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Abstract: The energy sector is a major contributor to greenhouse gas (GHG) emissions and other types of air pollution that negatively impact human health and the environment. Policy targets to achieve decarbonisation goals for national energy systems will therefore impact levels of air pollution. Advantages can be gained from considering these co-impacts when analysing technology transition scenarios in order to avoid tension between climate change and air quality policies. We incorporated non-GHG air pollution into a bottom-up, technoeconomic energy systems model that is at the core of UK decarbonisation policy development. We then used this model to assess the co-impacts of decarbonisation on other types of air pollution and evaluated the extent to which transition pathways would be altered if these other pollutants were considered. In a scenario where the UK meets its existing decarbonisation targets to 2050, including the costs of non-GHG air pollution led to a 40% and 45% decrease in PM10 and PM2.5 pollution (respectively) between 2010 and 2050 due to changes in technology choice in residential heating. Conversely, limited change in the pollution profile for transportation were observed, suggesting that other policy strategies will be necessary to reduce pollution from transport.

Quantifying the co-impacts of energy sector decarbonisation on outdoor air pollution in the United Kingdom

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Keywords

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***Highlights**

- Strategies to decarbonise energy systems should consider other air pollutants
- Energy systems models can show decarbonisation pathway co-impacts on PM, NO_x & SO_x
- Considering non-GHG pollution eliminates carbon & air quality policy tensions
- Transport particulate pollution challenges will only be addressed by modal shifting

1. Introduction

There exists widespread agreement in the scientific community that outdoor air pollution can be detrimental to the environment and human health, both through its contribution to global climate change and local air quality challenges (Watts et al., 2015; World Health Organization, 2013). While outdoor air pollution levels have improved considerably in the UK since the famous “pea soupers” (smog) seen in the first half of the 20th century, an estimated 40,000 people still prematurely die each year due to exposure to outdoor air pollution and cost the UK economy £20 billion (Royal College of Physicians, 2016). In London, up to 9,416 people die prematurely due to anthropogenic PM2.5 and NO2 pollution exposure alone, with an estimated annual monetised cost of £1.4–3.7 billion (Walton et al., 2015).

Under the Environment Act 1995, the UK Government and devolved administrations in England, Scotland, Wales and Northern Ireland are responsible for producing a national air quality strategy. This strategy was last reviewed and published in 2007 and set out a plan for meeting the UK’s air quality objectives via action at national, regional and local levels for a number of pollutants including nitrogen dioxide, particulate matter, and sulphur dioxide. Under Part IV of this Act, along with Order 2002, local authorities in the UK are required to measure their local air quality and establish air quality management areas for locations requiring improvement (UK DEFRA, 2013).

The UK is also subject to a number of directives at the European (EU) level, including the National Emissions Ceilings Directive (2001/81/EC) and the EU Air Quality Directive

(2008/50/EC) and its legally binding limits on outdoor air pollution levels. The former requires that Member states develop and maintain national programmes to meet emissions ceilings and required reporting of emissions inventories for sulphur dioxide (SO2), nitrogen oxides (NOx), non-methane volatile organic compounds (NMVOCs), and ammonia (NH3). The latter includes limits for particulate matter (both PM10 and PM2.5) and nitrogen dioxide (NO2). Further action is needed; the UK Supreme Court ruled in 2015 that the government must take action to reduce air pollution levels to meet EU Air Quality Directive limits for outdoor air pollution, which it currently violates.

In parallel, the UK has set a long-term national GHG reduction target of 80% by 2050 compared to 1990 levels, with a series of interim carbon budgets that will require significant changes in the energy system. Most recently, the UK Government set out the 5th carbon budget (2028 – 2032) in late July 2016 based on guidance published by the Committee on Climate Change in 2015 (Committee on Climate Change, 2015; Department for BEIS, 2016; Department of Energy and Climate Change, 2016).

There is significant value to be gained from insights on the trade-offs and synergies between proposed air quality and climate interventions (Lott and Daly, 2015; Pye et al., 2008; Pye and Palmer, 2008). Much of the outdoor air pollution in the United Kingdom arises from the use of fossil fuels. Furthermore, multiple air pollutants are often produced by the same energy system technologies (e.g. fossil fuel power plants, gasoline and diesel vehicles). Studies have shown how the inclusion of these multiple externalities greatly change the relatively competitiveness of different fuels (Shindell et al., 2012).

However, such externalities are not included in the costs of energy technologies today. Furthermore, no peer-reviewed papers have been published on a methodology that endogenizes these air pollution co-impacts and corresponding damage costs into a national whole energy systems optimisation model. Given that these optimisation models are central to energy sector policy assessment – including the 2016 impact assessment for the fifth carbon budget level published by the UK Department of Energy and Climate Change - the addition of other air pollutants provides valuable additional insights on the co-impacts of climate and air quality interventions (Department of Energy and Climate Change, 2016).

Within the published literature, many studies exist that internalised local air quality externalities into an energy system optimisation process (Bhattacharyya and Timilsina, 2010; ETSAP, 2014a; Klaassen and Riahi, 2007; Kudelko, 2006; Loulou et al., 2005; Nguyen, 2008; Pye et al., 2008; Pye and Palmer, 2008; Rafaj and Kypreos, 2007; Zvingilaite, 2011, 2013; Zvingilaite and Klinge Jacobsen, 2015). But these studies only considered a portion of the energy system (e.g. the electricity generation or regional heating systems). Furthermore, a number of studies have focused on the co-benefits of climate change policies using integrated assessment models (Amann et al., 2009; Bollen et al., 2009; Department of Energy and Climate Change, 2009; Intergovernmental Panel on Climate Change, 2007; Nemet et al., 2010; Östblom and Samakovlis, 2004; Stern and Taylor, 2006; Zvingilaite, 2011). But, only two of these models included an estimate of the economic value of air quality co-benefits (Department of Energy and Climate Change, 2009; Stern and Taylor, 2006).

For the UK, research has been conducted to examine particular strategies for simultaneously reducing carbon and non-GHG emissions such as increased levels of active travel, household energy efficiency, and clean car penetration (Jarrett et al., 2012; Jensen et al., 2013; Watts et al., 2015; Wilkinson and Tonne, 2011; Woodcock et al., 2009). But, again, these studies did not holistically look at the whole energy system or at the full range of air pollution co-benefits considered in this research.

Outside of the peer-reviewed literature, two consulting reports (Pye et al., 2008; Pye and Palmer, 2008) integrate non-GHG air pollution into a whole energy systems model, quantifying changes in air quality pollutant emissions under different UK policy scenarios. In this work, they included three pollutants (SO2, NO2, and PM10) into the UK MARKAL energy systems model and found that “air quality emissions could be significantly reduced in future years as a result of technology improvements, improved efficiency and less use of polluting fuels under a reference case… [and] benefits due to [air quality] emission reductions are estimated at between £0.9–1.0 billion in 2050” (Pye et al., 2008). At the time, the authors noted that the model “could be further developed to assess both climate and air quality targets simultaneously. This could be done by including emission ceilings, for example, for air quality pollutants, which the model would factor in as part of the optimisation process” (Pye et al., 2008).

In this paper, we further enhance the analysis in Pye and Palmer (2008) by considering 3 additional pollutants (PM2.5, NMVOCs and NH3), and develop a more rigorous representation of emission factors in the model based on the latest inventory information. The approach and methods used are described in this manuscript, including a discussion of the extent to which non-GHG air pollutants can be mapped to an energy systems model, in this case UKTM-UCL. Results from six (6) scenarios are then presented with a corresponding discussion. We conclude with the key insights gained from this work.

2. Approach

This section provides a brief overview of UKTM-UCL and explains how an air pollution emissions and damage cost database for particulate matter (PM10 and PM2.5), nitrogen oxides (NOx), sulphur oxides (SOx), ammonia (NH3), and non-methane volatile organic compounds (NMVOCs) was added to the model in order to endogenize air pollution co-impacts. This section concludes with a description of the set of six (6) scenarios that we used to explore the impacts of incorporating non-greenhouse gas air pollution on UK decarbonisation strategies.

2.1 UKTM-UCL

The MARKAL (Market Allocation) and subsequent TIMES (The Integrated MARKAL-EFOM System) model generators are perhaps the most well-known dynamic technology-economic models and have been used to simulate many national and international energy systems (ETSAP, 2014a, 2014b; Loulou et al., 2005). These models combine “two different, but complementary, systematic approaches to modelling energy: a technical engineering approach and an economic approach" (ETSAP, 2014a). They are bottom-up, perfect-foresight, linear optimisation models that identify the lowest-cost pathway for meeting all energy demands in an economy across all energy sectors, subject to constraints such as emissions targets. They are maintained by the International Energy Agency's Energy Technology Systems Analysis Programme (Loulou et al., 2005).

The UK TIMES Model (UKTM-UCL)1 is a technology-oriented model that represents the entire UK energy system as a single region, spanning from imports and domestic production of fuel resources, through fuel processing and supply, explicit representation of infrastructures, conversion to secondary energy carriers (including electricity, heat and hydrogen), end-use technologies and energy service demands. A generic TIMES model structure is displayed graphically in Figure 1.

UKTM-UCL was developed to replace the UK MARKAL model, which has contributed underpinning insights to policy processes over the last decade, including the Climate Change Act 2008 (Dodds et al., 2014). UKTM has been co-developed with the UK Department of Energy and Climate Change (DECC), who use it to provide evidence to support their long-term climate policy.

2.2 Air quality pollutant emissions database

We incorporated an air pollutant emissions database into UKTM-UCL for six (6) air quality pollutants: particulate matter that is either less than 10 or less than 2.5

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[1] https://www.ucl.ac.uk/energy-models/models/uktm-ucl (accessed April 2016)

micrometres in diameter (PM10 and PM2.5), nitrogen oxides (NOx as NO2), sulphur dioxide (SOx as SO2), ammonia (NH3), and non-methane volatile organic compounds (NMVOCs). This update allows air pollution emissions accounting by year out to 2050. A full list of the emission factors included in this database by sector and technology are found in Appendix A: Supplementary Material.

Emission factors (EFs) for the current energy system were compiled from the UK National Atmospheric Emissions Inventory (NAEI)2 using the latest publically available dataset, the 2013 NAEI. However, some of the NAEI EFs were confidential due to commercial sensitivity and other EFs did not directly match the UKTM fuels and technologies. In these cases, the closest match in the NAEI was used or alternative data sources were identified and documented in consultation with experts. The NAEI is made up of data from the Greenhouse Gas Inventory (GHGI) and the Air Quality Pollutant Inventory (AQPI) combined with a range of activity data sources. These activity data are collected from a range of sources, including national energy statistics and data collection from individual industrial facilities. In turn, the EFs published in the NAEI account for technologies that have already been installed to reduce air pollution (e.g. flue gas desulphurization).

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[2] Emission factors (EFs) were mapped from the National Atmospheric Emissions Inventory (NAEI), published online at http://naei.defra.gov.uk (accessed November 2015), which provides the official annual air quality pollutant emission estimates for the United Kingdom. The inventory is structured around reporting under the United Nations Economic Commission for Europe (UNECE) Convention on Long Range Transboundary Air Pollution (CLRTAP) and emission estimates are presented in Nomenclature for Reporting (NFR) format.

Two types of emission factors were used in this analysis and were differentiated by sector. Fuel-based EFs were used for all sectors, with the exception of road transport, which used activity-based factors and electricity, which used a mixed approach. This choice was based on expert judgement that further detailed technology-based disaggregation was not merited given the model's characterization of the air pollution sources.

Fuel-based factors account for emissions based on the amount of fuel that is burned (e.g. grams per PJ) versus activity-based factors that are structured around the activity undertaken (e.g. grams per mile travelled). Activity-based factors are more appropriate for transport in order to account for non-tailpipe emissions – including tyre, brake, and road wear – as well as approved European Union Standards (e.g. Euro VI standards for road vehicles) that would be ignored using a fuel-based EF. These activity-based EFs were based on test cycle emissions as opposed to real world, which could have important implications on the output emissions levels and corresponding policy recommendations.

For the fuel-based EFs used in this work, we assumed that technology changes would not impact significantly on emissions. Rather, pollution levels would be most impacted by efficiency of fuel use and total fuel demand. When modelling out to 2050, there are a range of new technologies, not currently in the system, for which emissions information therefore does not exist. Such technologies include carbon capture and storage (CCS), for which some estimates have been made (European Environment Agency, 2011). For hydrogen production, air pollution EFs were generally assumed to be the same as for electricity generation; for SMR plants, PM, NOx and SO2 EFs were based on Contadini et. al. (Contadini et al., 2001). For biofuel production, no emission factors were assumed due to the absence of data estimates. For alternative fuel vehicles, we have used additional information published by the NAEI (Murrels and Pang, 2013).

For the transport sector, hot exhaust emissions as well as non-tailpipe emissions from tyre wear, brake wear, and road abrasion were included for all road transport. Cold start emissions and evaporative emissions were not included for these technologies because a detailed transport emission model would be needed for proper accounting. These emissions make up about 10% of NOx emissions from cars and 5% of LGV NOx emissions. For shipping and aviation, emissions were calculated by taking the total emissions from the NAEI for each pollutant and dividing it by the activity values in UKTM for the base year.

Furthermore, the impact of approved standards that will directly impact air pollution emission factors for specific technologies is included. For example, air pollution standards for new motor vehicles are included through Euro VI. Potential future policies that could impact EFs for individual energy technologies are not included in this work.

A post-mapping evaluation revealed the extent to which the UKTM-UCL accounted for these six (6) air pollutants, since the model only represents the energy system, while significant emissions of specific pollutants come from other parts of the economy. A majority of NOx, SOx and PM (both PM10 and PM2.5) air pollution were represented in UKTM in 2010, with NOx and SOx having the most complete coverage as shown in Table 1. Conversely, sectoral coverage of NH3 and NMVOC emissions was limited, representing an opportunity for future model development. For the air pollution emissions that were included in UKTM, a calibration exercise was undertaken to compare the UKTM 2010 base year against the corresponding NAEI sector totals, with the objective to be within 10-15% difference.

In the case of particulate matter, the majority of PM_{10} emissions that were not included are from agricultural sources (livestock and crops) as well as mining and quarrying. A more detailed breakdown of the sources of these excluded emissions is shown in Table 2.

For NMVOC and NH_3, emissions are dominated by non-energy sources not characterised in UKTM - solvents, fugitive emissions and emissions from the agricultural sector (e.g. from manure).

2.3 Damage Cost Database

In the UK, two broad methods have been used to estimate the cost of air pollution – a detailed “impact pathway” and a simpler “damage cost” approach (Her Majesty’s Treasury, 2013; Miller and Hurley, 2010). The impact pathway approach requires detailed emission, air quality modelling and health impact assessments and is therefore resource intensive. The damage costs approach uses the outputs of impact pathway studies to quantify the monetary impact of changes per unit of pollutant emitted (Department for Environment Food and Rural Affairs, 2013; Walton et al., 2015). These damage costs are a more direct and straightforward way to place an economic value on the impacts of air pollution on both public health and the environment (including both buildings and materials) in UKTM-UCL, and therefore to include in the optimization process.

Crucially, the damage costs approach does, at the national level, factor in the spatial distribution of air pollution and the likely exposure. It is therefore appropriate to use such nationally-derived damage costs values in a model such as UKTM-UCL. While recognised as a credible approach for policy appraisal, the limitation is the implicit assumption that such damage cost values hold for future years, in which this spatial distribution of pollution–exposure–impact may change.

The damage costs that were used in UKTM-UCL were developed by the UK Department for Environment, Food and Rural Affairs (DEFRA) and are shown in Table 3. All values represent the cost impact of a change in pollution by one tonne in a given year ("annual pulse damage costs").

These costs include the air pollution impacts of PM_{10} and $PM_{2.5}$ on health, including both chronic mortality and morbidity effects as well as building soiling impacts. For NO_x, these values include the health impacts of secondary particulate matter resulting from NO_x emissions but does not include the health impacts of ozone formation as the result of NO_x emissions. The SO_x damage costs include this secondary PM formation and impacts of SO_2 on health and building materials. For NH_3, these costs include the health impacts of secondary particular matter formation (Department for Environment Food and Rural Affairs (DEFRA), 2011). In the case of PM air pollution, the values are more disaggregated to reflect the relative impact of pollution source on the population and surrounding built environment (e.g. PM from power plant stacks versus urban transport). Damage costs were not included for NMVOCs, as DEFRA does not publish these values. In turn, this type of pollution is inventoried, but is not included in the cost-optimisation process.

When these damage costs are excluded from individual scenarios, the model simply accounts the emission levels across these air pollutants, with no direct effect on the model solution. When air pollution damage costs are included, these costs are factored into the optimisation process and so can impact energy technology choices. In the implementation stage, these costs are included as an emissions tax, incurred for every tonne of pollutant emitted.

2.4 Scenario Development

A set of six (6) scenarios were developed to better understand the relative impacts of the inclusion or exclusion of the damage costs for outdoor air pollution. These scenarios included a baseline (base), reference (ref), and low greenhouse gas (lowGHG) both with and without damage costs as shown in Table 4.

The base and ref scenarios did not include the UK's 2050 decarbonisation goal or interim targets. The latter included a £30 per tonne carbon price that was linearly phased in from 2015 to 2030 and then held constant to 2050 in order to simulate a central case where the system moves away from the most carbon-intensive technologies (e.g. coal in the electricity sector) but long term decarbonisation goals are not achieved. In the lowGHG scenario, the energy system was required to meet existing UK decarbonisation targets for a total reduction in greenhouse gas emissions of 80% by 2050 compared to 1990 levels including interim targets through the 4th Carbon Budget. In late July 2016, the UK Government set a 5th Carbon Budget of 1,725 million tonnes of carbon dioxide equivalent for the 2028–2032 budgetary period in agreement with recommendations from the Committee on Climate Change (Department for BEIS, 2016). The reduction trajectory used in this analysis is broadly consistent with the recently agreed 5th Carbon Budget.

3. Results

The scenarios examined the period to 2050 for the United Kingdom using demand drivers that relied upon official population and economic growth projections and energy efficiency expectations. Results are first given in terms of total emissions by scenario and by sector. Details are then provided for the case of particulate matter (PM_{10} and $PM_{2.5}$) with comments on other pollutants in order to compare the effect of including damage costs in the scenarios for the entire energy sector as well as the residential and transport sub-sectors. Throughout these discussions, the air pollution co-impacts presented result from fuel-switching, efficiency gains, and technology changes (e.g. switching hybrid vehicles in transport or from coal to natural gas in power generation).

Primary energy consumption in 2050 by fuel type is displayed in Figure 2 for all scenarios. Overall, the inclusion of damage costs in the base scenario led to increased use of natural gas and decreased use of biomass and biofuels as well as coal and coke in 2050. Decarbonisation ambitions resulted in increased use of nuclear power for the ref and lowGHG scenarios. For the latter, the inclusion of damage costs had little impact on final primary energy consumption in 2050, though the pathway taken was significantly different as discussed in the following sections.

3.1 Scenarios without damage costs

For the three scenarios without damage costs (base, ref and lowGHG), the decarbonisation of the energy sector resulted in significant co-benefits for reducing air pollutant emissions. For particulate matter, decarbonisation in low GHG resulted in an additional 34% (41 kilotonne) decrease in PM_{10} and 38% (29 kt) decrease in $PM_{2.5}$ pollution levels in 2050 compared to the base and ref scenarios, respectively because of shift away from fossil fuels (including coal).

However, decarbonisation in the lowGHG scenario resulted in increased PM pollution between 2020 and 2045 due to increased fuel switching to biomass for residential heating. Depending on the geographic distribution of this biomass use, this trend could give rise to concerns over pollution exposure levels in urban areas and corresponding policy questions for local governments. This mid-term PM emissions increase was avoided with the inclusion of damage costs, as discussed in the next section.

The differences in NO_x emission levels in 2050 across scenarios were also notable, with an additional 25% (125 kt) and 18% (84 kt) reduction in emissions in the lowGHG compared to the base and ref cases. The most dramatic absolute reductions between scenarios in 2050 were seen for SO_x pollution levels. Overall, decarbonisation in the lowGHG scenario led to a 58% reduction (203 kt) in SO_x emissions compared to the base case. The difference between the lowGHG and ref scenarios was 100 kt in 2050. These results are displayed in Figure 3.

3.2 Scenarios that include damage costs

When including damage costs in the optimisation process, the model selected somewhat different technologies and fuels across all scenarios. Again, this is because the model explicitly sees the external costs of air pollution, which therefore becomes an economic determinant in energy system choices. For example, coal was replaced by natural gas for electricity generation, which resulted in decreasing emissions per unit of electricity generated. There was also a decrease in biomass switching in the residential sector in favour of natural gas, electricity and other renewables as indicated previously, showing the inherent air quality risks in decarbonisation pathways that rely heavily on bioenergy use.

Overall, for the base and ref scenarios, the inclusion of damage costs resulted in lower 2050 air pollution levels across all air pollutants as shown in Figure 4. This figure illustrates the impact of including damage costs for each scenario on emissions of PM_{10}, $PM_{2.5}$, NO_x, and SO_x. For SO_x, large reductions are realised in the base and ref scenarios due to the phase out of coal. However, in the lowGHG scenario, these reductions are already driven by the CO_2 constraint in this decarbonisation scenario. For NO_x, the impact of damage costs is less dramatic than with SO_x due particularly to effective NO_x control in new transport technologies.

For PM emissions, including damage costs led to reductions in emission levels in all sectors. In the lowGHG scenario, the inclusion of damage costs prevented fuel switching in residential heating technologies to biomass which, in turn, avoided the rise in PM pollution between 2020 and 2045 as shown in Figure 5 for PM_{10}.

The focus of the remainder of this section is on transport due to its significant role in PM_{10} air pollution through to 2050 as seen in Figure 5. For this sector, the inclusion of damage costs resulted in limited technology shifts. For the base scenario, we also observed decreasing emission trends from all forms of road transport, except for cars. For the ref and lowGHG scenarios, less dramatic technology shifts were observed, indicating that energy sector decarbonisation was the driving force behind the technology pathway chosen by the model.

With regards to road transport, total PM_{10} emissions declined slightly to 2020 across all scenarios and then slowly increased to 2050 to within 5% of 2010 levels as shown in Figure 6. A similar trend was seen with $PM_{2.5}$. These two outputs show the growing importance of non-tailpipe (i.e. road, tyre, and brake wear) particulate matter pollution that is directly a function of distance travelled and not of the type of fuel used. It also illustrates how increasing demand for road transport could slowly outstrip previous improvements in PM mitigation efforts through improvements to engine technology.

For NO_x pollution, non-tailpipe emissions are not a consideration and a distinct downward trend in total emissions was seen in all scenarios as more efficient and cleaner road transport technologies are adopted over time (as illustrated in Figure 6). Similarly, SO_x emissions from road transport decreased in 2050 compared to the base year, though less dramatically. Of note is that SO_x emissions in the transport sector are predominately produced by non-road transport (in particular, international shipping). As mentioned, there are no options for targeted SO_x abatement for these technologies in the UKTM-UCL model at this time. Non-GHG air pollution emissions over time for the lowGHG_DAMC scenario are displayed in Figure 6.

With regards to cars, the inclusion of damage cost accelerated the transition away from diesel vehicles to petrol and hybrid electric cars. This trend is shown in Figure 7 for the base and base_DAMC scenarios, as these scenarios isolate the impact of damage costs on this technology trend. For the base scenario, diesel vehicles are phased out completely by 2040 versus 2030 when damage costs are included.

While the inclusion of damage costs resulted in significant reductions in total pollution levels for non-GHG emissions, they did not dramatically impact total GHG emission levels in the scenarios considered here as shown in Figure 8. In particular, there was no noticeable difference in the pace of decarbonisation in lowGHG scenarios, though differences were observed in individual technology choices across the energy system. The only significant exception to this observation was found in the ref scenario, where damage costs noticeably accelerated energy sector decarbonisation between 2020 and 2035 – though 2050 GHG emission levels were essentially unaffected.

In summary, the impact on the decarbonisation pathway was not observed at the aggregate level but rather at the sectoral level, and in the specific low carbon technology and fuel choices that were made (e.g. less biomass use if damage costs are included). This is interesting because it implies that, while accounting for external costs of air quality pollution in climate policy analysis does not significantly impact carbon reduction levels, it does have an important bearing on the particular choices that are made in order to achieve these carbon reductions.

The changes in choices driven by the inclusion of damage costs have limited impact on costs, as shown in Figure 9. If the emissions tax component is removed (dark red), the actual additional costs of energy system expenditure are minimal (increases of 0.15% to 0.5%). In summary, the inclusion of the tax, which can be recycled back and therefore considered revenue neutral, results in large air pollution emission benefits as described earlier but with minimal impact on overall energy system costs. By far the largest emissions tax is raised in the transport sector (over 75%), reflecting both the size of this sector and the difficulty that exists in reducing these emissions further by energy-led interventions only.

5. Discussion & Conclusions

Across all scenarios, it is clear that climate policy has significant benefits for reducing air pollution emissions in the UK. Furthermore, the inclusion of air pollution damage costs in the optimisation process changed the mix of fuels and technologies selected by the model. These choices, for example, eliminated concerning trends in residential air pollution emission levels, showing the importance of simultaneously considering the impact of climate policy on efforts to reduce air pollution and vice versa. They can also support the UK’s continued efforts to meet National Emissions Ceiling Directive targets, which now include national emission "reduction commitments" applicable from 2020 and 2030 for SO_2, NO_x, NMVOC, NH_3, fine particulate matter ($PM_{2.5}$) and methane (CH_4).

That being said, this work showed that technoeconomic energy systems models can provide significant insight on PM, NO_x, and SO_x air pollution, but not NMVOC and NH_3 as the vast majority of emission sources for these pollutants are non-energy sectors and therefore not captured in UKTM-UCL. Furthermore, failure to consider non-GHG air pollution creates tension between decarbonisation, air pollution, and public health policies and could create mid-term air pollution challenges between 2025 – 2040. Considering damage costs in the decarbonisation pathway reduced particulate matter pollution from residential heating systems using biomass fuel 2025 and 2040.

These results suggest that the government should be particularly cautious with regards to supporting bioenergy use for local application in urban areas. In particular, incentives related to “renewable heat” could be problematic if they support increasing use of biomass in residential heating applications. In this work, increasing levels of biomass use for residential combined heat and power systems resulted in a spike in particulate matter air pollution in absence of targeted air pollution abatement technologies.

Particulate matter air pollution from transport was not significantly impacted by the inclusion of damage costs, indicating that targeted policies would be required to substantially reduce these emissions in the future, even if there were a move away from internal combustion engine vehicles. This is because non-tailpipe particulate matter air pollution increasingly dominated air pollution in road transport over time without policies to decrease total demand in this sector.

This results indicates that focused action is needed to target non-tailpipe emissions (i.e. from road, tyre and brake wear) of particulate matter. This action could include efforts to support mode shifting and other behavioural change that would reduce total demand for car use in order to avoid air pollution level rebounding over time resulting from increasing demand. Future work should also be undertaken to increase understanding of the impact of hybridization and energy-recovery (e.g. regenerative braking) in vehicles on non-tailpipe emission levels, which could be significant.

This framework and the resulting insights illustrate the importance of understanding the relationship between greenhouse gas and other air pollution emissions. The former is a growing concern and the latter is an immediate public health problem in the UK. Understanding the trade-offs and synergies between these two groups of air pollutants could be critical to effective policy design. Concerning climate policy, cost increases across the system are modest but result in the large co-impacts of air pollution reduction. Such insights are crucial for helping develop and deliver the low carbon agenda.

This work presented an analysis focusing on air pollution emissions. Additional insights would be gained through the analysis of the model's outputs in a detailed air quality model. This type of work is currently being undertaken in a collaborative project between authors on this manuscript and researchers at Kings College London.

Further improvements could be made by additional study of the likely emissions factors for new technologies as well as biofuel production. With the latter, the inclusion of emission factors greater than zero would reasonably impact the use of these fuels in scenarios where damage costs are considered. This approach did not include all air pollution abatement options, but in effect restricted responses to fuel switching and efficiency gains through technology turnover. Future work is needed in this area to combine work specifically on air quality abatement technologies and their incorporation in energy system optimisation models as well as end-of-pipe measures. This will be vital for better understanding the impacts of different air quality policy interventions on CO_2 emission reduction.

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Table(s)

Table 1: Air pollution inventory mapping between NAEI and UKTM

	Type of Air Pollution					
	NOx (as NO_2)	NMVOC	SOx (as SO_2)	NH_3	$PM_{2.5}$	PM_{10}
% of NAEI inventory mapped in UKTM	94%	15%	92%	5%	74%	58%

Table 2: Particulate matter emissions that were excluded from UKTM in the 2010 emissions calibration, by sector

Sector	**PM10**	**PM2.5**
Mining and quarrying	5%	1%
Iron and Steel process	3%	3%
Road Paving	3%	2%
Off road combustion	3%	4%
Waste open burning	1%	2%
Livestock	14%	4%
Crops	4%	1%
Fugitives (exploration and production of fossil fuels)	2%	2%
Other (including glass and other mineral products)	7%	7%
Excluded from UKTM	**42%**	**26%**

Table 3: Damage costs by sector and subsector (modified from DEFRA, 2013)[1]

Air Pollutant	**Sector**	**Annual Pulse Damage Costs (GBP per tonne - 2010 prices)**		
		Low	**High**	**Central**
PM	Electricity supplies industries (ESI)	£2,072	£3,007	£2,645
	Domestic	£24,029	£34,875	£30,690
	Agriculture	£8,287	£12,026	£10,583
	Industrial	£21,543	£31,267	£27,515
	Waste	£17,815	£25,856	£22,753
	Transport	£41,429	£60,129	£52,913
NO_x (as NO_2)	Electricity supplies industries (ESI)	£383	£1,533	£958
	Domestic	£4,444	£17,778	£11,111
	Agriculture	£1,532	£6,130	£3,832
	Industrial	£3,984	£15,938	£9,962
	Waste	£3,294	£13,180	£8,238
	Transport	£7,662	£30,651	£19,157
SO_x (as SO_2)	--	£1,439	£2,025	£1,781
NH_3	--	£1,678	£2,444	£2,151
NMVOCs	--	None	None	None

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[1] In the model implementation phase, damage cost values were adjusted over time with a 2% uplife to take into account willingness to pay.

Table 4: Scenario overview

Scenario Name	Carbon target/price?	Damage costs?
base	No	No
ref	Yes - £30/tonne in 2030	No
lowGHG	Yes – 80% reduction by 2050 with interim targets	No
base_DAMC	As above	Yes
ref_DAMC	As above	Yes
lowGHG_DAMC	As above	Yes

Figure(s)

Figure 1: TIMES Model Generic Structural Diagram (adapted from (Remme et al., 2001))

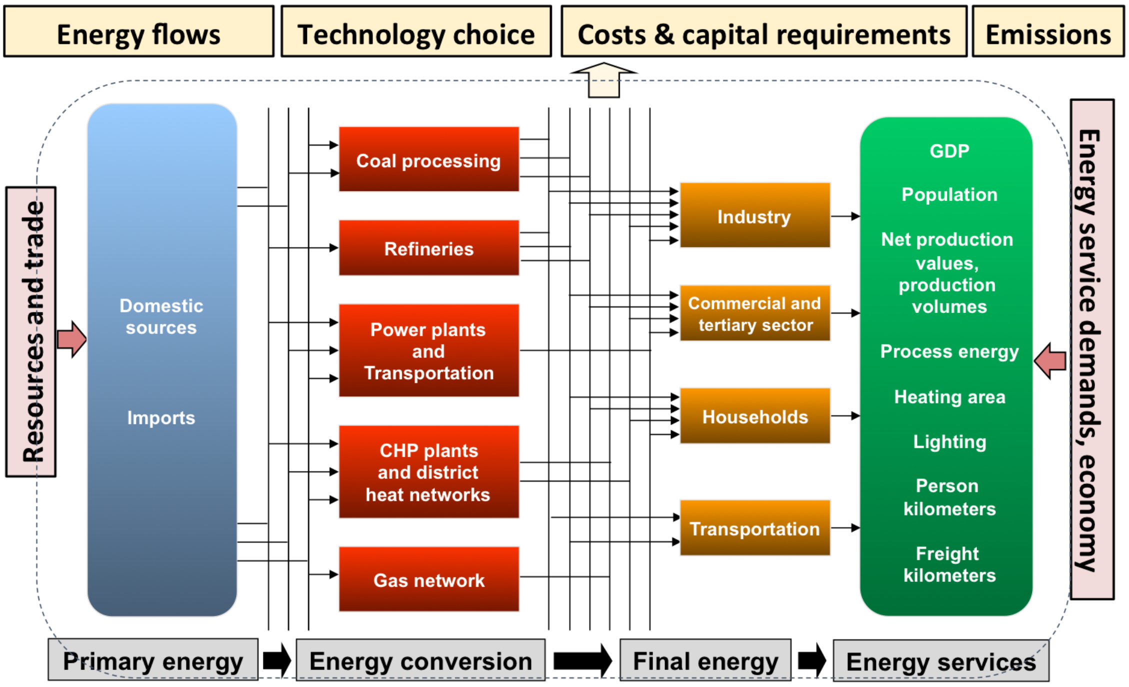


Figure 2: Primary energy consumption (PJ) in 2050 by scenario

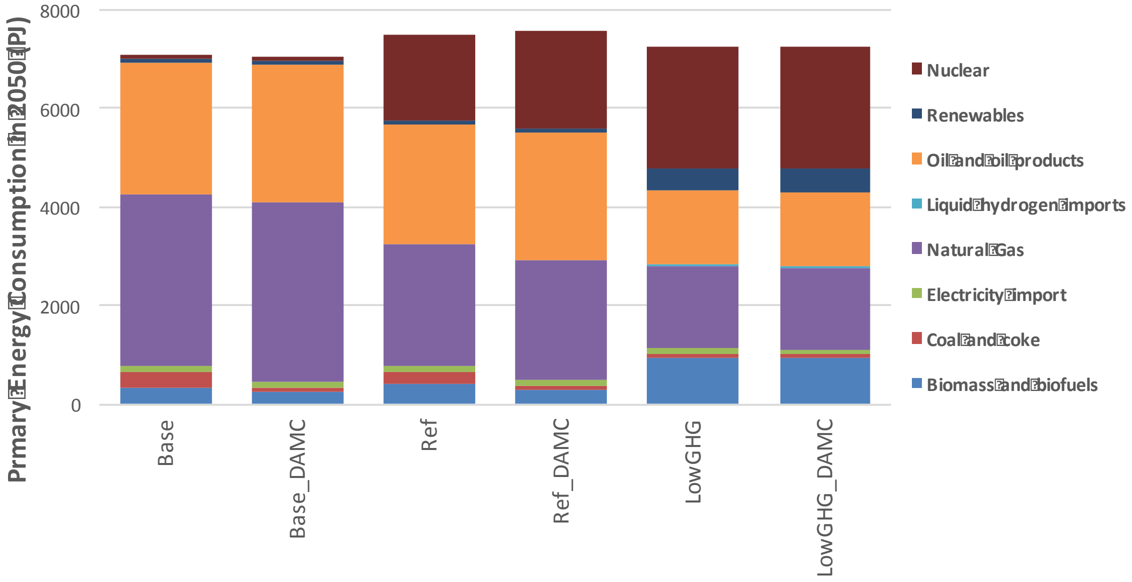


Figure 3: Total air pollution emissions by type in the UK for scenarios without damage costs, 2010-2050

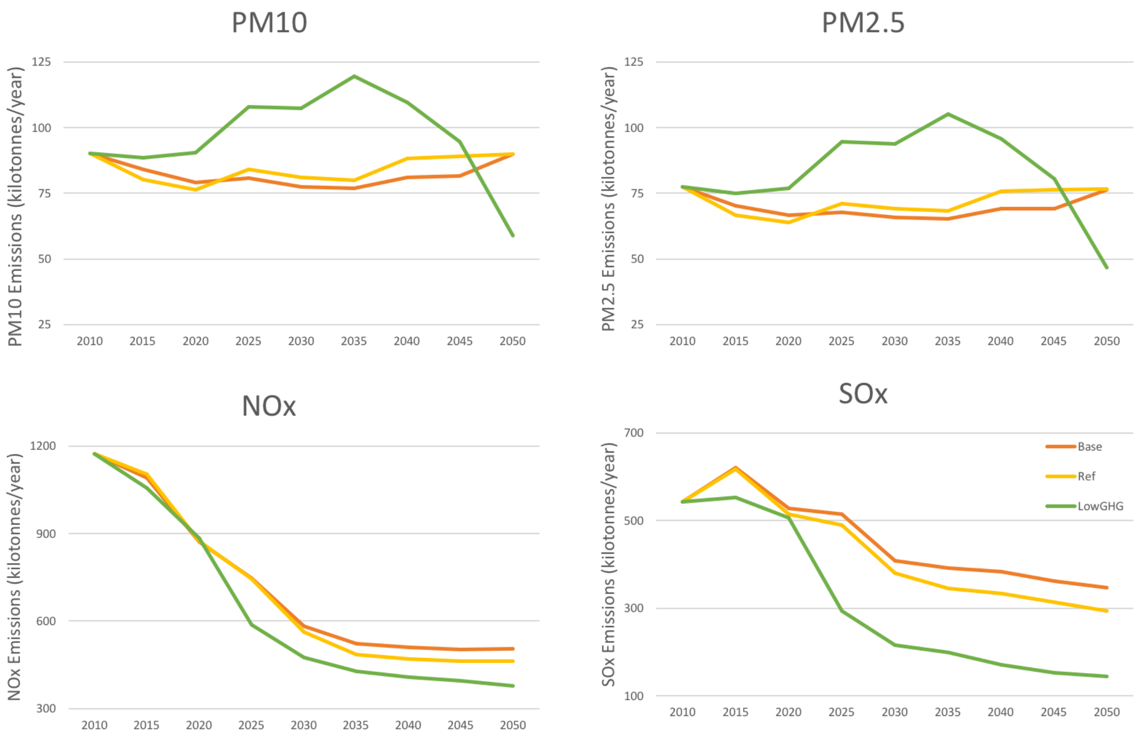


Figure 4: Air pollution levels in 2050 by scenario

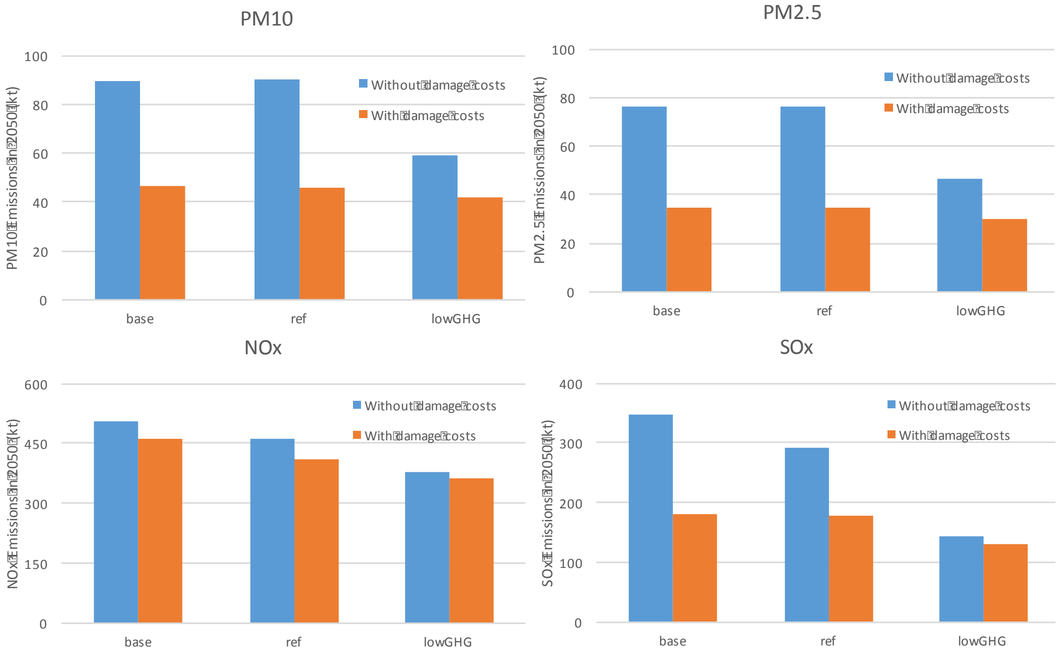


Figure 5: Total PM_{10} emissions from energy by sub-sector, 2010-2050

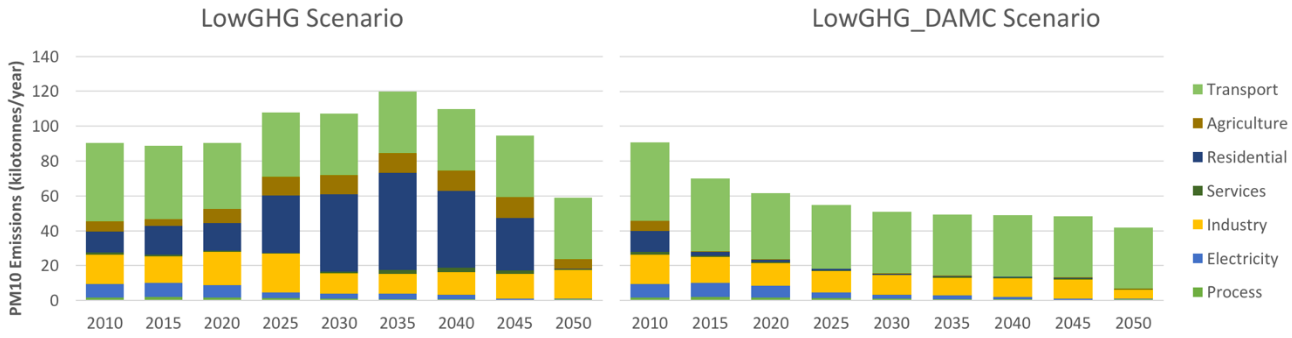


Figure 6: Total non-GHG air pollution emissions from road transport by technology for the lowGHG_DAMC scenario, 2010-2050

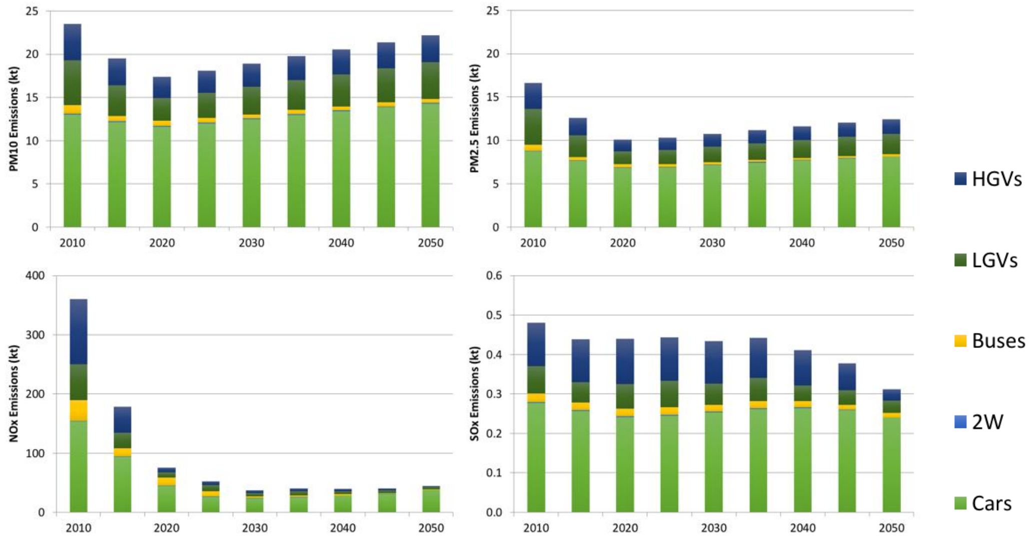


Figure 7: Transport demand by engine type (bvkm) for the Base and Base_DAMC scenarios

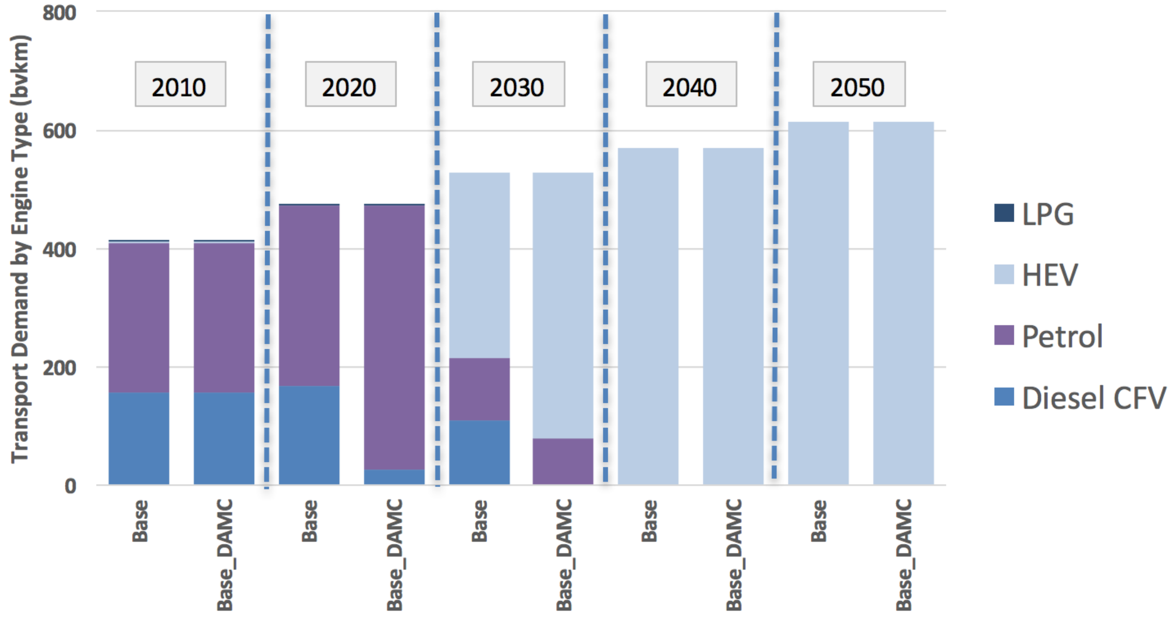


Figure 8: Total annual carbon dioxide equivalent emissions in the UK for six scenarios, 2010-2050

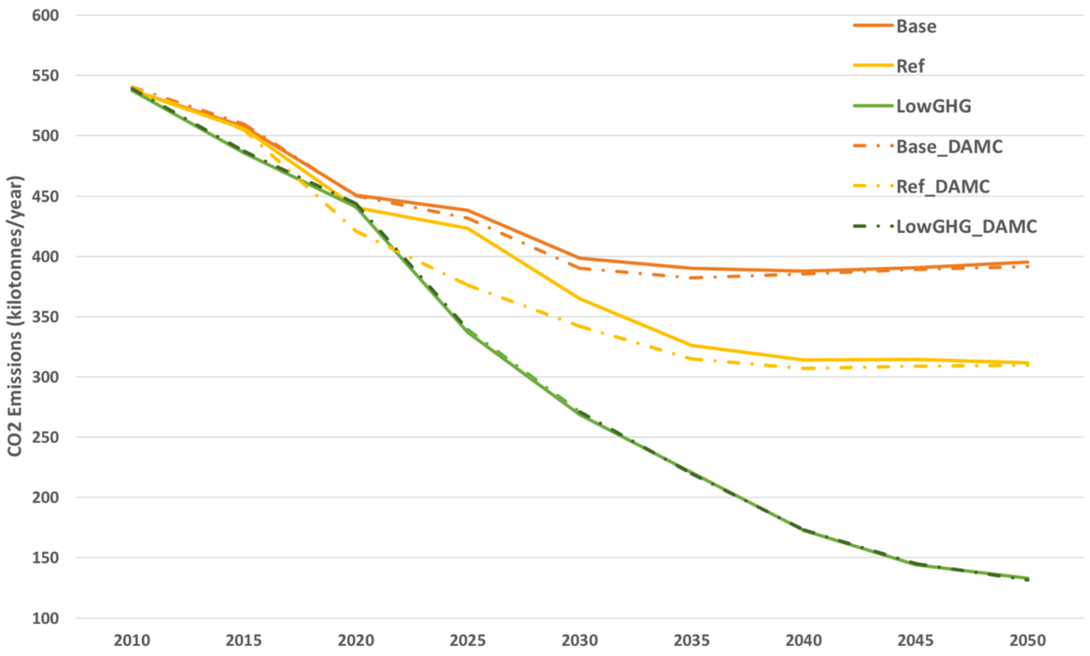
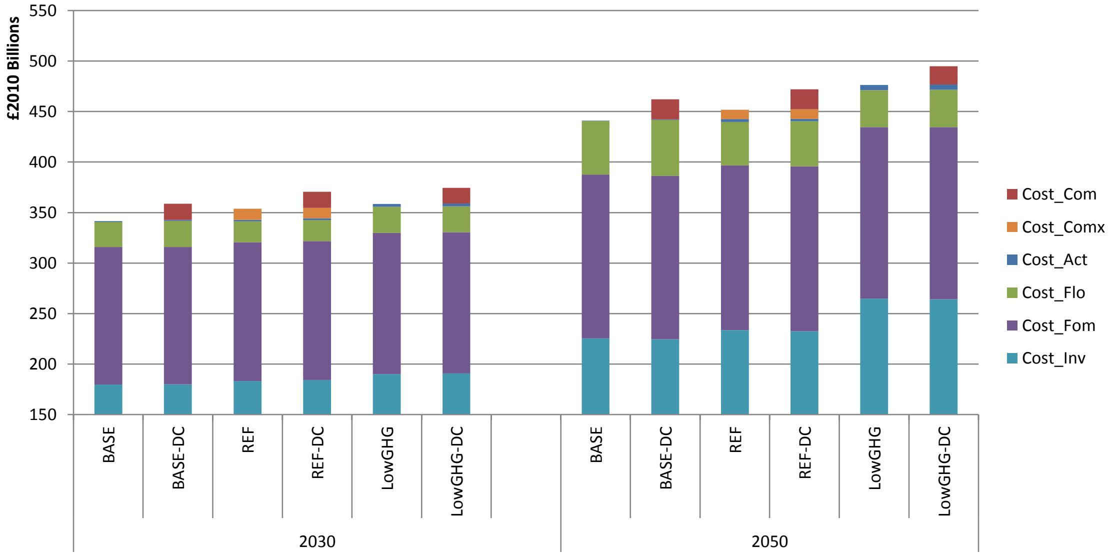


Figure 9: Overall System Costs (annual, undiscounted), including CO_2 or air pollution tax levels



Legend: investment costs, annualised (Cost_Inv); fixed operation and maintenance (Cost_Fom); energy/fuel (Cost_Flo); variable operation and maintenance (Cost_Act); CO2 tax/shadow price (Cost_Comx); air pollution damage costs (Cost_Com)