Health and environmental co-benefits and conflicts of actions to meet UK carbon targets

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Abstract

Many actions to reduce greenhouse gas emissions have wider impacts on health, the economy and the environment, beyond their role in mitigating climate change. These ancillary impacts can be positive (co-benefits) or negative (conflicts). This paper presents the first quantitative review of the wider impacts on health and the environment likely to arise from action to meet the UK's legally-binding carbon budgets.

Impacts were assessed for climate measures directed at power generation, energy use in buildings and industry, transport and agriculture. The study considered a wide range of health and environmental impacts including air pollution, noise, the upstream impacts of fuel extraction and the lifestyle benefits of active travel. It was not possible to quantify all impacts, but for those that were monetised the co-benefits of climate action (i.e. excluding climate benefits) significantly outweigh the negative impacts, with a net present value of more than £85 billion from 2008 to 2030. Substantial benefits arise from reduced congestion, pollution, noise and road accidents as a result of avoided journeys. There is also a large health benefit as a result of increased exercise from walking and cycling instead of driving. Awareness of these benefits could strengthen the case for more ambitious climate mitigation action.

Policy relevance

This paper demonstrates that actions to mitigate greenhouse gas emissions have significant wider benefits for health and the environment. Including these impacts in cost-benefit analysis would strengthen the case for the UK (and similar countries) to set ambitious emissions reduction targets. Understanding co-benefits and trade-offs will also improve coordination across policy areas and cut costs. In addition, co-benefits such as air quality improvements are often immediate and local, whereas climate benefits may occur on a longer timescale and mainly in a distant region, as well as being harder to demonstrate. Dissemination of the benefits, along with better anticipation of trade-offs, could therefore boost public support for climate action.

Keywords: co-benefits, health, external costs, climate change mitigation, energy technologies, transport policy.

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Introduction

Climate policy is typically evaluated in terms of the cost per tonne of greenhouse gas emissions avoided (the marginal abatement cost). However, this narrow approach ignores many important benefits and costs of climate mitigation policy, such as the health benefits of reduced air pollution, or the visual impacts of wind farms. Policy makers need to take these external costs and co-benefits into account to ensure an optimal outcome for society.

A growing body of research demonstrates that the co-benefits of climate policy are very significant, and can partly or fully offset the cost of climate mitigation (Nemet, Holloway and Meier, 2010). Various studies have estimated the benefits for human health from a reduction in local and regional air pollution (Bollen, Brink, Eerens and Manders, 2009; Bollen, Guay, Jamet and Corfee-Morlot, 2009) with some also including the impacts of acidification and eutrophication on eco-systems (EEA 2006; Holland, 2009; Holland, Amman et. al, 2011; Rafaj, Schöpp, Russ, Heyes, and Amman, 2013). Recent work has addressed the co-benefits from reducing short-lived greenhouse gases that also damage health and crops: black carbon, methane (an ozone precursor) and ozone (Shindell et al., 2012; UNEP, 2011; West et al., 2013; Wilkinson et al., 2009). Some researchers have also assessed energy security impacts (Bollen, Sebastiaan and van der Zwaan, 2010; McCollum et al., 2013; OECD, 2007).

The full range of potential impacts is even wider. For example, additional health and environmental effects include changes in biodiversity, abstraction and pollution of water, waste generation and physical and emotional wellbeing. Other economic effects include changes in fuel poverty, competitiveness and energy security (see Smith, 2013, for a comprehensive review).

This paper presents the first systematic, semi-quantitative review of the full range of health and environmental co-benefits and trade-offs likely to arise from actions to meet climate targets in the UK. As far as the authors are aware, this is the first study of this type in any country. The aim was to assess the impacts of a mitigation scenario aimed at meeting the UK's legally binding carbon targets. The work comprised a review and synthesis of existing data, with impacts being assessed qualitatively and, where possible, quantified and monetised. Full details are available in ApSimon and Oxley (2013) and Forster, Korkeala, Warmington, Holland and Smith (2013).

This study focuses on health and environmental impacts. Economic and social impacts on energy security, competitiveness and fuel poverty have been assessed in a parallel study (CCC, 2010, Chapter 8; CCC, 2013). Wider socio-economic impacts may also occur, including impacts on employment and trade: these have not been assessed.

Method

The climate policy scenario

The study assessed the impacts of measures proposed by the Committee on Climate Change (CCC), the UK statutory advisor on carbon budgets, in their Medium Abatement scenario, which represents the most cost-effective way in which the UK could meet its first four legislated carbon budgets for the period 2008-27 (Committee on Climate Change, 2010). The scenario assumes implementation by 2030 of the measures listed in Table 1. This was compared against a baseline scenario following UK government projections of demand, with the further assumption that additional demand for electricity was met by a 50:50 split of coal and gas-fired power stations (Figure 1).

Table 1: Measures included in the CCC's Medium Abatement scenario

Sector	Measures
Power	A large shift from coal and gas to nuclear and renewable (mainly wind) capacity, together with carbon capture and storage (CCS) (Figure 1)
Buildings and industry: heat supply	• Heat pumps: ground source (2.6 million units) and air source (4.5 million units) • Solar thermal heating (1 million units) • Biomass boilers (880,000 units in buildings; providing 5% of space heat and 25% of process heat in industry) and district heating (providing 2% of total heat in buildings) • Biogas heating (providing 4% of total heat in buildings and industry)
Residential buildings: energy use	• Fabric improvements: insulate 90% of available lofts (7.6 million above baseline) and cavity walls (4.6 million); insulate 40% of available solid walls (3.1 million); insulate floors (1.4 million) and pipework (0.8 million); improve glazing (new (0.8 million) or replacement (1.1 million) double glazing) • Improve air tightness in 2.1 million properties, including draught exclusion around windows and doors • Thermostatic heating controls (0.7 million units) • More efficient wet appliances (fridges, freezers) (13.5 million units) • More efficient electronic appliances (593 million units) • Behavioural measures: turning down the thermostat, turning off unnecessary lights, washing clothes at lower temperatures (saving 21TWh/y by 2030)
Non-residential buildings: energy use	Total savings of 36 TWh/y by 2030 from: • Heat efficiency: most efficient boiler; more efficient air conditioning; insulation and glazing • Heat management: programmable thermostats, reducing room temperature • Light and appliance management: sunrise-sunset timers, light detectors, computer management • Lights and appliances: more efficient lights, fridges, freezers,

	monitors • Process efficiency: compressed air, variable speed drives
Industry: energy use	Total savings of 34 TWh/y by 2030 from: • Process improvements including more efficient motors and other appliances, increased recycling of steel in electric arc furnaces, and improvements to refinery processes • CCS applied to industrial processes • Switch from cement and steel to wood for construction
Surface transport	• Increased penetration of electric vehicles (18% of car fleet by 2030), plug-in hybrids (42% of car fleet) and hydrogen fuel cell buses (23% of bus fleet) • Uptake of biofuels (11% of liquid fuel energy) • Increased efficiency of new vehicles (new car 80g CO_2/km by 2030) • 'Smarter choices' to reduce car vehicle kilometres by 5%: active travel (walking and cycling instead of driving); demand reduction through avoiding trips; and a shift from car use to public transport. It was assumed that each of the three sub-measures reduced car kilometres by 1.67%. • 7% of HGV vehicle kilometres saved through improved logistics • Eco-driving (4% of HGV fuel saved) and strict enforcement of the 70mph speed limit on motorways
Aviation	Aviation emissions return to 2005 levels by 2050, via: • Demand reduction: setting a carbon price, avoiding travel through video conferencing, modal shift to high speed rail and limiting air travel capacity; • Improvements to air traffic management and operations; • Improved engine & airframe efficiency; • Use of biofuels.
Shipping	Implementation of the Energy Efficiency Design Index (EEDI). Only the impact of speed reduction of ships was assessed; this is considered to be one of the most cost-effective measures available to meet the EEDI.
Agriculture and forestry	• Greenhouse gas emissions from the agriculture sector are reduced by 4.5 $MtCO_{2e}$ by 2020 (consistent with the UK Low Carbon Transition Plan (Department of Energy and Climate Change, 2009), scaled up from England to the UK) and by a further 5.45 $MtCO_{2e}$ by 2030, using an unspecified mix of the following measures: - Timing of fertiliser application - Avoiding excess fertiliser - Improved genetics in beef/dairy cattle - Improved fertility in dairy cattle - Use of propionate precursors in beef/dairy cattle feed - Use of maize silage for dairy cattle feed - Anaerobic digestion at poultry farms - Species introduction (nitrogen-efficient plants) - Anaerobic digestion at pig farms

	- Coverage of slurry tanks & lagoons at beef/dairy farms - Afforestation • In addition, 10,000 hectares per year of woodland are assumed to be created. • A further hypothetical scenario was assessed to investigate the impact of dietary change (reducing meat and dairy consumption). This was not part of the core Medium Abatement scenario, but was developed separately for the CCC (Audsley et al., 2011).

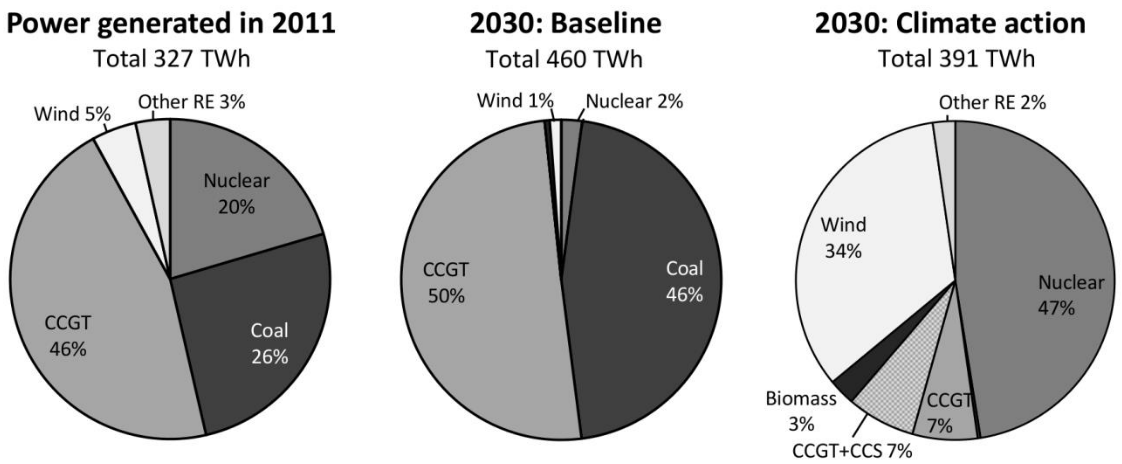

Figure 1: UK power generation in 2011 (left) and assumed scenarios for 2030 with climate action (centre) and without climate action (right)

Impacts considered

The method for identifying and quantifying impacts was based on UK government guidance for appraising policy impacts on human health (Department of Health, 2004) and the environment (Dunn, 2012). The impacts considered are:

- Diet
- Lifestyle (exercise)
- Psycho-social environment (e.g. stress, crime)
- Housing Conditions (e.g. cold, damp, indoor air quality)
- Air quality impact of SO_2, NOx, PM and NH_3 emissions (impact on health and ecosystems, including eutrophication, acidification and materials damage)
- Heavy metals and other trace pollutants
- Major accident risk
- Occupational health
- Road traffic accidents
- Congestion
- Noise
- Waste generation (hazardous and non-hazardous)
- Water pollution (impact on human health and ecosystems)

- Water abstraction
- Landscape
- Land take
- Biodiversity and ecosystems (impacts not covered elsewhere, e.g. habitat loss)
- Soil erosion/fertility
- Subsidence
- Geophysical factors (e.g. ultraviolet light, radiation)
- Infection
- Resource use (metals/minerals)

Impacts cover the full lifecycle of each measure, including, for example, fuel extraction, equipment manufacture, installation, heat or power generation, transport, decommissioning and waste disposal.

Assessment of impacts

All measures were first assessed qualitatively to determine the associated impacts, based on a literature review and expert judgement. Where possible, the costs or benefits were then quantified and monetised. The literature review was carried out in February 2013, including a search of both academic and grey literature for papers on "co[-]benefit(s)" or "trade-off(s)" and "climate", followed by a search on specific topics, e.g. oil spills or active travel, as necessary. Although the literature on co-benefits is extensive, few papers contain quantified estimates for impacts other than air quality. This resulted in a reliance on a small number of studies, some of which are quite old, and there is therefore a high level of uncertainty attached to some estimates. This study should not therefore be considered as a comprehensive quantitative review, but as a scoping study that indicates the relative magnitude of different impacts and serves as a useful starting point for future work. The main data sources used to generate quantitative estimates are summarised in Table 2.

Table 2: Main data sources used to generate quantitative estimates

Sector	Main impacts quantified	Main data sources
All sectors: air pollution	Air pollution: SO_2, NO_x, NH_3, PM10	IGCB (2008)
Power	Accidents, occupational health, noise, water use, waste	General: Berry et al. (1998); Dones et al. (2004); ExternE (1995, 1998); Morris and Camino (2011) Nuclear: DTI (2006); ORNL/RFF (1995)
Buildings and industry	Noise reduction from double glazing	Department for the Environment, Food and Rural Affairs (2013)
Surface transport	Congestion	Cars: Department for Transport (2012a) Ratio of bus and HGV to car: CE Delft (2011)
	Road accidents: *Demand reduction; modal shift*	Cars: Department for Transport (2012a) Ratio of bus and HGV to car: CE Delft (2011).
	Switch to walking and cycling	Woodcock et al. (2009)
	Heavy metal pollution	CE Delft (2011)

	Habitat loss	CE Delft (2011)
	Noise: *Electric vehicles* *Other vehicles*	 Department for the Environment, Food and Rural Affairs (2013) CE Delft (2011)
	Lifestyle benefits of exercise	Woodcock et al. (2009)
Agriculture and forestry	Health benefits of reduced consumption of meat and dairy produce	Friel et al. (2009); Rohrman et al. (2013)
Upstream fuel production	Accidents, pollution, occupational health	ExternE (1995, 1998); Dones et al. (2004); Berry et al. (1998); Eckle, Burgherr and Edouard Michaux (2012); Cohen (2010)

The impacts of air pollution on human health, crops and materials were assessed by calculating the change in emissions of fine particles ($PM_{2.5}$ and PM_{10}), sulphur dioxide (SO_2) and nitrogen oxides (NOx) for each measure, and then applying standard damage costs per tonne of pollutant following UK government guidance (IGCB, 2008).

For other impacts, costs or benefits per functional unit (e.g. per kWh of heat or power generated or saved, or km travelled) were estimated. The total impact for each measure was then calculated by multiplying the impact per functional unit by the change in functional unit as a result of the implementation of that measure in the abatement scenario, to generate a cost or benefit for each year.

Results were expressed as the net present value of the stream of costs or benefits over the scenario period (2012 to 2030 for the power sector, 2008 to 2030 for other sectors), using a discount rate of 3.5%/yr. For nuclear power impacts a discount rate of 3% has been applied, as this was the rate used in the primary literature and there was insufficient information to recalculate. The resulting inconsistency has little effect relative to the uncertainties of modelling the long-term impacts of nuclear power.

For effects that were assessed only qualitatively, consideration was given to whether the change in activity within the scenario was sufficient for an impact to be highlighted as ‘significant’.

Thus for the power sector, the change in kWh of power generated by each power generation technology in each year was defined relative to the baseline scenario. The cost or benefit for each impact in each year was then calculated by multiplying the change in power generated by the external cost per kWh.

For the transport sector, the impact in each year was estimated by multiplying the impact per vehicle kilometre by the change in vehicle kilometres. Estimates of the health and accident impacts of active travel in terms of disability-adjusted life-years (DALYs) per avoided car km were derived from Woodcock et al. (2009), with DALYs valued at £50,198 according to published UK government guidance (IGCB, 2008, converted to 2012 GBP). The noise benefits of electric vehicles were assessed using an updated but unpublished UK government value of £60,000 for a DALY. Other impacts were mainly based on figures from CE Delft (2011) which were expressed in euros/km, so it was not possible to determine an equivalent DALY value.

For buildings and industry, the total change in fuel use in the CCC abatement scenario was calculated (taking account of both energy savings and changes in the fuel mix) and used to derive estimates of air quality and fuel extraction impacts. Noise impacts were also estimated for installation of double glazing in buildings. It was assumed that moving from single to double glazing might reduce inside noise levels by up to 10dB, and that replacing old double glazing with new could deliver a maximum reduction of 5dB.

For agriculture and forestry, the assessment was mainly qualitative. However, the health and air quality benefits of an additional dietary change scenario were estimated. Although not in the CCC core scenario, this was an additional option considered explicitly by the CCC in its analysis for the 4th carbon budget, which assumed a 50% reduction in the consumption of animal products in the UK, to be replaced by plant-based food products (Audsley et al., 2011). For air quality, the impact of reduced ammonia emissions on ecosystems was estimated and health impacts of secondary PM formation monetised. For dietary impacts, an estimate was based on Friel et al. (2009), which modelled the impact of a 30% reduction in intake of saturated fats from animal products. Impacts were scaled by a factor of 50/30 to account for the difference in animal product consumption between the two scenarios. This may over-estimate the benefits, as the impacts are not necessarily linear. Friel et al. used two different calculation methods: the mid-point of these results was taken, using a DALY value of £50,198 (see above).

Caveats and uncertainties

1. This research is based on a review and evaluation of existing literature. There are significant data gaps. Some of the sources used are now dated and others may be of questionable relevance to the UK. Even for those sectors where quantitative estimates have been derived, there remain a number of effects that could only be assessed in qualitative terms. Totals for quantified values should therefore be used with caution, as in most cases they are likely to omit certain important impacts (italicised in table 3).

2. There is considerable uncertainty involved in quantifying environmental impacts and in ascribing monetary values to those impacts. Figure 2 illustrates the sensitivity of our estimates to assumptions on air quality and dietary health impacts and the value of a DALY.

3. For some impacts quantification has been undertaken for some technologies but not for others. For example, life cycle analysis for wind power includes estimates of heavy metal emissions, yet these were not accounted for in the analysis of coal-fired generation, where emissions are likely to be greater (though the impacts of other pollutants dominate in both cases).

4. The nuclear fuel chain provides some particular challenges:

    - The potential for major accidents that combine large consequence with very low probability

- High level wastes that will remain hazardous for over 100,000 years
- Risks of nuclear proliferation and aggressive use of radioactive substances (excluded due to lack of data)

Any positive discount rate will result in long term effects such as the effects of nuclear waste disposal or nuclear accidents being evaluated as effectively zero. Therefore, the damage estimates for nuclear should be treated with great caution. To assess sensitivity, the impacts of nuclear waste disposal were also estimated using a discount rate of zero (see Table 9 comments).

5. Efforts were made to account only for those impacts external to the resource costs. However, some impacts might be partly internalised, for example through the payment of fines and compensation for accidents such as oil spills.

Results

Qualitative assessment of impacts

Table 3 presents a summary of the main impacts that have been assessed as significant. Impacts where no quantification was possible are shown in italics.

Quantitative assessment of impacts

A breakdown of the main quantified impacts and associated damage costs is presented in tables 4 (air pollution), 5 (other transport impacts) and 6 (dietary change).

Table 3: Main external health and environmental impacts of the CCC's Medium Abatement Scenario. Those that have not been quantified are shown in italics. Other impacts have been at least partially quantified.

	Negative impacts (costs)	Positive impacts (benefits)	Mixed or uncertain impacts (costs or benefits)
Power	• Risk of major accidents at nuclear power plants • Risks associated with nuclear waste management, uranium mining and fuel processing • *Landscape impacts of dispersed renewable technologies* • *Impacts of additional fuel production, solvent production and waste generation for Carbon Capture and Storage* • *Risks of nuclear proliferation*	• Air quality benefits of a switch from fossil fuels to nuclear and renewables for health • *Air quality benefits for the environment: acidification, eutrophication, eco-toxicity (this is also an unquantified benefit for the other sectors, below)* • Benefits from avoided coal and gas production from switch to renewables and nuclear- see 'upstream fuel production', below	
Road transport	• Potential road accident increase from walking and cycling if extra safety measures not implemented • Upstream impacts of increased electricity production for electric vehicles	• Health (exercise) benefits of active transport • Congestion benefits of smarter choices and HGV logistics • Road accident benefits of demand reduction and HGV logistics • Air quality and noise benefits of electric vehicles, hydrogen buses, smarter choices and improved HGV logistics • Benefits of avoided oil production - see 'upstream fuel production', below • *Road accident and congestion benefits of speed limiting* • *Air quality and noise benefits of hybrid cars and vans, efficient vehicles, speed limiting and eco-driving*	

	Negative impacts (costs)	Positive impacts (benefits)	Mixed or uncertain impacts (costs or benefits)
Aviation and shipping		• *Noise reduction from improved efficiency in aviation* • *Air quality impacts around airports* • *Air quality and wildlife impacts of limiting shipping speeds* • *Benefits from avoided oil production - see 'upstream fuel production', below*	
Heat	• Possible air quality impact of switching from gas to biomass • Upstream impact of increased electricity production for heat pumps	• Air quality benefits from switching from fossil fuels to solar heating and heat pumps • *Benefits of biogas and biomass from waste in avoiding the costs and impacts of waste disposal (land take, odour, emissions etc)* • Benefits from avoided fossil fuel production - see 'upstream fuel production', below	• *Biodiversity, landscape and soil fertility impacts of energy crops*
Domestic, non-residential and industrial energy use	• *Impacts of additional fuel production, solvent production and waste generation for CCS in industry*	• Air quality benefits of avoided fuel combustion from energy efficiency and behaviour change • *Health and social benefits of improved insulation etc in housing* • Benefits from avoided fossil fuel production from energy efficiency and behaviour change - see 'upstream fuel production', below • Benefits of more efficient industrial processes: reduced waste, noise, heat and vibration.	
Agriculture and forestry		• Human health benefits of dietary change (very large benefit) • *Land take benefits from dietary change* • *Water quality benefits (e.g. from more efficient fertiliser application and dietary change)* • *Air pollution benefits (e.g. from anaerobic digestion, dietary change, reduced fertiliser use)*	• *Biodiversity, land and water impacts of afforestation*

	Negative impacts (costs)	Positive impacts (benefits)	Mixed or uncertain impacts (costs or benefits)
Upstream fuel production	**(most measures result in a reduction of these impacts, with the exception of land take for biofuels)** • Occupational health in coal mining, oil production, etc. • Major accidents from coal mining, oil and gas extraction (including oil spills) • Air pollutant emissions from oil and gas extraction and processing • Greenhouse gas emissions • *Land take for biofuel production*		

Table 4. Main quantified external health and environmental impacts of the CCC's Medium Abatement scenario relative to the baseline during the use stage. Values presented as Net Present Value over the scenario period (£$_{2012}$, million), annual cost in 2030 in brackets.

	Power	Road transport	Industry	Heat	Residential buildings	Non-residential buildings	Agriculture	Comment
Diet							*162,516 (11,258)*	* Reduced fat intake from halving consumption of meat and dairy produce (not part of core scenario)
Lifestyle		26,101 (2,548)						* Increased walking & cycling in place of car journeys
Major accident risk	-56 (-16)							* Increase in nuclear power
Occupational health	-208 (-31)							* Increase in offshore and onshore wind, and also nuclear power
Road Accidents		1,531 (231)						* Smarter choices & HGV logistics reduce accident rates * Small increase in accidents from more walking & cycling (can be mitigated)

	Power	**Road transport**	**Industry**	**Heat**	**Residential buildings**	**Non-residential buildings**	**Agriculture**	**Comment**
Air quality (based on PM10)	2,275 (466)	600 (106)	869 (134)	1,114 (297)	642 (78)	138 (14)		* Energy saving and shift to renewables and nuclear cut fossil fuel emissions from power generation and buildings * Smarter choices and HGV logistics reduce vehicle km * Electric vehicles, hydrogen buses reduce emissions intensity
Noise	86 (22)	947 (148)			4,905 (383)			* Electric vehicles and smarter choices reduce noise levels from traffic * Glazing measures reduce exposure to noise
Heavy metals	40 (8)	144 (34)						* Smarter choices and HGV logistics reduce vehicle km * Electric vehicles, hydrogen buses reduce emissions intensity
Water abstraction	565 (122)							*Less coal and gas-fired power generation cuts water use
Biodiversity and ecosystems		210 (27)						* Smarter choices and HGV logistics reduce vehicle km, and reduce habitat loss and fragmentation
Congestion		48,450 (8,423)						* Smarter choices and HGV logistics reduce vehicle km and associated congestion
Total for quantified impacts, use phase	**2,702**	**77,984**	**869**	**1,114**	**5,547**	**138**	***162,516***	*Interpret with caution: coverage incomplete

Notes: Coverage is not complete, even within sectors. See Table 7 for a list of omitted impacts. Totals should be interpreted with caution because many significant impacts are not quantified. No quantitative estimates have been derived for the aviation and shipping sectors.

Air quality estimates are presented using a damage cost for particulates referenced against PM10, and NPV is calculated over the period 2010 to 2030.

For other impacts, NPV is calculated over the period 2008-2030 except for the power sector where it is 2012-2030.

Discount rate is 3.5% except for nuclear where it is 3%, as there was insufficient information to re-calculate from the data source.

Table 5. Main quantified external health and environmental impacts of the CCC's Medium Abatement scenario relative to the baseline during the other life-cycle stages. Values presented as Net Present Value over the scenario period (£$_{2012}$, million), annual cost in 2030 in brackets

	Power	**Road transport**	**Industry**	**Heat**	**Residential buildings**	**Non-residential buildings**	***Agri-culture***	**Comment**
Major accident risk	1121 (193)	1 (0.1)	21 (3)	31 (4)	7 (1)	2 (0.2)		* Reduction in coal power means lower risk of coal mining accidents
Occupational health	47 (11)	13 (1)	12 (1)	101 (16)	27 (3)	15 (1)		* Increase in occupational health risk from nuclear, wind and CCS is more than offset by decrease in risk from coal * Switch from fossil fuels in end-use sectors reduces risk from coal and oil
Road Accidents	-129 (-17)							* INCOMPLETE. Increase in wind drives increases in cost, but accidents not quantified for other power technologies
Air quality (based on PM2.5)	-1,008 (-148)	50 (5)	10 (1)	151 (25)	46 (2)	26 (2)		* Biomass, wind and nuclear all increase the relative air quality emissions associated with the supply chain. Potential benefit from reduced coal and gas generation not quantified. * Switch from fossil fuels in end-use sectors reduces pollution from coal and oil
Noise	30 (5)		1	1				* Reduction in coal use decreases noise from mining and coal transport
Hazardous waste/nuclear	-3 (-1)							* Increase in hazardous waste from nuclear. At zero discount rate this would increase to -£10,154 million.
Hazardous waste/other	-11 (-1)	4 (0.4)	1	13 (2)	2 (0.2)	2 (2)		* Decrease in oil use in end use sectors reduces hazardous waste generation * For power sector, only manufacture of solar PV panels quantified. Potential benefit from reduced coal-fired power generation not quantified.
Heavy metals	-65							* INCOMPLETE: power sector estimate includes increase in emissions from supply of wind farm components but not emissions from other power technologies, which could not be quantified
Total for quantified impacts, other life cycle phase	**-18**	**69**	**45**	**297**	**81**	**46**		*Interpret with caution: coverage incomplete

	Power	Road transport	Industry	Heat	Residential buildings	Non-residential buildings	*Agri-culture*	Comment
Total quantified effects for the sector	**2,683**	**78,052**	**914**	**1,411**	**5,629**	**184**	***162,516***	*Interpret with caution: coverage incomplete

Notes: Coverage is not complete, even within sectors. See Table 7 for a list of omitted impacts. Totals should be interpreted with caution because many significant impacts are not quantified. No quantitative estimates have been derived for the aviation and shipping sectors.

Air quality estimates are presented using a damage cost for particulates referenced against PM2.5, and NPV is calculated over the period 2010 to 2030.

For other impacts, NPV is calculated over the period 2008-2030 except for the power sector where it is 2012-2030.

Discount rate is 3.5% except for nuclear where it is 3%, as there was insufficient information to re-calculate from the data source.

Table 6: Quantified impacts and damage costs for additional dietary change scenario

	2010	2030	NPV 2008-2030
UK population, thousands	62,735	71,766	
Original data: 30% decrease in saturated fats			
Method 1: DALYs saved (2850/million population)	178795	204532	
Value of DALYs saved, £M 2012	8975	10267	**148,214**
Method 2: DALYs saved (900/million population)	56462	64589	
Value of DALYs saved, £M 2012	2834	3242	**46,804**
Mid estimate of two models - value of DALYs saved, £M 2012	**5905**	**6755**	**97,509**
Data extrapolated linearly for a 50% decrease in saturated fats			
Method 1: DALYs saved	297992	340887	
Value of DALYs saved, £M 2012	14959	17112	**247,024**
Method 2: DALYs saved	94103	107648	
Value of DALYs saved, £M 2012	4724	5404	**78,007**
Mid estimate of two models - value of DALYs saved, £M 2012	**9841**	**11258**	**162,516**

Damage costs or benefits for all sectors are summarised in tables 8 and 9. As noted above, not all impacts could be quantified. The 'totals' presented in these tables thus omit a number of potentially significant impacts (italicised in table 3).

To simplify presentation, impacts are separated into two categories (Table 7): those occurring during the 'use' phase (Table 8), and those occurring during upstream and downstream lifecycle stages, such as fuel extraction and waste disposal (Table 9). For the transport, industry and buildings sectors, electricity use was defined as an upstream process whereas on-site or in-vehicle fuel combustion falls within the 'use' phase.

Table 7: Examples of impacts occurring during use phase and other lifecycle stages

Sector	Use phase	Other lifecycle stages
Power	• Direct emissions from power generation • Landscape impacts of wind turbines • Accidents during power station operation (e.g. nuclear accidents) • Noise from power station operation	• Upstream impacts of fuel extraction (e.g. coal mining and gas rig accidents, water pollution from coal mines, emissions from gas flaring, landscape impacts of opencast coal mines, impacts of uranium mining and processing, pollution from fertilisers used in biofuel production) • Noise, congestion, accidents and pollution from fuel transport and distribution (e.g. methane leaks from gas pipelines, oil tanker accidents, rail noise from coal transport) • Impacts of material extraction for operation or construction phases (e.g. metal mining and processing for power station or wind turbine components; limestone quarrying for flue gas desulphurisation (FGD)) • Impacts of equipment

		manufacturing (e.g. pollution from solar panel factories) • Impacts of waste disposal (coal ash, FGD waste, nuclear waste, used solvent from CCS)
Buildings and industry: heat supply	• Direct emissions from heat production (boilers, furnaces) • Noise and accidents from boiler and furnace operation	• Upstream impacts from fuel production (as above) • Emissions from equipment manufacture • Impacts of waste disposal
Buildings and industry: energy use	• Avoided direct emissions from heat generation in boilers and domestic fires due to energy savings • Improved living conditions due to insulation and air tightness (warmer, quieter) • Risk of health impacts if air tightness measures result in inadequate ventilation	• Avoided upstream impacts from fuel production due to heat savings (as above) • Avoided power production impacts due to electricity savings • Emissions from equipment manufacturing (e.g. insulation)
Surface transport and aviation/shipping	• Direct emissions from vehicle operation • Noise, congestion and accidents from vehicle operation • Health benefits from switch to active travel	• Upstream impacts (or avoided impacts) from fuel production and distribution (oil spills, power generation for electric vehicles, etc, as above) • Resource use for vehicle manufacture (metals, plastics etc) • End-of-life vehicle disposal • Infrastructure impacts of roads, car parks etc: habitat fragmentation, landscape impacts
Agriculture/forestry	• Emissions and water pollution from fertiliser application • Emissions from livestock • Water use during agriculture • Landscape, land take, recreational and biodiversity impacts of farmland or forests • Health impacts of diet change	

Table 8. **Main quantified external health and environmental impacts of the CCC's Medium Abatement scenario relative to the baseline during the use stage. Values presented as Net Present Value over the scenario period (£$_{2012}$, million), annual cost in 2030 in brackets.**

	Power	**Surface transport**	**Industry: energy use**	**Buildings and industry: heat supply**	**Residential buildings: energy use**	**Non-residential buildings: energy use**	**Agriculture**	**Comment**
Diet							*162,516 (11,258)*	* Reduced fat intake from halving consumption of meat and dairy produce (not part of core scenario)
Lifestyle		26,101 (2,548)						* Increased walking & cycling in place of car journeys
Major accident risk	-56 (-16)							* Increase in nuclear power
Occupational health	-208 (-31)							* Increase in offshore and onshore wind, and also nuclear power
Road Accidents		1,531 (231)						* Smarter choices & HGV logistics reduce accident rates * Small increase in accidents from more walking & cycling (can be mitigated)
Air quality (based on PM10)	2,275 (466)	600 (106)	869 (134)	1,114 (297)	642 (78)	138 (14)		* Energy saving and shift to renewables and nuclear cut fossil fuel emissions from power generation and buildings * Smarter choices and HGV logistics reduce vehicle km * Electric vehicles, hydrogen buses reduce emissions intensity
Noise	86 (22)	947 (148)			4,905 (383)			* Electric vehicles and smarter choices reduce noise levels from traffic * Glazing measures reduce exposure to noise

	Power	Surface transport	Industry: energy use	Buildings and industry: heat supply	Residential buildings: energy use	Non-residential buildings: energy use	Agriculture	Comment
Heavy metals	40 (8)	144 (34)						* Smarter choices and HGV logistics reduce vehicle km * Electric vehicles, hydrogen buses reduce emissions intensity
Water abstraction	565 (122)							*Less coal and gas-fired power generation cuts water use
Biodiversity and ecosystems		210 (27)						* Smarter choices and HGV logistics reduce vehicle km, and reduce habitat loss and fragmentation
Congestion		48,450 (8,423)						* Smarter choices and HGV logistics reduce vehicle km and associated congestion
Total for quantified impacts, use phase	**2,702**	**77,984**	**869**	**1,114**	**5,547**	**138**	***162,516***	*Interpret with caution: coverage incomplete

Notes: Coverage is not complete, even within sectors. See Table 7 for a list of omitted impacts. Totals should be interpreted with caution because many significant impacts are not quantified. No quantitative estimates have been derived for the aviation and shipping sectors.

Air quality estimates are presented using a damage cost for particulates referenced against PM10, and NPV is calculated over the period 2010 to 2030. For other impacts, NPV is calculated over the period 2008-2030 except for the power sector where it is 2012-2030.

Discount rate is 3.5% except for nuclear where it is 3%, as there was insufficient information to re-calculate from the data source.

Table 9. Main quantified external health and environmental impacts of the CCC's Medium Abatement scenario relative to the baseline during the other life-cycle stages. Values presented as Net Present Value over the scenario period (£$_{2012}$, million), annual cost in 2030 in brackets

	Power	**Surface transport**	**Industry: energy use**	**Buildings and industry: heat supply**	**Residential buildings: energy use**	**Non-residential buildings: energy use**	***Agri-culture***	**Comment**
Major accident risk	1121 (193)	1 (0.1)	21 (3)	31 (4)	7 (1)	2 (0.2)		* Reduction in coal power means lower risk of coal mining accidents
Occupational health	47 (11)	13 (1)	12 (1)	101 (16)	27 (3)	15 (1)		* Increase in occupational health risk from nuclear, wind and CCS is more than offset by decrease in risk from coal * Switch from fossil fuels in end-use sectors reduces risk from coal and oil
Road Accidents	-129 (-17)							* INCOMPLETE. Increase in wind drives increases in cost, but accidents not quantified for other power technologies
Air quality (based on PM2.5)	-1,008 (-148)	50 (5)	10 (1)	151 (25)	46 (2)	26 (2)		* Biomass, wind and nuclear all increase the relative air quality emissions associated with the supply chain. Potential benefit from reduced coal and gas generation not quantified. * Switch from fossil fuels in end-use sectors reduces pollution from coal and oil
Noise	30 (5)		1	1				* Reduction in coal use decreases noise from mining and coal transport
Hazardous waste/nuclear	-3 (-1)							* Increase in hazardous waste from nuclear. At zero discount rate this would increase to -£10,154 million.
Hazardous waste/other	-11 (-1)	4 (0.4)	1	13 (2)	2 (0.2)	2 (2)		* Decrease in oil use in end use sectors reduces hazardous waste generation * For power sector, only manufacture of solar PV panels quantified. Potential benefit from reduced coal-fired power generation not quantified.
Heavy metals	-65							* INCOMPLETE: power sector estimate includes increase in emissions from supply of wind farm

	Power	**Surface transport**	**Industry: energy use**	**Buildings and industry: heat supply**	**Residential buildings: energy use**	**Non-residential buildings: energy use**	***Agri-culture***	**Comment**
								components but not emissions from other power technologies, which could not be quantified
Total for quantified impacts, other life cycle phase	**-18**	**69**	**45**	**297**	**81**	**46**		*Interpret with caution: coverage incomplete
Total quantified effects for the sector	**2,683**	**78,052**	**914**	**1,411**	**5,629**	**184**	***162,516***	*Interpret with caution: coverage incomplete

Notes: Coverage is not complete, even within sectors. See Table 7 for a list of omitted impacts. Totals should be interpreted with caution because many significant impacts are not quantified. No quantitative estimates have been derived for the aviation and shipping sectors.
Air quality estimates are presented using a damage cost for particulates referenced against PM2.5, and NPV is calculated over the period 2010 to 2030.
For other impacts, NPV is calculated over the period 2008-2030 except for the power sector where it is 2012-2030.
Discount rate is 3.5% except for nuclear where it is 3%, as there was insufficient information to re-calculate from the data source.

Discussion by sector

Power

The main co-benefits of the abatement scenario are related to air quality improvements arising from the switch from coal, and to a lesser extent gas, to nuclear and renewables. Set against this is an increase in the risk of nuclear accidents and the impacts of nuclear fuel production and waste disposal, together with landscape impacts from increased deployment of onshore wind power.

The difficulties in assessing nuclear power impacts have been noted above. To illustrate one problem, the impacts of nuclear waste disposal over the scenario period were estimated to exceed £10,000 million before discounting, yet discounting at a rate of 3% reduces these impacts to just £3 million. It has also not been possible to quantify visual impacts of renewable technologies, a highly controversial issue in the UK. Despite a growing body of research on the visual impact of wind farms (see Atkinson-Palombo and Hoen, 2014, for a review), no estimates of the external cost per kWh were identified. Further research would be useful here.

The study highlights potential impacts from carbon capture and storage. Some emissions (NO_x, NH_3) are likely to increase whereas others (PM, SO_2) could decrease (EEA, 2011). There will also be an increase in upstream impacts associated with increased fuel production to power the carbon capture process, and new impacts associated with solvent manufacture and waste solvent disposal.

Upstream fuel production impacts

Efficiency and fuel switching in buildings, industry and transport will lead to lower consumption of coal, oil and gas, which will in turn reduce the upstream impacts of extracting, refining and distributing those fuels.

The benefits that have been quantified amount to around £60 million in 2030, with a net present value of £537 million from 2008 to 2030 (Table 10). Much of this benefit will occur outside the UK, as most of the fossil fuel used in the UK is imported. However, because not all impacts have been quantified, this provides only a minimum estimate.

Table 10: Damage cost values used in the assessment of upstream fuel production impacts, and NPV by fuel

Upstream effects	Damage, £/tonne oil	Damage, £/1000m^3 gas	Damage, £/tonne of coal
Air pollution	-5.55		
Occupational health	-1.46	-0.37	-0.34
Hazardous waste (oil spills)	-0.47		
Major accident risk	-0.08	-0.08	-2.30
Noise			-0.08
Total NPV 2008-2030, £million	**379**	**113**	**45**

Impacts that were not quantified due to lack of data include landscape, land take, water pollution, water abstraction, waste disposal and biodiversity. This includes the landscape, land take and associated biodiversity impacts of opencast coal mining, and subsidence and acidic mine drainage from deep coal mining. For oil production, there is considerable uncertainty over the impacts of oil spills, and biodiversity impacts may well be underestimated. The extent to which impacts of major spills will be internalised through compensation payments will vary between regions depending on the strength of regulation. For gas production and transport, the impact of fugitive methane emissions on air quality was omitted: methane is a significant source of health impacts and crop losses via its role as a precursor to ground-level ozone formation.

Further impacts will arise from fuel switching to bioenergy. These impacts are highly dependent on the source of the biomass. Biofuels derived from waste material tend to have beneficial impacts, through reducing the impacts of waste disposal such as methane emissions, odour, litter, vermin, visual impact and land take (for landfill sites) or air quality (for incinerators). Biofuels derived from energy crops will have large land take impacts, but the impacts on landscape, soil quality, water quality, water scarcity and biodiversity can be either positive or negative depending on the type of crop planted, the former use of the land, the need for irrigation and the use of agro-chemicals (Campbell and Doswald, 2009; Smith, 2013; Zah et al., 2007). For this study, use of biomass in the UK is consistent with the CCC's Bioenergy review, which projects the size and types of resource that could be utilised while reflecting concerns over global food production, biodiversity and water stress (Committee on Climate Change, 2011).

If the fuel mix diversifies to include unconventional sources such as shale gas, tar sands or oil from sensitive regions such as the Arctic, which tend to have greater environmental impacts than conventional fuels, the upstream benefits of energy-saving measures could increase.

Surface transport

Substantial benefits arise from reduced congestion, pollution, noise and accidents as a result of avoided journeys through 'smarter choices' (active travel, a shift to public transport and demand reduction). The largest benefit is from reduced congestion, estimated as £8.4 billion per year in 2030, with a net present value of £48 billion from 2008 to 2030. This partly reflects the high economic cost of time lost due to traffic delays value according to the UK Department for Transport. However, more detailed research is needed to account for the variation of congestion costs with time, location and local traffic conditions. The benefit can be maximised by targeting support for active transport on areas where congestion is significant.

Perhaps surprisingly, there is also a large health benefit as a result of increased exercise from walking and cycling instead of driving. Around 34,000 disability-adjusted life-years (DALYs) are saved in 2030, valued at over £2.5 billion per year, with a net present value of £26 billion from 2008 to 2030. This reflects the significant health impact of sedentary lifestyles in the UK, where one study estimates that physical inactivity costs the National Health Service almost £11 billion per year (Sustainable Development Commission, 2007). Two-thirds of attributable deaths in high income countries are due to unhealthy diet and lack of exercise, and heart disease and strokes are the leading causes of death for people over 45 (World Health Organisation, 2009).

Estimates of the impacts of active travel were based on Woodcock et al. (2009) which modelled a 27% reduction in car kilometres in London, considered to be the maximum feasible reduction based on the rates of walking and cycling already achieved in Copenhagen, Amsterdam and some other

European cities. This equates to an average distance of 3.4 km / day cycled and 1.6 km/ day walked for young men aged 15-29, with smaller distances for most other population groups. The change assumed in the CCC scenario is far smaller than that in Woodcock et al: a 1.7% shift from car to active travel (assuming that one third of the 5% reduction through 'smarter choices' is achieved through active travel). This adds 113km to the 374km already walked and cycled each year by the average person in the UK (Department for Transport, 2013), an increase of just 30%. Thus, even though active travel may be harder outside London where distances are longer, the CCC scenario should be feasible. Some inaccuracy may arise from applying accident rates for London to the whole UK, but the main impact is health benefits which are independent of location.

Smarter choices and improved HGV logistics also give a net reduction in accidents due to reduced traffic. However, this masks a smaller increase in accidents as a result of increased walking and cycling, because cyclists and pedestrians suffer higher accident rates than drivers (around 11 times more fatalities per km; Department for Transport, 2012b). It is important to note that this impact is not solely a function of total vehicle travel. It can be significantly reduced, or even turned into a benefit, by investment in safety measures, especially the provision of safe cycle routes and improved driver awareness (Pucher, Dill and Handy, 2009; Rabl and de Nazelle, 2011).

Further health and environmental benefits accrue from reduced air pollution. The air quality benefits of five measures (electric cars and vans, hydrogen buses, smarter choices and HGV logistics) are estimated as £105 million in 2030, with a net present value of £600 million from 2010 to 2030. Additional air quality benefits could arise from more efficient vehicles and eco-driving. The air quality benefits of electric vehicles are offset to some extent by additional emissions from power generation, but these tend to take place away from centres of population, which limits the health impacts. The benefits of electric vehicles are enhanced by the switch to cleaner power generation technologies, such as renewables, envisaged in the CCC mitigation scenario.

Noise reduction benefits from smarter choices and the use of electric vehicles are estimated as £148 million in 2030, with a net present value of £947 million (based on data in CE Delft, 2011, for smarter choices and using guidance from Department for Environment, Food and Rural Affairs, 2013, for electric vehicles). Further noise benefits (not quantified) will arise from the use of plug-in hybrid vehicles and hydrogen buses, and from speed limiting and eco-driving.

The noise and air quality benefits of a switch to public transport are offset by emissions from public transport vehicles (trains, buses and coaches). The benefits can therefore be enhanced by investing in cleaner and quieter vehicles for public transport.

Transport mitigation measures also provide an extensive range of upstream benefits related to avoided extraction and refining of oil (see above).

Aviation and shipping

Impacts in this sector were not quantified, but the qualitative analysis identified the potential for substantial co-benefits.

For aviation, the greatest potential co-benefits were related to measures to limit flights and flying time, including capacity constraints (Holland, Mann, et al., 2011). These gave benefits for air quality and noise around airports. If there was a sufficient reduction in flights, the need for expansion of UK airport capacity would be avoided, which would have significant benefits in terms of land take, landscape and potentially biodiversity depending on the site.

Behavioural change to avoid flights, e.g. through videoconferencing or voluntary reductions in leisure travel, can also achieve these impacts, though enforced capacity reductions could be more effective in the UK (Holland, Mann, et al., 2011). If flights are avoided through switching to rail then the impacts of rail travel will partially offset the benefits.

Technical improvements are thought to offer fewer benefits, partly because opportunities for further efficiency improvements in UK aircraft are limited, and also because environmental gains for this option are partly offset by increased impacts associated with scrapping older aircraft and replacing them with new ones. This will create waste (old aircraft) and emissions (from the manufacturing process), and use extra resources, with associated impacts from mining and processing of metals. These impacts could be mitigated by recycling old aircraft parts and materials, and ensuring that the manufacturing process is as clean and efficient as possible.

Switching to biofuels offers fewer benefits, with air quality impacts being fairly similar to those from conventional fuels (except for reduced heavy metal emissions), and with no reduction in noise or land take. Impacts from biofuel cultivation must also be offset against the benefits.

For shipping, there are large air quality benefits because of reduced emissions of SO_2 and NOx. The benefits of slow steaming could include reduced collisions with marine mammals. Ship collisions are the main cause of mortality for the last few hundred North Atlantic right whales, for example, but the risk of a collision proving fatal is greatly reduced at slower speeds (Vanderlaan and Taggart, 2007). There could also be benefits from reduced noise, which has damaging impacts for marine life. Power consumption is proportional to the cube of speed, so by operating at lower speeds, ships significantly reduce their power requirement and hence their fuel consumption and associated polluting emissions. For example, Klanac, Nikolić, Kovač and McGregor (2010) showed that reducing speed from 15 knots to 10 knots cut fuel consumption by a factor of five, providing significant private economic benefits to the shipping operator (even allowing for increased labour costs and reduced productivity per ship).

Industry and buildings

Co-benefits in these sectors are related to avoided use of fuels and electricity through energy efficiency measures, resulting in air quality improvements from avoided fuel combustion. There are also co-benefits associated with the avoided upstream impacts of fuel and electricity production (see above).

However, some other important impacts arise. Energy efficiency in buildings can potentially improve living conditions and reduce fuel poverty, with significant benefits for health and well-being, as well as associated savings in healthcare costs. Benefits of improved insulation and draught-proofing include reduced exposure to cold, damp, mould and draughts, reduced noise levels and reduced exposure to outdoor pollution. Of those benefits that have been quantified, the largest is the noise benefit from double glazing in residential buildings, estimated as £400 million in 2030 with a net present value of £4.9 billion – outweighing the benefits of reduced air pollution. However this represents a maximum estimate.

In the industry sector, the abatement scenario relies mainly on energy-saving measures. However, many efficiency improvements may also result in other benefits. More efficient motors, for example, can generate less noise, heat and vibration, and require less maintenance, leading to improvements in working conditions that can result in productivity improvements, as well as cost savings. Increased use of recycled materials has additional benefits for resource security as well as avoiding the impacts of raw material extraction.

Going beyond the CCC medium abatement scenario, Allwood, Cullen and Milford (2010) highlight the need for material efficiency as well as energy efficiency in order to achieve carbon reduction targets. An ambitious move towards a zero-waste economy and closed-loop manufacturing could result in far greater economic and environmental co-benefits, from avoided resource extraction, avoided waste disposal costs, avoided energy and water costs, avoided effluent generation and productivity improvements.

A switch to more efficient appliances could result in negative impacts from increased resource use and disposal of old appliances. This can be mitigated by discouraging premature replacement and maximising recycling of old appliances.

Behaviour change such as switching off unused lights is a cheap, instantaneous and effective measure that achieves all the upstream benefits of avoided fuel use without generating any adverse impacts.

For options involving a switch to bioenergy, benefits are offset against the impacts of producing and burning the biofuel (see above). Emissions from bioenergy combustion vary significantly with the type of combustion device, and estimates are highly uncertain. Biomass produces no more particle emissions than coal or oil, when burnt in the same boiler, and heavy metal emissions are lower, but particle emissions are higher than for natural gas. For this reason, UK government guidelines recommend a switch to biomass only where the alternative is oil or coal, and only in rural areas (Environmental Protection UK and LACORS, 2009). Greater use of bioenergy in densely populated urban areas could increase exposure to particle pollution, especially where small domestic units are used. Impacts can be mitigated by encouraging combustion of biomass in large units with the best available technology for pollution control. It should be noted that although combined heat and power (CHP) is a highly efficient technology and minimises emissions per unit of delivered energy, it generally requires siting of combustion facilities close to habitation, where the impacts of air pollution will be higher.

For heat pumps, the benefits of avoided fuel combustion are offset by the need for additional electricity to drive the pump, which has impacts dependent on the generation type (e.g. coal vs wind).

Agriculture and forestry

Significant benefits arise from measures to reduce excess application of fertilisers, such as improved timing to minimise run-off, or more targeted application. This will reduce both air and water pollution, with benefits for health and ecosystems. Fertiliser application leads to emissions of nitrous oxide, nitrogen oxides and ammonia. Nitrous oxide is the main ozone-deleting substance under current emissions (Davidson 2012), leading to more cases of skin cancer. Nitrogen oxides and ammonia are damaging to health, with additional impacts on ecosystems and crops. They lead to the formation of secondary particulate pollution, and nitrogen oxides also contribute to the formation of ground-level ozone. In addition, run-off of excess fertiliser from agricultural land is a major source of nitrate and phosphate water pollution, which can lead to acidification and eutrophication of surface water and associated biodiversity loss. Nitrate in water can have impacts for human health above certain levels, and must be removed by water companies to meet the EU standard of 50mg nitrate per litre.

Anaerobic digestion of farm waste and manure leads to a wide range of benefits. Emissions of methane, ammonia, hydrogen sulphide and nitrogen oxides from slurry and manure storage will be reduced, leading to improved air and water quality and reduced odour. Biogas will displace fossil fuels (thus avoiding the impacts of fuel production), and the digestate can be used as a soil improver. Economic benefits can also accrue to farmers from sale or use of the biogas and digestate.

Afforestation can lead to benefits for biodiversity, landscape, recreation and air, soil and water quality (trees absorb pollution, and tree roots stabilise soil and filter out water pollution). However, these benefits depend on the choice of species planted, the cultivation method and the previous use and biodiversity value of the land. Benefits can often be maximised by choosing mixed native species rather than monocultures of non-native species, by avoiding sites with high existing biodiversity or landscape value, and by using sustainable cultivation methods (minimising the need for agrochemicals or irrigation).

The additional dietary change scenario was predicted to provide very large health benefits from reduced intake of saturated fat, worth an estimated £11 billion in 2030, with a net present value of £162 billion from 2008 to 2012, though the health impacts of saturated fat consumption are subject to considerable uncertainty. There would also be substantial co-benefits for biodiversity, food security and health from a shift from livestock to arable farming, arising from reduced water use, land use and pollution. Ammonia emissions from manure and fertiliser are estimated to be reduced by 45%, cutting the proportion of UK ecosystems at risk from acidification from 27% to 21%, and those at risk from eutrophication from 47% to 28%. This is a far larger change than could be achieved with conventional emission abatement methods. However, change of this magnitude could have significant impacts on the UK farming economy, rural communities and landscape (Audsley et al., 2011).

It should be noted that the scenario assumes no change in the proportion of agricultural imports and exports. The environmental benefits could be reduced if UK production is redirected to overseas markets, though health impacts for UK consumers will be unaffected. Although the scenario assumes substitution with UK-produced fruit, vegetables and grains, there could also be greater imports of plant-based protein such as pulses and beans that are not traditionally produced in the UK. To maximise benefits and minimise any adverse effects, plant-based alternatives should be produced sustainably.

Mitigation of negative impacts and enhancement of positive impacts

Although many climate abatement measures result in co-benefits, the study identified a number of negative impacts. Careful policy design can often mitigate the negative impacts and enhance the co-benefits.

Table 11 summarises the main negative impacts that have been identified, along with potential mitigation options. Table 12 lists the main opportunities identified for enhancement of co-benefits.

Table 11: Mitigation options for negative externalities associated with the climate abatement measures

Negative impact	Potential mitigation options
Landscape and perceived noise impacts of wind turbines	Sensitive siting; adherence to planning guidelines; early consultation with local communities; offering local communities a financial share in the benefits.
Accident risks and waste disposal problem of nuclear power	Strict safety standards and independent regulation; development of fourth generation reactor designs with passive safety features and lower waste production, though it is unclear whether this can be achieved within a reasonable cost and timeframe.
CCS: increased upstream fuel production to power the process, with associated impacts and emissions	Use low impact fuels to power the capture, transport and storage processes where possible, e.g. renewably generated electricity. Cannot be completely mitigated.
CCS: solvent production, use, regeneration and disposal with associated emissions e.g. ammonia	Extent of problem not yet clear: requires further research. Mitigation options not yet identified.
Bioenergy: land take, landscape, water use, air quality and biodiversity issues at production stage.	Sustainable sources and production methods: maximise production of bioenergy from waste, e.g. anaerobic digestion. Minimise production from crops, and minimise use of agrochemicals and irrigation for energy crops. Avoid conversion of land of high biodiversity or landscape value. Particular care is needed if biomass is imported, as the sustainability of the supply chain will be hard to control without strict standards and verification.
Bioenergy: combustion emissions	Avoid replacing gas with biomass in urban areas (in line with current policy). High standards of pollution control for bioenergy combustion plant. Improved efficiency of boilers, including uptake of combined heat and power.
Biomass: noise from shredding of solid biomass	Sensitive siting; soundproofing of buildings; choice of best machinery
Impacts associated with additional electricity production for electric vehicles and heat pumps	Switch to cleaner, lower impact power production e.g. renewables
Risk of increased accidents due to more people walking and cycling	Invest in road safety improvements, especially safe cycle paths separated from traffic. Other measures include improved junctions, driver training (especially for HGV and bus drivers) and traffic calming.
Health risk to cyclists from inhalation of traffic fumes	Cleaner vehicles; provision of off-road cycle routes
Afforestation: land take, landscape, water use and biodiversity issues	Minimise use of agrochemicals and irrigation. Avoid conversion of land of high biodiversity or landscape value.
Solar PV: use of rare metals	Maximise recycling of solar panels; R&D into alternative materials
Occupational health impacts of wind turbines	Strict safety regulations; raise awareness of potential safety issues
Biodiversity impacts of tidal power (habitat loss, barrier to migrating fish, damage due to turbines)	Alternatives to full-height ebb-only barrage designs (tidal lagoons, fences, reefs)
Building insulation and air tightness: Potential decrease in indoor air quality and increased	Install additional ventilation system if necessary (this will partly offset climate and environmental benefits)

risk of exposure to radon gas due to decreased natural ventilation	
Waste generation and increased resource usage from switch to more efficient vehicles, aircraft, appliances and boilers	Avoid excessively premature discard of existing equipment; maximise reuse and recycling of old equipment; encourage upgrading rather than complete replacement where possible (this is rarely possible at present but could be facilitated by encouraging a shift to modular, reusable components in future)
Hazardous waste from electric vehicle batteries	Recycling of batteries; R&D into cleaner batteries

Table 12: Opportunities for enhancement of co-benefits

Co-benefit	Potential enhancement options
Health and wellbeing benefits of better home insulation	Target households in fuel poverty
Congestion and noise benefits of smarter transport choices	Target support (e.g. provision of new cycle paths) on high-traffic areas e.g. city centres
Air quality and avoided upstream fuel production benefits of shift to public transport	Cleaner and more fuel-efficient buses, coaches and trains
Health (exercise) benefits of switch to walking and cycling	Target people with sedentary lifestyles, e.g. through awareness campaigns, perhaps via GPs, or workplace incentives. Measures to improve the safety, convenience and enjoyment of walking and cycling, which would increase the uptake, include: provision of safe and pleasant cycling and walking routes; provision of secure cycle parking; better information and signposting of walking and cycling routes; cycle training; awareness campaigns to highlight the health benefits; encouraging employers to provide changing facilities; speed limiting for vehicles; cleaner vehicles (to reduce exposure to traffic fumes); smarter urban planning to enable shorter (i.e. more walkable) travel distances between home, work, school, shops and leisure activities. Health benefits will also be strongly enhanced in combination with improvements to diet.
Environmental benefits of cut in meat and dairy consumption (optional scenario), through avoided fertiliser use, land use and water use	Ensure that crops grown to replace meat and dairy component of diet are produced sustainably, with minimal use of agrochemicals and irrigation

Conclusions

This study provides a broad overview of a wide range of health and environmental co-benefits and conflicts. As noted earlier, there are many caveats, uncertainties and data gaps, and quantitative results should be treated with caution. The main use of this research is in demonstrating the scale and breadth of the impacts associated with climate policy, in providing guidance on which impacts are likely to be most significant (and therefore merit further research to improve quantification), and in identifying negative impacts and trade-offs and suggesting options for mitigating them.

The wide range of potentially significant impacts that have been identified highlights the importance of taking an integrated view of climate policy, and not basing policy on climate impacts alone. Although the analysis is for the UK, it is likely that a similar broad range of co-benefits and conflicts will exist for other Western nations, although there will be important differences (e.g. in the magnitude of the congestion and lifestyle benefits).

Notwithstanding the limitations of the study, four conclusions stand out.

1. All heat and power generation technologies have some negative impacts, so climate measures that switch between different technologies (such as from fossil fuels to nuclear or renewables) often involve trade-offs between different impacts. For this reason, measures that reduce overall consumption of heat, power and transport fuel tend to have a wider range of benefits. However, it should be noted that the benefits of fuel saving could be reduced if associated financial savings are spent on energy-consuming goods or services (see Smith, 2013, for a discussion of the policy implications).

2. The potential co-benefits to human health associated with lifestyle changes – exercise through walking and cycling, and reduced meat and dairy consumption - are very large, even though these mitigation options play a relatively minor role in the CCC scenario, accounting for under 7% of GHG abatement.

3. For the impacts that were quantified in monetary terms, the benefits outweigh the disbenefits by a significant amount - more than £85 billion for the core CCC scenario (2012 pounds, net present value over the period 2008 to 2030), plus £165 billion for the extra scenario of eating less animal produce (though this estimate has a high degree of uncertainty). However it is important to remember that some important impacts, both positive and negative, were not quantified.

4. Co-benefits should be viewed in the context of the wider socio-economic impacts of climate policy (Jensen et al., 2014) including impacts on competitiveness, fuel poverty, energy security (CCC, 2010, Chapter 8; CCC, 2013), trade and employment (Smith, 2013). Although this scoping study omits those wider impacts, in Figure 2 we show that the co-benefits quantified in this study significantly offset the estimated resource costs of attaining the CCC's Medium Abatement scenario, reducing the cost from 0.6% of UK GDP to under 0.1%[1]. Policy makers should also note that climate action will reduce the costs of complying with air quality legislation (ApSimon, Amann, Astrom and Oxley, 2009). However, these savings are not additional to the air quality benefits evaluated here, because compliance costs should be internalised in the future market costs of fossil fuel technologies.

[1] Figure 2 excludes the costs of achieving behaviour change such as an increase in walking and cycling. These costs, and any associated welfare impacts, would be highly dependent on the method used to achieve change, whether through persuasion (such as education, or provision of better cycling facilities), or through coercive methods such as increased taxation.

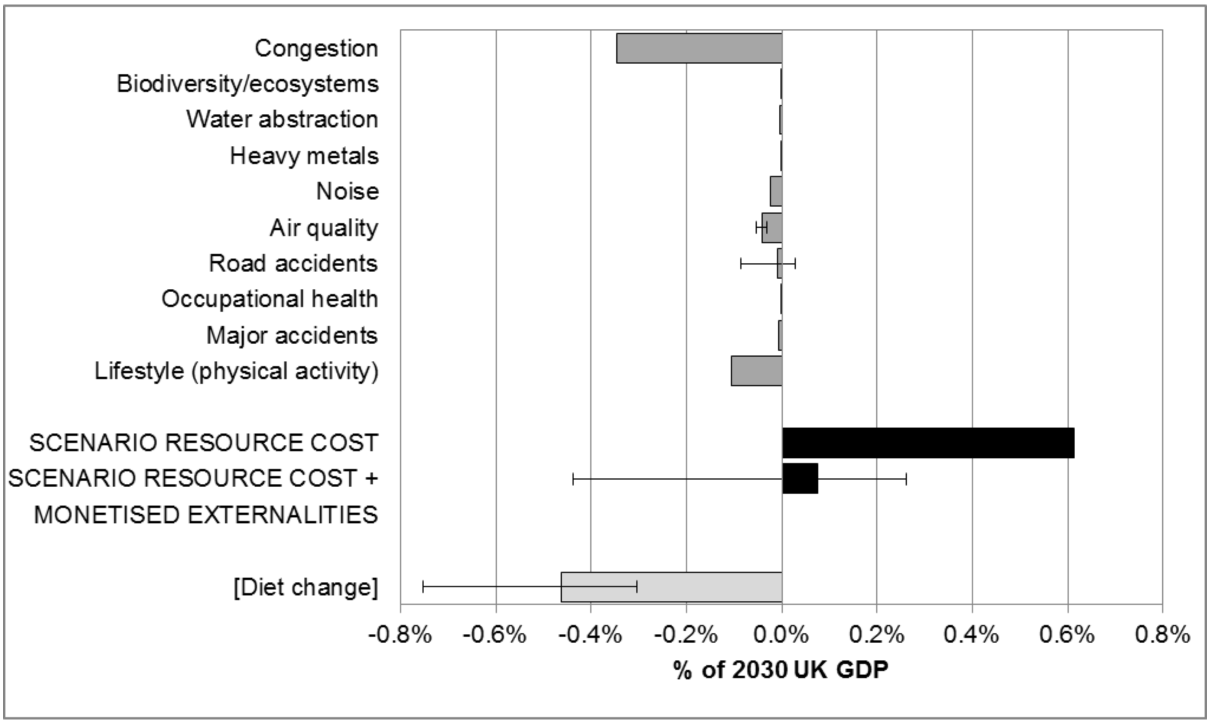

Figure 2: Comparison of quantified and monetised externalities vs. estimated total resource cost of the CCC Medium Abatement scenario

Despite the uncertainty attached to these estimates, the magnitude of the potential benefits emphasises the need to fully integrate co-benefit analysis in future climate policy decisions. Including these benefits in the cost-benefit analysis of climate policy would strengthen the case for setting ambitious climate targets. Co-benefits such as air quality improvements are often immediate and local, whereas climate benefits may occur on a longer timescale and mainly in a distant region, as well as being harder to demonstrate. Dissemination of the benefits, along with better anticipation of trade-offs, could therefore strengthen public support for climate action.

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