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From long-term targets to cumulative emission pathways: Reframing UK climate policy

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ABSTRACT

In March 2007, the EU reaffirmed its commitment to making its fair contribution to global mean surface temperatures not exceeding 2 °C above pre-industrial levels. In line with this, the UK Government has laid legal foundations for an emissions cut of 60% by 2050. Whilst 2050 reductions dominate the target-setting agenda, long-term targets do not have a scientific basis and are leading to dangerously misguided policies. If a policy is to be scientifically credible, it must be informed by an understanding of cumulative emissions and associated emissions pathways. This analysis of current UK climate policy illustrates how following the "correlation trail" from global temperature thresholds to national emissions pathways fundamentally reframes the UK's targets. Considering cumulative emissions, carbon cycle feedbacks and the omission of emissions from international transport dramatically increases both the scale and immediacy with which emissions need to be reduced; for example, within the UK, 6–9% p.a. reductions beginning as early as 2012. The implications of this are stark; society can no longer await the decadal timeframes necessary for a transition to low-carbon energy supply. If the 2 °C threshold is to maintain any meaningful currency, industrialised nations have little option but to radically and urgently curtail their demand for energy.

1. Introduction

Within the UK and the EU there is broad political agreement that we should make our fair contribution to "avoiding dangerous climate change…." (DEFRA, 2006).[1] In the absence of any explicit global consensus on an appropriate metric for delineating dangerous from acceptable climate change, European leaders have suggested that the EU takes the lead internationally to "ensure that global average temperature increases do not exceed pre-industrial levels by more than 2 °C" (European Commission, 2007). Within the UK, the 2006 Climate Change Programme (DEFRA, 2006), the 2006 Energy Review (DTI, 2006) and the 2003 Energy White Paper (DTI, 2003) all serve to underline the UK Government's commitment to the importance of the 2 °C threshold.

This future global temperature threshold can be "correlated" with a range of future atmospheric CO_2 concentrations and subsequently linked to a range of global cumulative emission budgets. The "correlation trail" from a global temperature threshold, such as 2 °C, to a national carbon emission pathway is both partially value-driven (e.g. emission apportionment) and complicated by a range of scientific uncertainties (e.g. climate sensitivity). Nevertheless, establishing such a trail is necessary if national carbon reduction strategies are to remain appropriately evidence-based. The application of an apportionment regime to a range of global budgets delivers national emission budgets for a given period (Den Elzen and Meinshausen, 2006). From the national cumulative emission budget, national emission pathways can be generated describing alternative future pathways that lie within a nation's cumulative emission budget.

Prior to the publication of the Stern Review (Stern, 2006) into the economics of climate change, and Tyndall's Living Within a Carbon Budget (Bows et al., 2006), UK energy and climate change policy documents generally neglected the importance of cumulative emissions, and their impact upon CO_2 stabilisation levels. Whilst Stern and others consider a global cumulative emission trajectory (Meinshausen, 2006; Stern, 2006; Anderson and Bows, 2008), this paper considers how addressing carbon cycle feedbacks, cumulative emissions and the current omission of emissions from international aviation and shipping undermines the UK's current emphasis on a long-term emission-reduction target. The "correlation trail" from global temperature changes to national carbon emission pathways is presented for the UK using the most recent global cumulative carbon budgets available in conjunction with the apportionment regime underpinning the UK Government's long-term carbon reduction target (60% by 2050). Such a "correlation trail" provides an explicit and sequential

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[1] p. 9, paragraph 9.

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process facilitating an understanding of the pathway's constraints in remaining within budget. In describing the "correlation trail", this paper firstly presents the latest scientific understanding of the temperature response to changing global atmospheric CO_2 concentrations, and in turn considers the considerable impact of the carbon cycle on global emission budgets. The link to the national scale is then made, and the calculations relating to the UK's carbon budget and consequent emission pathway, in the context of the UK Government's choice of apportionment, described. A discussion of the policy implications of the "correlation trail" follows an assessment of some of the limitations of the approach.

2. The global picture

Despite the many uncertainties surrounding the issue of climate change, there are several undisputed issues crucial to the climate and energy policy debate. Firstly, the global consumption of energy derived from fossil-fuel sources is continuing to rise. Secondly, this consumption is giving rise to increasing emissions of CO_2, which, according to the IPCC, is "the most important anthropogenic greenhouse gas" (IPCC, 2007). Thirdly, for CO_2 emissions to peak and begin to decline within the coming decade will require an unprecedented and global effort to both reduce energy consumption and decarbonise global energy supplies.

The latest IPCC report (IPCC, 2007) links its global emission scenarios with "best estimate" temperature increases of between 0.6 and 4 °C.[2] However, recently published research illustrates that the rate of growth of CO_2 emissions between 2000 and 2005 exceeds that of even the "highest" (4 °C) IPCC scenario (Raupach et al., 2007). As cumulative emissions of CO_2 have more influence on the ultimate temperature rise than do emission pathways (Jones et al., 2006), due to the long life-time of CO_2 in the atmosphere, rising global levels of CO_2 are rapidly reducing the options for effective emission mitigation. As such, global emission trends impact directly on national carbon mitigation policy and therefore national policy must be considered in the evolving global context if nations are to continue to aim for a 2 °C threshold.

Through the "correlation trail" from global mean temperature rises and CO_2 concentrations to national emission pathways, governments are able to quantify their role in global CO_2 mitigation based on carbon budgets.[3] However, as the understanding of the link between temperature and global CO_2 emissions improves, the policy community must update its mitigation strategies to ensure they remain evidence-based. In making the link between temperatures and carbon budgets, two key areas of improving scientific understanding, *climate sensitivity* and the *carbon cycle*, are central to the debate, and have a considerable impact on any derived national climate policy.

2.1. Climate sensitivity

Climate sensitivity is a measure of the climate system response to sustained radiative forcing. It is usually defined as the global surface warming following a doubling of greenhouse gas concentrations from pre-industrial levels of 280 parts per million by volume (ppmv). To put this into context, CO_2 concentrations are currently around 385 ppmv, but if the other greenhouse gases are included by allocating them a "carbon equivalence value" then the current greenhouse gas concentration is estimated to be ~430 ppmv CO_2 equivalent (CO_2e).[4] The likely range of climate sensitivities, as published in 2007 by the IPCC, is between 2 and 4.5 °C, with a best estimate of 3 °C. In other words, if global concentrations of greenhouse gases stabilise at 560 ppmv CO_2e at some point in the future, then according to the IPCC it is "likely" that global mean surface temperatures will ultimately rise by 3 °C above pre-industrial levels. Similar analysis shows that stabilising CO_2e concentrations at 550 ppmv provides between a 63% and 99% chance of exceeding 2 °C; at a 450 ppmv CO_2e stabilisation concentration, the range is 26–78% chance (Meinshausen, 2006).

To put these temperature rises into context, it is estimated that the global and regional impacts of a 2 °C rise will include the destruction of the vast majority of coral reefs, three billion people experiencing water stress and changes in global cereal production that could expose up to 220 million more people to the risk of hunger. At 3 °C, few ecosystems would be able to adapt and there would be much larger losses in global cereal production than predicted at 2 °C, potentially exposing a further 400 million people to hunger (Warren, 2006). Clearly, the lower the temperature rise, the less significant will be the impacts likely to be suffered.

Given that the science relating to climate sensitivity informs decisions as to the appropriate CO_2 concentration at which to aim, the next consideration relates to the emissions budget associated with a related CO_2 concentration. This is where carbon cycle feedbacks have a central role.

2.2. Carbon cycle feedbacks

The atmospheric concentration of CO_2 depends not only on the quantity of CO_2 emitted into the atmosphere (natural and anthropogenic), but also on climate change-induced changes in the strength of carbon sinks within the ocean and biosphere. For example, as the atmospheric concentration of CO_2 increases (at least within reasonable bounds), so there is a net increase in the take-up of CO_2 from the atmosphere by vegetation (carbon fertilisation). Changes in temperature and rainfall induced by increased CO_2 affect the absorptive capacity of natural sinks and alter the geographical distribution of vegetation and hence its ability to store CO_2 (Jones et al., 2006). Rising temperatures increase the rate of decomposition of carbon and hence decrease the storage capacity of the land.

The complicated and interactive nature of these effects leads to uncertainties with regard to the size of the carbon cycle feedbacks (Cranmer et al., 2001; Cox et al., 2006). Nevertheless, the implications of carbon cycle feedbacks for climate policy are profound. To achieve a desired CO_2 stabilisation level, the cumulative CO_2 emissions must be within certain bounds. Putting a value on these cumulative emissions is highly dependent on the degree to which carbon cycle feedbacks are included within a particular model. Results of recent research show that the carbon budget available is reduced significantly when carbon cycle feedbacks are included within models (Matthews, 2005, 2006; Jones et al., 2006). In this paper, the consequences for national climate policies of including the results of carbon cycle-feedback studies are illustrated.

[2] In terms of temperatures in 2090–2099 relative to 1980–1999.

[3] The total quantity of carbon dioxide that may be released over a given period of time.

[4] Carbon equivalence values are assigned to non-CO_2 greenhouse gases through the use of global warming potentials—or how much atmospheric warming a unit mass pulse emission that gas would lead to over a particular timeframe. See p. 31 (IPCC, 2007) for more information. The reader should note that in some policy documents it is not always clear whether it is CO_2 or CO_2e that is being referred to.

3. Carbon budget analysis

To understand how the "correlation trail" fundamentally reframes current UK climate policy, it is necessary to consider the origins of the UK's current 60% carbon reduction target. This section explores UK climate policy development, the importance of mitigating emissions in relation to a cumulative carbon budget and the necessity of including all sectors' emissions within global carbon reduction targets. The analysis subsequently considers carbon budgets implied by the 2 °C threshold once the latest carbon cycle-feedback results are incorporated, the UK's contribution to such an emission budget and the subsequent implications for the UK's emission pathway.

3.1. UK climate policy development

One of the first UK Government policy documents to refer to the link between global mean surface temperature rise and a stabilisation level of 550 ppmv CO_2 was the 2000 Climate Change Programme (DEFRA, 2000, p. 130). The related 60% target can be charted back to the same year and the work of the Royal Commission on Environmental Pollution's (RCEP) influential *Energy—the changing climate* report (RCEP, 2000). Within their report, the RCEP developed UK energy scenarios aimed at reducing CO_2 emissions by 60% from 1990 levels by 2050, a reduction the RCEP claimed represented the UK's "fair" contribution to stabilising global atmospheric CO_2 levels at 550 ppmv. The RCEP chose a 550 ppmv stabilisation level in order to defer an increase in global mean temperatures of 2 °C and to reduce the number of people at risk from coastal flooding and water shortages (RCEP, 2000, p. 31). Thus, the RCEP makes the link between stabilisation at 550 ppmv and a global mean rise in temperature of 2 °C, but does not claim that this stabilisation level will necessarily prevent rising of global temperatures by more than 2 °C above pre-industrial levels.

Following further assessments by the Government's Performance and Innovation Unit, and modelling work by the Intergovernmental Analysts Group, the 60% target became one of the primary objectives of UK energy policy, with the subsequent 2003 Energy White Paper making a firm correlation between the 60% target, stabilisation at 550 ppmv and keeping temperature rises below 2 °C (DTI, 2003, pp. 28, 29). In supporting documentation for the 2003 Energy White Paper (DEFRA, 2003), DEFRA emphasised that the correlation between 2 °C and 550 ppmv is related to climate sensitivity, and, should this be at the higher end of estimates, far more stringent cuts would be required; however, this is not made explicit in the DTI's main policy document.

Despite the rise up the political agenda of climate change and energy issues since 2000, UK carbon emissions[5] continue to rise (see Table 2). Emissions did reduce during the 1990s but, in the main, the reductions were a fortuitous consequence of a decline in manufacturing and the substitution of coal for gas in power stations. Recent failings of energy policy to prevent further growth in emissions prompted reviews of both the Climate Change Programme and the Energy White Paper. Both the new Climate Change Programme (DEFRA, 2006) and 2006 Energy Review (DTI, 2006) refer to the evolving science of climate change, particularly informed by research on CO_2e concentrations and temperatures presented at a pivotal conference organised by DEFRA at the UK Met Office in 2005 entitled "Avoiding Dangerous Climate Change" (Schellnhuber et al., 2005). Whilst still adhering to the language of 2 °C and a 60% target, these documents acknowledge that a 2 °C temperature rise is more closely aligned with a 450 ppmv as opposed to a 550 ppmv level (DEFRA, 2006, p. 13). It is worth highlighting that there is considerable ambiguity within UK policy documents as to whether stabilisation concentrations relate to CO_2 or CO_2e.

More recently, the Queen's Speech of November 2006 announced plans for a Climate Change Bill to come before parliament. This Bill has led to the formation of an independent climate change committee to advise Government departments responsible for overseeing policies to achieve the UK's 60% carbon reduction target. The target will be thus placed on the statute books and become binding for current and successive governments. Although enshrining a carbon reduction target in statute illustrates the quick rise of climate change targets from the domain of policy analysts through to the political mainstream, their scientific legitimacy is questionable with respect to the cumulative budget argument discussed within this paper.

All of the policy documents referred to above focus on the end-point, namely the level of emissions reduction in 2050. However, as it is the cumulative emissions of CO_2 that are crucial to atmospheric CO_2 concentrations, any national climate change target based on temperature must follow the "correlation trail" linking temperature rises with CO_2 concentrations, global emission budgets and hence national budgets that, on aggregate, equate to total global budgets. The Climate Change Bill has gone some way to address this issue by setting interim targets for 2020 and introducing 5-year budgeting periods. However, the emission pathway presented within the draft Bill (DEFRA, 2007a) neglects empirical emissions data between 2000 and 2007, assuming emissions reduce from 2000 onwards, and omits emissions from aviation and shipping. The implied budget (the area under their curve) does not therefore relate to a realistic emission pathway for avoiding "dangerous climate change" (Anderson and Bows, 2007). If national targets are to succeed in achieving their climate change objectives, they must be both inclusive and based on the latest empirical data coupled with an understanding of climate sensitivity and carbon cycle feedbacks.

3.2. Global carbon budget

Global CO_2 emissions are generated from a variety of sources and accumulate over time, increasing the atmospheric concentration of CO_2 and leading to higher global mean surface temperatures. CO_2 concentrations can be stabilised only if sustained action is taken to mitigate anthropogenic CO_2 emissions, particularly from energy use. To this end, it is appropriate to consider global cumulative emissions budgets over a particular timeframe. The latest IPCC report (IPCC, 2007) presents a new range of global carbon budgets incorporating carbon cycle feedbacks and based on a number of studies, including those recently published for 450 ppmv CO_2[6] (Jones et al., 2006; Matthews, 2006). These cumulative emission budgets for differing CO_2 stabilisation levels illustrate the significant budget reduction resulting from the inclusion of carbon cycle feedbacks within all the models they considered. As each model differs both in relation to how it incorporates carbon cycle-feedback processes and in its more general parameterisations, a range of values is given by the IPCC for each level. Table 1 illustrates the old and new ranges for 450 ppmv presented in the 2007 report (IPCC, 2007). The average value for the *with-feedback* models is some 26% lower over the 21st century than was that of the models *without feedback*.

[5] Even if international aviation and shipping emissions are excluded.

[6] If considering a global CO_2 alone budget, this applies to a global CO_2 alone atmospheric concentration. If the budget is for the basket of 6 greenhouse gases, this is for a global CO_2e concentration. Therefore, the figures for the carbon budget within the IPCC can be applied in both ways, as long as they are not subsequently related to temperatures. If relationships are made between emission concentrations and temperatures, then CO_2e is appropriate.

Table 1
Comparison of 21st century cumulative carbon values for stabilising atmospheric CO_2 concentrations based on the latest IPCC report

Cumulative totals (from 2000 to 2100)	IPCC lower bound (GtC [$GtCO_2$])	IPCC upper bound (GtC [$GtCO_2$])	IPCC average (GtC [$GtCO_2$])
450 ppmv CO_2 old	630 [2312]	710 [2606]	670 [2459]
450 ppmv CO_2 new	375 [1376]	600 [2202]	490 [1798]

Consequently, the cumulative carbon budgets used previously by, for example, the RCEP, to generate global and subsequently national emission budgets to meet particular stabilisation levels, overestimated substantially the emissions space available. The remainder of this section explores the implications of the reduced global budget for the UK.

3.3. The UK carbon budget

Apportioning global budgets between nations provides meaningful national budgets within which nations must maintain emissions if they are to make their fair contribution to stabilising atmospheric CO_2 concentrations. The UK Government's 60% carbon reduction target has its origins in the emission apportionment regime "Contraction and Convergence" (C&C) (Meyer, 2000). The central tenet to this regime is that the atmosphere is a global common into which each individual on the planet has an equal right to emit. The regime assumes the global carbon budget is distributed between nations, depending on their emissions in the start year of the analysis (e.g. 2000), an atmospheric CO_2 concentration target and individual nations' populations. To determine the UK's cumulative emission budget for the new IPCC global cumulative emissions (Table 1), the C&C approach is employed with a convergence year—the year in which nations converge at equal per capita emissions—of 2050.[7] This is the same year as that used within the 2000 RCEP report and hence that underpinning the 60% target.

3.3.1. The need for an inclusive inventory

To correctly apportion global carbon budgets between nations, and be able to relate the result to a particular CO_2 concentration, national carbon budgets must be based on comprehensive as opposed to partial carbon inventories.[8] However, as a legacy of international climate agreements' omission of emissions from international aviation and shipping activities, the UK Government's carbon reduction policies continue to be informed by an inventory that covers only the UK's "domestic" sectors. The UK is not alone in this regard. The omission of international emissions from carbon targets occurs in almost all nations and regions. This may be reasonable if the percentage of a nation's total carbon budget attributable to these sectors is negligible, but this is not the case for the majority of industrialised nations. In the UK, for example, CO_2 emissions from the aviation sector alone accounted for an estimated 6% of the UK's total in 2004 (Anderson et al., 2005). To adequately devise climate policy for nations whose "international" emissions are a significant proportion of their total, these international sectors must be included.

The UK's proportion of emissions from international shipping continues to, at best, receive scant regard within the Government. The omission of aviation from the inventory, however, is of particular concern. Not only do its carbon emissions start from a relatively high base (approximately a half of the CO_2 emissions from private car transport (DEFRA, 2007b)), but its unprecedented growth rate, unless urgently and dramatically curtailed, will ultimately make aviation a dominant CO_2 emission sector (Bows and Anderson, 2007). One additional adjustment made to the C&C and RCEP approach within this assessment is therefore the inclusion of international bunker emissions (i.e. emissions for international aviation and shipping). The inclusion of emissions from both international aviation and shipping is central to this paper, and represents a substantial numerical and analytical departure from all previous non-Tyndall assessments of UK emissions budgets and emission pathways—for example, the pathways developed within the RCEP, IAG and draft Climate Change Bill (RCEP, 2000; IAG, 2002; DEFRA, 2007a).

For national carbon emissions (emissions generated by households, industry, services and national transport activities), data are compiled for the UK Government by the National Environment Technology Centre (NETCEN) in line with the United Nation Framework Convention on Climate Change (UNFCCC)'s submission requirements. Although the UK's national carbon emissions inventory does not include emissions generated by the UK's international aviation or shipping industries, data for these sectors are collected and submitted separately as a memo to the UNFCCC. These emissions are referred to as emissions from international bunkers. To estimate the emissions from the UK's international aviation industry, NETCEN takes into account aircraft movements, distances travelled, deliveries of aviation spirit and turbine fuel, and the consumption of aviation turbine fuel by the military (Watterson et al., 2004). These data include both passenger and cargo aircraft.

"International bunker" fuel sales are used by the UNFCCC to estimate the emissions from shipping, without taking into account the destination or source of the freight in question. The term "bunkers" refers to fuels purchased for international transport activities. Due to the relatively small energy penalty incurred in carrying fuel on ships, there is a tendency to bunker excess fuel when the price is low. Consequently, national bunker records do not adequately reflect nations' shipping activities and hence emissions submitted to the UNFCCC for UK shipping do not appropriately represent emissions from the UK's international marine activities. This conclusion is well illustrated by a brief comparison of the UK's UNFCCC submission compared with that of the Netherlands (UNFCCC, 1997). According to the data, the UK's emissions from international shipping were 5.9 $MtCO_2$ in 2004, based on the "bunker fuel sold" at UK ports. The equivalent figure for the Netherlands is 46.8 $MtCO_2$ in 2000. For the purposes of the UNFCCC, emissions are being apportioned on the basis of port fuel sales. As such, the Netherlands is, under this regime, responsible for a disproportionate level of emissions.

In the absence of reliable shipping-emissions data, a coarse-level estimate is made in this paper based on the UK's proportion

[7] Although reasonable to consider other apportionment regimes, this analysis focuses on the UK government's choice of regimes, and therefore does not consider the alternatives that, for example, are assessed in Den Elzen and Meinshausen (2006).

[8] It could reasonably be argued that the inventory should also include all greenhouse gases. However, it appears more appropriate to have complementary rather than combined inventories for CO_2 and non-CO_2 emissions. (It may still be appropriate to combine the inventories in terms of CO_2eq for approximate correlations with temperature.) The inventory discussed here is for CO_2 only. It is assumed that non-CO_2 emissions will also be subject to a suite of reduction policies (see footnote 13 for a discussion of non-CO_2 emissions).

Table 2
National and aviation CO_2 emissions from DEFRA statistics (DEFRA, 2007b), including land use and forestry (note—figures are rounded up)

Year	Government total ($MtCO_2$)	Aviation (international) ($MtCO_2$)	Shipping (international)[a] ($MtCO_2$)	Tyndall total ($MtCO_2$)
1990	592	16	15	623
1995	550	20	17	587
2000	549	30	18	598
2003	555	30	20	604
2004	555	33	20	608
2005	554	35	20	609
2006(p)[b]	561(p)	36(p)	20(p)	617(p)

Shipping emissions estimated from method outlined previously.
[a] This remains a provisional figure and is subject to adjustment as Tyndall-Manchester research on the issue develops.
[b] (p) = provisional figure.

of global GDP. Assuming a nation's proportion of total global marine bunker fuel very approximately equates to a nation's proportion of global GDP suggests the UK's shipping activities are currently responsible for an estimated 18 $MtCO_2$ when using bunker fuel data from the International Energy Agency (IEA).[9] The uncertainty associated with this method has not been quantified, but will be affected by, for example, uncertainty in the global marine bunker fuels sold, for which only a poor approximation is currently available. This issue is under investigation in an ongoing Tyndall Centre project. If the IEA's estimate of sales in global marine bunker fuel is correct, estimating UK shipping emissions on the basis of GDP is likely to be an underestimate given the UK is an island state. Moreover, recent research suggests that the IEA figure could also be a significant underestimate (Corbett and Kohler, 2003; Eyring et al., 2005).

Having estimated international bunkers attributable to the UK, a new UK carbon budget can be calculated in which estimates of the CO_2 emissions from international aviation and shipping are included. Using the above method, the UK's total annual carbon emissions are estimated here to be some 10% higher than the UK Government's estimate in Table 2: an increase that makes a marked difference to the rate at which the nation's carbon budget is being consumed.

This shift from a partial to a full energy-related carbon inventory places a very different complexion on the scale of the problem. Government figures addressing only "domestic" emissions, when compared with 1990, suggest the UK is making moderate reductions in its CO_2 emissions: although it should be noted that this reduction occurred between 1990 and 1995 with no significant change achieved since 1995. However, even compared with 1990, the reality is that despite the substantial penetration of relatively low-carbon gas into the electricity mix, allied with the relative decline in the UK's heavy industries, emissions of CO_2 were little changed in 2006 from those in 1990 once international emissions have been included. Since 2005, emissions have continued to rise, with emissions in 2007 likely to be somewhat higher than the 1990 value. The absence of real quantified progress in reducing emissions is particularly concerning, as the reductions that have occurred in the power and heavy industry sectors were, to some extent, one–off and not the product of a strategic and judicious climate change programme. This, at least in part, explains why emissions did show some decline between 1990 and 1995. Emissions were 2% higher by 2006 than in 1995.

[9] Available online from www.esds.ac.uk under energy balances.

In its standard form, the C&C approach omits the emission burden associated with international bunker fuels.[10] Remedying this omission requires several adjustments to the approach: the inclusion of global bunker emissions in the total CO_2 emissions, both in the starting year and in the years spanning 1990–2000[11]; adjusting the UK's starting value to incorporate its bunker contribution; and adjusting the global total to remove the additional CO_2 that has been added specifically to the UK's starting budget in the year 2000.

3.3.2. *Estimating the UK's comprehensive cumulative carbon budget*

Once the above adjustments have been made, the IPCC's new cumulative emission range (Table 1) can be used to estimate the UK's 2000–2050 carbon budget; the results are presented in Table 3 for a 450 ppmv CO_2 stabilisation level.

Based on this approach, the UK's carbon budget for 2000–2050 ranges from around 17 to 23 $GtCO_2$. Between 2000 and 2005, UK CO_2 emissions amounted to some 3.6 $GtCO_2$. Consequently, between 16% and 21% of the budget has been emitted or "spent" in just the first 5 years of the century. Spending the budget at this rate is evidently not compatible with the UK's commitment to the 2 °C threshold. This point is further illustrated when considering that at current UK emission rates (~600 $MtCO_2$ per annum) the total budget, even within the "high" scenario, will be spent in its entirety in just over 38 years, or in 28 years for the "low" scenario.

3.4. *National carbon pathway*

The global emission pathway taken to achieve stabilisation is much less important than the associated cumulative carbon budget (Jones et al., 2006). However, under a very constrained carbon budget, high global annual emissions in early years will considerably constrain possible future emission pathways (Stern, 2006). This argument also holds for national emission pathways. When estimating both global and national carbon pathways on a 50-year timescale, it is crucial both to use the latest data and to estimate the likely impact of current climate policies on short-term emission levels. Unfortunately, often the analysis conducted at national and global levels does not take this approach (Stern, 2006; DEFRA, 2007a). For example, within both the UK's 2007 Climate Change Bill and Energy White Paper, modelled rather than empirical data are used for the period 2000–2005. These modelled data underestimate the empirical data, with the subsequent emission trend potentially overestimating the short-term reductions in carbon. Under the carbon budget constraints calculated using the method outlined in this paper, carbon pathways for the UK for the period between 2000 and 2050 are constructed, based on the assumptions described in Table 4. Unlike the other sectors of the UK's economy, international aviation and shipping emissions are assumed to continue to grow at rates marginally below recent levels until the peak year.

The scenarios developed in this paper are presented in Fig. 1. The earliest peak date of the three scenarios is 2012, with the latest being 2018. The pathways demonstrate that, if the higher end of the IPCC estimates is considered appropriate, the UK can afford to begin the emission decline slightly later than if the lower estimate is used. In relation to the annual emission reductions,

[10] The tool produced by the GCI omits bunker fuels at present, although it does indicate an intention for them to be included at some stage in the future.

[11] The Contraction and Convergence model uses a chosen 110-year cumulative budget over which to calculate a global emissions trajectory. This 110-year interval spans 1990–2100. Consequently, when adding bunker emission to the model, adjustments to each year between 1990 and 2000 must be made (Bows and Anderson, 2008).

Table 3
Global and UK carbon budgets for 450 ppmv CO_2 stabilisation level

Global budget over 21st century GtC [$GtCO_2$]	UK budget over a 50-year period GtC [$GtCO_2$]	Scenario name
375 [1376]	4.6 [16.9]	Low
490 [1798]	5.4 [19.8]	Medium
600 [2202]	6.3 [23.1]	High

Table 4
Information and assumptions used to produce the UK's CO_2 emission pathways

Years	Data/assumption
2000–2005	NETCEN *national* carbon emissions estimates (DEFRA, 2007b) NETCEN *aviation* carbon emissions estimates (DEFRA, 2007b) Tyndall *shipping* carbon emission estimate
2006	NETCEN *national* carbon emissions provisional estimate (DEFRA, 2007c) International *aviation* estimate based on a 6% growth on the previous year Tyndall *shipping* carbon emission estimate
2006–2012	All national sectors, on aggregate, stabilise emissions at 2006 levels International aviation emissions grow at the 1990–2005 average of 6% International shipping emissions grow at 2%
2012–2050	A choice of earlier or later response to addressing emissions reductions constrained by the carbon budget available

these scenarios imply that the most challenging pathway incorporates average annual emissions reductions of 9% per year between 2020 and 2030, the "medium" pathway 6% and the least challenging pathway of 4% over the same period. Such rates of decline are unprecedented, and appear to be receiving no consideration within the UK Government. Furthermore, if some sectors reduce their emissions by less than the aggregate percentage reductions required, then other sectors must compensate to remain within budget.

The implications of the high level of emissions being released currently, coupled with an assumed continuation of such levels in the short-term, leaves the UK essentially locked into a very steep and declining emission pathway between 2020 and 2050. Consequently, if the UK does not embark on a rapid programme of decarbonisation as a matter of urgency, it will be unable to make its fair contribution to a 450 ppmv CO_2 future.

4. Limitations and uncertainty

Attempting to relate a global mean surface temperature change to national cumulative carbon budgets through following a "correlation trail" necessarily demands assumptions be made with respect to both a range of scientific uncertainties and on how policy is framed. The principal assumptions underpinning the analysis developed within this paper are outlined in this section.

4.1. Global greenhouse gas emissions

This study focuses solely on CO_2 and adopts 450 ppmv CO_2 as the target atmospheric concentration. There are three main reasons why this is the case:

I. The UK's 60% target is currently for CO_2 alone.
II. Although a 450 ppmv CO_2e stabilisation concentration offers more chance of not exceeding 2 °C, global greenhouse gas emissions are already around 430 ppmv and are rising at between 2 and 3 ppmv per year. Consequently, stabilising at 450 ppmv CO_2e is considered highly improbable.
III. Policy messages for climate change and energy can be drawn from a study of CO_2 alone, particularly for nations such as the UK, where the bulk of greenhouse gas emissions are CO_2 generated through energy consumption.[12]

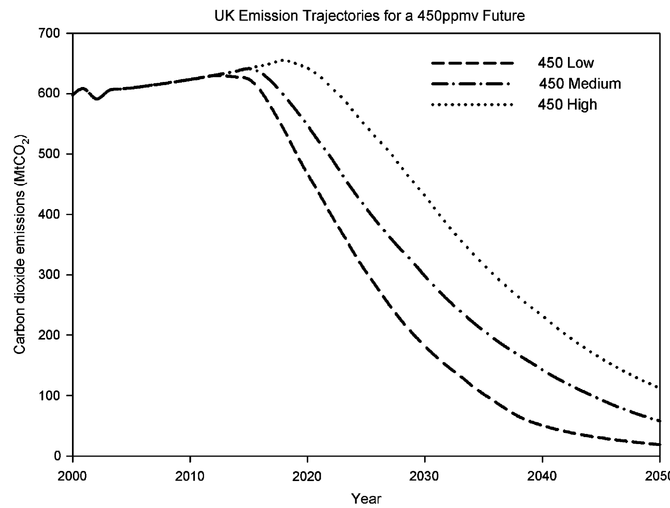

Fig. 1. UK CO_2 emission trajectories consistent with a 450 ppmv future.

If the analytical approach developed here were to be applied on a much larger scale or to areas with different proportions of greenhouse gas emissions, it would be important to use CO_2e as well as to potentially include the radiative forcing impacts of non-greenhouse gases such as contrails and cirrus clouds.

One key constraint to using CO_2 only is that it is important to consider the other greenhouse gases when relating a certain CO_2 concentration to temperature increases. To deal with this situation, it is assumed that the drive to reduce CO_2 emissions applies equally to the other greenhouse gases, with the outcome being that emissions are curtailed at a greater rate than is achieved for CO_2 alone.[13] Moreover, based on current scientific understanding, it is assumed that the relative impact of these additional gases is not greater than is currently believed to be the case.[14] With these assumptions, it appears reasonable to equate the 450 ppmv CO_2 figure with a CO_2e range of between 475 and 500 ppmv. Such concentrations, whilst offering a substantially

[12] The non-CO_2 emissions from a growing aviation industry will similarly grow unless measures are taken to address independently these emissions. However, there can be a trade-off between non-CO_2 emission reduction and fuel-burn, for example, modifying altitude of flight to reduce contrail formation (Williams and Noland, 2005). In the context of this carbon-based study, these non-CO_2 emissions from aviation are excluded from the analysis.

[13] The UK Government's own figures on reductions in the basket of six gases demonstrate, arguably, the greater scope for reductions in non-CO_2 as compared with CO_2 emissions. Between 1990 and 2004, whilst Government figures identify a 7% reduction in CO_2 emissions (excluding international aviation and shipping), they identify a 44% reduction in non-CO_2 greenhouse gases. The assumption that there exists similar if not greater scope for reductions in non-CO_2 as compared with CO_2 emissions is made in full recognition that the diminishing returns in terms of non-CO_2 greenhouse gas reductions may exceed those related to CO_2 only. This is an issue that demands further science and policy research. Furthermore, NO_x emissions from aircraft that interact to create ozone and deplete methane are the focus of a current target to be reduced by 80% by 2020.

[14] According to Meinshausen (2006, p. 269), a 550 ppmv CO_2eq equates to, approximately, a 475 ppmv CO_2—in other words, that the non-CO_2 basket of six gases contribute in the region of 14% of the warming attributable to a 550 ppmv CO_2eq concentration.

better chance of not exceeding the 2 °C threshold than 550 ppmv CO_2, nevertheless are estimated to provide only a 30–40% chance of not exceeding 2 °C.[15]

4.2. Carbon cycle feedbacks

Only recently have CO_2 stabilisation studies begun to incorporate the impact of carbon cycle-feedback mechanisms (Matthews, 2005; Jones et al., 2006), despite a number of previous studies illustrating that there will likely be decreases in terrestrial and oceanic carbon uptake due to climate change (Cox et al., 2000; Friedlingstein et al., 2001). The new cumulative carbon range for a 450 ppmv stabilisation level published in the IPCC (2007) report and presented in Table 1 illustrates the significance of such feedbacks. Clearly, cutting the global cumulative budget over 100 years by a quarter, as is the case for the 450 ppmv stabilisation, has significant implications for national carbon targets and temperature thresholds. Even when the uncertainties within global climate models are factored into the analysis, the new cumulative carbon range given by the IPCC (including feedbacks) does not overlap the earlier range in which feedbacks were excluded. In this Tyndall study, the IPCC's upper, lower and average values are used to apportion global emissions to the national scale.

4.3. Chosen apportionment regime

To assess the appropriateness of UK Government climate policy, it is useful to employ the same apportionment methodology as underpins the UK Government's own 60% carbon-reduction 2050 target. However, it is also important to consider the appropriateness of this regime in more general terms. How global cumulative emissions are shared out to produce national carbon budgets is as much a political as a scientific issue. Different apportionment regimes to C&C, such as the multi-convergence approach (Hohne et al., 2003), will, to some degree, produce different national carbon budgets. However, the lower the global cumulative carbon budget, the more the constraints on industrialised nations' ability to delay making significant carbon reductions. Under the 450 ppmv budget, no apportionment regime would permit industrialised nations to make only moderate emission reductions (Wit et al., 2005). Globally, CO_2 emissions from energy use alone amount to some 29 $GtCO_2$ (8 GtC) each year. Given a 450 ppmv cumulative emission value of between 1376 $GtCO_2$ (375 GtC) and 2202 $GtCO_2$ (600 GtC) for the 21st century, 8–13% of the 100-year budget has been consumed by energy emissions (i.e. not including deforestation) in the first 6 years, and currently emissions are rising at a faster rate than they were in the 1990s (Raupach et al., 2007). Given a 450 ppmv budget, reduced by carbon cycle feedbacks and the unprecedented rate at which this budget is being spent, the apportionment regime used in this paper is appropriate for conducting analysis on the scale of reductions necessary by industrialised nations.

4.4. C&C uncertainties

Within the C&C approach, uncertainties arise both from the CO_2 and population data used to derive national carbon budgets, with the principal uncertainty arising from variable emissions-data collection.[16] Many nations, the UK and most other European countries included, have a reasonable history of collating data and have established practices for doing so. By contrast, some industrialising nations have only begun collecting data in recent years and hence their data track-record and collection procedures are likely to be less robust than for those with more established procedures. Overall, uncertainties in global CO_2 emissions from energy and industrial processes are thought to be in the region of −6% to +10% (Gregg Marland, personal communication), with the uncertainties somewhat larger for many industrialising nations. Such uncertainties influence the historical carbon emissions recorded, and hence future emission projections. According to the Carbon Dioxide Information Analysis Center (CDIAC—Gregg Marland, personal communication), it is more likely that emissions are being underestimated than overestimated. If this is the case, the cumulative global carbon budgets available for the post-2006 period are also being overestimated.

4.5. Aviation and shipping emissions

Whilst the robustness of the estimate of shipping emissions within this paper is significantly constrained by the quality of data available, emissions from aviation are relatively accurate, being derived from actual flights departing the UK. By contrast, shipping emissions are arrived at through a coarse method based on estimates of UK GDP as a proportion of global GDP. The shipping-emissions calculation uses a global marine bunker fuel estimate that is subject to a high degree of uncertainty. For example, estimates can vary from around 150 Mtoe for global marine bunker fuel data taken from the IEA Data for the year 2000 compared with some 280 Mtoe from academic sources (Corbett and Kohler, 2003; Eyring et al., 2005). Consequently, the figure for the UK used in this paper could be a significant underestimation.[17]

4.6. Emission pathways

The pathways produced within this analysis are "what if" scenarios and are not mathematically modelled predictions or forecasts. Consequently, it is meaningless to quantify uncertainty associated with the pathways. However, as they stand, the pathways provide essential guidance to policy makers. Given the scale of current emissions and their rates of growth, delaying action on meaningful emission reduction now impacts significantly on the future rates of emission decline. Fig. 2 provides a stylised illustration of this point with the cumulative emissions under both early and delayed action the same. In practice however, low-carbon emission pathways will not undergo the step change towards emission reduction evident in Fig. 2, but will rather proceed through an initial decline in emission growth rate, an emission peak and finally actual emission reduction. It is this more realistic pathway that is presented in this paper in Fig. 1.

The recent Stern review addressed delaying mitigation in terms of the impact on the pathways to stabilisation. For global emissions, Stern states that it would be difficult to envisage greenhouse gas emissions reducing faster than 3% per year on a global scale (Stern, 2006, p. 203). Similarly, studies presented at DEFRA's "Avoiding dangerous climate change" conference in 2004 assume annual reductions do not exceed 2.5% per year due to the inertia within the system and the costs associated with early

[15] Based on Meinshausen (2006, Table 28.1, p. 270). The figures presented here represent what Meinshausen refers to as "mean" likelihoods. Meinshausen also offers upper and lower band probabilities for exceeding 2 °C: for 475 ppmv CO_2eq 38–90%; for 500 ppmv CO_2eq 48–96%; for 600 ppmv CO_2eq 74–100%; and for 650 ppmv CO_2eq 82–100%.

[16] For a more detailed assessment of the Contraction and Convergence approach, see Bows and Anderson (2008).

[17] Work to refine shipping figures is currently being undertaken with the Tyndall Centre at the University of Manchester. Early results suggest it will be necessary to further reduce the carbon budget available for the UK.

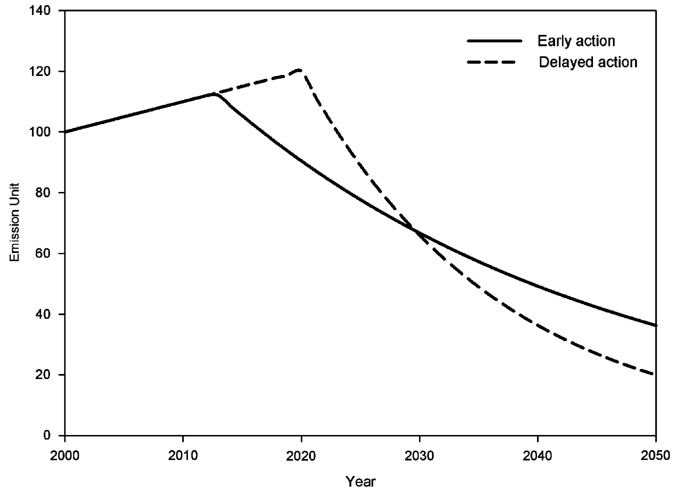

Fig. 2. Example of the impact of delaying carbon mitigation.

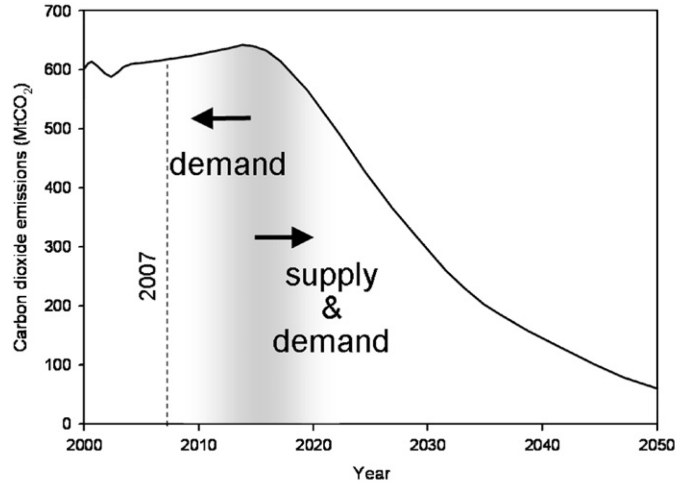

Fig. 3. Schematic representing the importance of cumulative emissions and messages for policy makers.

replacement of existing fossil-fuel-based capital stock (Den Elzen and Meinshausen, 2006). Assessing the socio-economic repercussions of emission reductions at either higher rates or of substantially exceeding 2 °C is beyond the scope of this study. However, given that those nations whose emissions are the highest will need to make much larger cuts than the global average, constraining emission rates to 2.5–3% per year has stark implications for the likely CO_2 stabilisation level and corresponding temperature rise.

5. Discussion and conclusion

The scenarios within this paper illustrate the scale and urgency of the challenge faced if the UK Government is to implement climate change mitigation policy commensurate with the 2 °C target, to which it re-affirmed its commitment in March 2007 (European Commission, 2007). The significant advances in scientific understanding of, for example, climate sensitivity and carbon cycle feedbacks, in addition to the inclusion of international transport emissions, point to an urgent need for the UK Government to update both its correlation between emissions and temperature and consequently its current climate change targets. With global CO_2 emissions exceeding even the "worst case" IPCC emission scenario (Raupach et al., 2007), the importance of establishing and maintaining a scientifically informed basis to policy is all the more important. Central to such a transformation of policy is the rejection of long-term emission targets (e.g. 60% by 2050) in favour of carbon budgets based on cumulative emissions and from which emission pathways can be described. Although the UK's draft Climate Change Bill does go some way towards addressing this concern with its 5-year budget proposal, the pathway presented within the Bill documentation is clearly and significantly at odds with the Government's aim to make its fair contribution to "avoiding dangerous climate change" (Anderson and Bows, 2007).

Proceeding along the "correlation trail", from global temperature targets (e.g. 2 °C) to national carbon emission pathways, demonstrates how the science underpinning climate change demands mitigation policies based on cumulative emissions. For the UK, this reframing of policy in terms of emission pathways suggests focussing on a long-term transition to low-carbon technologies is misguided, with real and substantial cuts being necessary in the short- to medium-term. Even if the UK's total emissions (including aviation and shipping) peak as early as 2014, emission reductions of the order of 6–9% per year (8–11% per year in terms of carbon intensity) will be necessary if the UK is to play its "fair" role in the 2 °C commitment.[18]

By continuing to stress long-term carbon mitigation targets, the UK Government is relinquishing opportunities for meaningful and timely reductions in energy demand, and consequently is forgoing urgently needed reductions in CO_2 emissions. Furthermore, the domination of the energy agenda by issues of supply, particularly electricity supply,[19] is eroding rapidly the UK's ability to stay within any reasonable 2 °C carbon budget. The schematic in Fig. 3 characterises the message, illustrating that only by tackling energy demand in the short term, and energy demand and supply in the longer term, will the UK be able to sustain the emission reductions necessary to remain within budget. Whatever the arguments for and against alternative low-carbon supply options, it is evident, under a 450 ppmv regime, that society does not have the luxury of waiting the decadal time frame necessary to bring about a transition to low-carbon supply. Consequently, if the UK is to demonstrate effective leadership on climate change and actively pursue a 450 ppmv pathway, it is incumbent on the Government to redress the balance of its policy agenda in favour of an early transition to a lower energy-consuming society. Certainly, for a UK Government serious in its desire to tackle climate change, the cogency of the arguments for urgently reducing energy demand as a means of mitigating CO_2 emissions can no longer be ignored.

Whilst the UK Government acknowledges the virtue of joined-up policies, the functioning of the different ministries, with their sometimes conflicting aims and objectives, demonstrates a continued aversion to analyse and implement policy on a systems-level basis. Explicit organisational and advisory structures, such as the Committee on Climate Change, must receive cross-ministerial support, with subsequent ministerial strategies

[18] Lower rates of reduction can be correlated with 450 ppmvCO_2 (approximately 500 ppmvCO_2e). However, this would suggest: (a) an acceptance of a 70% or more risk of exceeding 2 °C, (b) a rejection of growing evidence that several critical carbon sinks are showing signs of reducing their rate of uptake of CO_2 much earlier than anticipated, and (c) a failure to acknowledge the rapidly rising trend in global emissions (beyond the SRES worse case). Consequently, a focus on the lower end of the emission-reduction range would serve to significantly undermine the UK Government's and Parliament's commitment to 2 °C as the central tenet of its climate strategy.

[19] This is evident in both the 2007 and earlier 2003 Energy White Papers. Not only were issues of demand given much less prominence than issues of energy supply, electricity dominated the supply agenda despite currently representing only ~18% of the UK's final energy consumption.

and policies informed by a common analysis and coordinated to avoid inconsistent outcomes. The unwillingness of many decision makers, across all tiers of public and private governance, to address the carbon issue in absolute rather than relative terms and to establish an up-to-date and comprehensive inventory of CO_2 emissions, illustrates the gulf between the scale of the climate challenge and the inadequacy of many responses. Even when international aviation and shipping emissions are excluded, the UK's climate policies have had no discernable impact on emissions; with aviation and shipping emissions included, and despite the vociferous position the UK has taken on climate change, UK's CO_2 emissions continue to rise.[20]

Once the climate change issue is considered in relation to scientifically credible cumulative emissions rather than long-term reduction targets, the failure to institute deep emission reductions in the short term is brought into sharp focus. If the UK and indeed the EU are to genuinely engage with the accompanying challenges of their 2 °C commitment, there is little choice but for them to instigate a radical suite of policies explicitly designed to bring about stringent and urgent reductions in CO_2 emissions. The scale of the reductions identified in this paper is both unprecedented and far in excess of that contained within the UK's proposed Climate Change Bill (Anderson and Bows, 2007). If the analysis underpinning these conclusions is correct, reframing the debate in terms of cumulative emissions, based on a complete rather than partial emissions inventory, has fundamental implications for contemporary society.

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[20] At the same time, the emissions of the basket of six gases have fallen. However, rather than this be the outcome of judicious climate change policy, it is principally the consequence of a shift from gas- to coal-fired electricity generation and an export of heavier manufacturing and material processing.