definition of ecosystems and ecosystem Critical Loads for acidification and eutrophication are provided by CEH Bangor;
- Atmospheric dispersion of emissions is captured by the FRAME model (CEH Edinburgh) for UK sources, by EMEP for non-UK sources (integrated by the ASAM European scale module of UKIAM), and by the PPM model (Imperial College) for NO_X and $PM_{10/2.5}$ dispersion. The FRAME and EMEP models capture all relevant atmospheric chemistry whereas PPM assumes no chemistry; and then applies a simple relationship between NO_X and NO_2 dependent on total oxidant and type of location
- Emissions from shipping, which span the boundary between the UKIAM and ASAM, have been quantified spatially by AMEC; and, finally
- The BRUTAL sub-model derives road transport emissions across the national road network and provides high resolution (1km) modelling of UK road transport within the UKIAM, as well as a statistical approach to road-side concentrations for major roads.

In order to facilitate a more focussed approach within the UK, the UKIAM defines sources in relation to SNAP sectors or sub-sectors:

1. Combustion in Energy Industries: Major power stations are treated individually, small power stations are treated collectively as a spatially distributed source, as are refineries and offshore oil & gas.
2. Non-industrial Combustion: Domestic combustion is further split into fuel usage (gas, oil & coal), whereas public sector combustion is treated as a single dispersed source.
3. Combustion in Manufacturing Industries: The main industrial sectors are handled as separate sources (cement, iron & steel, sinter production, brick manufacture etc.), with the remainder categorised together as 'Other Industrial Combustion' except for Ashington which is treated as a major point source.
4. Production Processes: Treated as a single dispersed source except for Lynmouth Aluminium smelter which is treated as a point source.
5. Extraction & Distribution: A single dispersed source with minimal emissions.
6. Solvent Use: Mainly VOC emissions which are not currently captured by UKIAM.
7. Road Transport: Petrol and diesel cars, LGV's, HGV's and buses are handled as separate sources using the BRUTAL model.
8. Other mobile sources & machinery: Off-road emissions include shipping, aircraft, railways,
9. agricultural and industrial separately, with the remainder assumed to be domestic.
10. Waste treatment & disposal: is included as a single dispersed source.

11. Agriculture: Seven categories of livestock are included, with fertiliser emissions treated independently.
12. Natural emissions: Includes natural emissions as defined by NAEI

Output from the model

Routine outputs from the model include maps of concentration and deposition of different pollutants, and corresponding maps of exceedance of critical loads for protection of ecosystems and SSSIs as illustrated in part 2 of this report. These can be broken down in more detail by individual habitats.

For human exposure concentrations are integrated across the population and used to define mean concentrations for different regions or for the whole country. Similarly the model derives very simple statistics indicating urban areas and roads at risk of exceeding air quality limit values, where more detailed consideration is required to give a more precise analysis. Specific areas such as London have been considered in more detail, especially in relation to urban air pollution- for example in a study of the potential air quality impacts of the Mayor's decentralised energy strategy involving wide-ranging use of CHP and district heating plants within London.

In future work we plan to expand the range of the model to include VOCs and ozone, which have not been addressed in this report; and make stronger links with economic analysis and work on evaluation of damage costs for use in cost benefit analysis.

References

SSNIP final report (2012) Scientific support for national and international policy: summary for policy makers. Defra contract report AQ0902

Figure A1: The multiscale UKIAM modelling framework