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The Costs of Avoiding Dangerous Climate Change:
Estimates derived from a meta-analysis of the literature

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Abstract

This paper reviews the literature on the cost of avoiding dangerous climate change, defined as the costs of stabilising the climate as 450ppm CO_2-eq or lower, consistent with the achievement of the EU's 2ºC temperature target rise above pre-industrial levels. As confirmed by the IPCC AR4 Working Group III, Summary for Policy Makers (SPM), May 2007, there are very few studies on these costs, so we have supplemented the literature by using the meta-analysis conducted for the Stern Review to extrapolate the costs for the more stringent mitigation necessary for the 2ºC target. The paper emphasises the importance of the assumptions about methods and policies chosen by the modellers, and the uncertainty about the costs in terms of modelling approaches and policy options that may be adopted by governments.

If the models allow for (1) all the mitigation options agreed as feasible in the literature, i.e. including biomass, bio energy and land sinks, (2) induced technological change, and (3) the co-benefits of GHG mitigation, mainly in the form of reduced damages for air pollution on human health and crop productivity, the analysis suggests that the global costs by 2030 in trajectories towards stabilization at concentrations of 450ppm CO_2-eq by 2100 are around 2 to 3% of GDP. However, these costs are without international emission permit trading. With permit trading, the global average costs fall to 1 to 2% of GDP by 2030. If the policy also allows for the revenues from auctioned permits and carbon taxes to be recycled as a component of national environmental tax reforms (in which taxes on exports, labour and/or capital are reduced), national and global economies can benefit from deep mitigation, perhaps as much as 5% of GDP above baseline by 2030.

The possibility of realising such benefits depends on the existence of underemployed resources, e.g. under-utilisation of the rural workforce, a feature of many developing economies, and international co-operation on policy co-ordination, which is unprecedented in scale and duration. In other words, the global adoption of stringent mitigation targets, with well-designed and equitable supporting policies, involving co-ordinated international policies and national tax reform, could promote economic development; but the challenge for policy negotiators is formidable.

Keywords: meta-analysis; GHG mitigation; atmospheric stabilisation; carbon tax; CO_2 emission permit; induced technological change; environmental tax reform.
JEL Classification: Q54, Q52, Q43

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4CMR's overarching objective is *'To foresee strategies, policies and processes to mitigate human-induced climate change, which are effective, efficient and equitable, including understanding and modelling transitions to low-carbon energy-environment-economy systems.'* To address this objective, expert knowledge from many disciplines is essential, including expertise in communicating between disciplines and in filling poorly researched gaps in knowledge. The disciplines include economics, energy, environment, engineering, politics, systems analysis, applied mathematics and computing. The Centre is inter-disciplinary and its research effort is expected to be at the leading edge of UK and international research in the area of climate-change mitigation.

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1. Introduction

In 2007, with the IPCC's Fourth Assessment Report, the risks of continuing present trends in the growth of greenhouse gas (GHG) emissions have been established more firmly than ever. This paper extrapolates the evidence from the substantial number of modelling studies for stabilisation targets of 550ppm CO_2-eq and above to estimate costs for 450ppm CO_2-eq and below. The more stringent target is the one that has the best chance of achieving an average global temperature rise within 2ºC above pre-industrial, as adopted by the EU in January 2007, but even this target may not be enough to avoid dangerous climate change.

The starting point for the analysis is that deep cuts in global GHG emissions are necessary over the coming years. If the cuts are to happen at low cost, or even benefit, the world's energy system and land use will have to be radically transformed over the next 50 years. The energy system will have to switch from its present base on fossil fuels. And the fundamental drivers of land-use change, especially in the tropics, will have to be blocked, re-directed, or new drivers found to reverse deforestation and other practices leading to greenhouse gas emissions. Deployment and development of existing and new low-carbon technologies will be necessary on both sides (supply and demand) of the energy market. All no-regrets opportunities for energy saving and efficiency on the demand side will have to be exploited, especially new opportunities afforded by higher carbon prices. In addition, and more problematically in view of the risks of further deforestation, a substantial share of energy will have to come from land sinks and biomass with carbon capture and storage in order to reduce GHG concentrations as they threaten to rise above levels required for stabilisation.

The paper continues with a brief review of the studies that have addressed the problem of achieving the 2ºC target (section 2). We then outline in section 3 the results from the meta-analysis developed for the Stern Review (Barker *et al.*, 2006) covering the costs of mitigating global and regional GHG emissions over the period to 2100, and the effects of induced technological change. Section 4 explains how the meta-analysis has been used to extrapolate costs for the more stringent target. We present the costs of stabilising around 450ppm CO_2-eq in terms of different combinations of approaches and assumptions, as adopted in the literature, and as compared to the costs of the 550ppm CO_2-eq target. We show how the assumptions lead to different trajectories of GDP 2000-2100, above or below the baseline. Finally section 5 explores the implications of these findings for sustainable development, including sectoral effects and air pollution co-benefits. We show the extent to which policies, in the form of international emission trading and environmental tax reform, can reduce the costs.

It is important at the outset to emphasise that the uncertainty about the cost estimates increases for lower stabilisation targets. Such targets (which are implicit in the climate warming targets such as the EU's 2ºC over the 21st century) increasingly involve "overshoot" as the targets become more stringent. Overshoot in this context is a level of GHG concentrations that is too high for long-term stabilisation, so that the concentrations have then to be reduced by removal of CO_2 from the atmosphere by human action. The inherent uncertainty of costs becomes more pronounced because there are few underlying studies that address the economics of land use and new technologies (e.g. large-scale use of biomass with carbon capture and storage) that are required for the task. These new technologies are inherently speculative, without institutional structures to implement them, and with very limited experience of costs.

2. Literature on achieving the 2°C target

Studies which investigate the costs[1] of deep mitigation, e.g. more stringent stabilisation targets such as 450ppm CO_2-eq or lower, are very scarce as these targets are generally considered to be infeasible. This also implies that there is limited information on mitigation strategies which could stabilise GHG concentrations at the low levels required to meet the two-degree target with a higher level of certainty. den Elzen and Meinshausen (2005) explain the main issues and use the IMAGE-TIMER model to explore the scale of the emission cuts and how they might be achieved. We have reviewed four studies that have analysed such stringent targets: those by Azar *et al.* (2006), Riahi *et al.* (2006), Rao and Riahi (2006) and van Vuuren *et al.* (2007) (the last also with IMAGE-TIMER). The key results and conclusions are discussed below and summarised in Table 1.

Azar *et al.* (2006) assesses the role that Carbon Capture and Storage (CCS) could play in meeting more ambitious stabilisation targets by 2100, with the use of a global Energy-Economy model (GET 5.0), globally aggregated and including 3 end sectors and 10 primary energy options. Estimates of the costs of stabilising atmospheric CO_2 concentrations at 350 and 450 ppm CO_2-only (roughly 450 and 550ppm CO_2-eq), are presented, both with and without CCS technologies applied to fossil fuels and biomass. Results show that for 450ppm CO_2-eq costs are significantly reduced by 50%, from 26 to 13 trillion US$, where CCS technologies are included, with a reduction below base of 1.37% GDP by 2100. These costs are reduced further, from 26 to 6 trillion US$, when Biomass Energy with CO_2 Capture and Storage (BECS) is included. In this latter scenario GHG emissions become negative after 2070, reaching -4Gton CO_2-eq by 2100, with a reduction below base of 1.21% GDP.

Riahi *et al.,* (2006) use MESSAGE-MACRO, components of IIASA's integrated assessment model, to analyse three baseline scenarios (IPCC SRES A2, B1 and B2) which are not assumed to include any explicit climate policies. The modelling framework covers all GHG emitting sectors. The study then imposes a range of different climate stabilisation targets on these baselines to analyse the costs, feasibility and uncertainties of meeting a range of different stabilisation targets. The scenario B1 explores the lower range of the targets, 480ppm CO_2-eq, giving a reduction in GDP of 0.3% by 2100. Deep mitigation is only shown to be possible when considered under scenarios B1 and B2, and the lowest stabilisation target of 480ppm CO_2-eq can only be met under the B1 scenario, characterised by rapid technology diffusion and transfer.

Rao and Riahi (2006) also use MESSAGE-MACRO in the EMF21 multi-gas scenarios, but present a further scenario, which stabilises additional radiative forcing at $3.0W/m^2$, i.e. about 490CO_2-eq. Biomass with CCS, and forestry sinks are important mitigation options in extracting CO_2 from the atmosphere. GHG emissions become negative after 2070 reaching -6GtCO_2-eq by 2100, with a carbon price of $(2000)764/t$CO_2$-eq and a reduction below base of 3.9% GDP.

Van Vuuren *et al.,* (2007) have used the Integrated Assessment model IMAGE 2.3, covering 17 regions, to produce mitigation scenarios which include stabilization targets at 450 and 400ppm CO_2-eq, using the IPCC SRES B2 scenario baseline. The carbon price increases to around $(2000)760/t$CO_2$-eq by 2100 with costs of stabilisation at 450ppm CO_2-eq 2% of GDP by 2050, dropping to around 0.8% of GDP by 2100. The study then investigates

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[1] See (Barker *et al.*, 2006) for a discussion about the meanings and definitions of "costs" in this context.

whether changing the assumption on BECS, from the default assumption to a more optimistic assumption, could alone enable a target of 400ppm CO_2-eq to be met. Results show that with BECS the lower stabilisation target can be reached with a reduction below base of 1.1% GDP by 2100. However GDP losses may in fact be larger or smaller as the model does not capture the macro-economic impacts of climate policy or benefits from revenues and recycling.

Table 1: Comparison of modelling studies focusing on more stringent stabilisation targets

Author	Baseline Used	Change in GDP by 2030 from base	Change in GDP by 2100 from base	GHG reduction from Baseline by 2100	Permit Price By 2100	Underlying Assumptions
Azar *et al.*, (2006) GET (5.0)	C1 scenario from IIASA/WEC 450 ppm CO_2-eq	450 ppm CO_2-eq -4.92% of GDP With fossil capture -1.41% of GDP With BECS -0.69% of GDP	450 ppm CO_2-eq -1.77% of GDP With fossil capture -1.37% of GDP With BECS -1.21% of GDP	450 ppm CO_2-eq 23 to 0 With fossil capture 23 to 0 With BECS 23 to -3.9	-	Assumes use of carbon capture and storage technologies. Technology exogenous. BECS included as specific option.
Riahi *et al.*, (2006) MESSAGE-MACRO	IPCC B1 Scenario 480ppm CO_2-eq.	-	0.3% reduction from baseline	-	-	Assumes use of clean efficient technologies, mainly renewables.
Rao and Riahi (2006) MESSAGE-MACRO	IPCC B2 Scenario Approx. 490ppm CO_2-eq.	-	3.9% reduction from baseline	18.5 to -6	208 US$/ tCO_2-eq	Forest carbon sinks as explicit mitigation option. Mitigation technologies. Include ancillary benefits. Exogenous technological change.
Van Vuuren *et al.*, (2007) IMAGE 2.3	IPCC B2 Scenario for 450 and 400ppm CO_2-eq.	Energy system costs as %GDP: -1.25%	Energy system costs as %GDP: -0.8% for 450ppm -1.1% for 400ppm	450ppm 23 to 2.5 GtC-eq	207 US$/ tCO_2-eq	Full emission trading; nuclear available as mitigation option; CCS; climate policy induced learning and energy efficiency. For 400ppmCO_2-eq BECS included.

2.1 Summary

The assumptions made by the few studies available on the overall costs of meeting more stringent stabilisation targets (as reviewed by the IPCC WG III Report, 2007) are very important in determining the results. The studies also highlight that if more stringent targets are to be achieved then a combination of price policies, such as carbon taxes, and policies to drive technological development and energy-efficiency technologies, such as increased R&D spending, will be needed. Creating the right socio-economic and political conditions for mitigation is therefore very important.

Although global net present value costs of meeting stringent targets are estimated to be in trillions US$ and annual costs are as high as several percent of annual GDP, these mitigation costs are relatively modest compared to the projected levels of GDP from the economic growth assumptions in the scenarios. All four studies reviewed conclude that the more stringent targets of 450ppm CO_2-eq and, where included 400ppm CO_2-eq, can be met under certain assumptions and are technically feasible. However this finding is also dependent on the emissions baselines, which all appear to be relatively low. For higher baselines, it may prove impossible to meet the more stringent targets as highlighted by the Riahi *et al.* (2006) study, although the higher baselines also imply more opportunities for low-cost mitigation.

3. A meta-analysis of costs of stabilisation

3.1 The macroeconomic costs

Meta-analysis has been used (Barker *et al*., 2006) as a statistical technique to combine the quantitative results from three comparison studies, each covering a large number of models.

1) The **Innovation Model Comparison Project** (IMCP) covered 9 models and 924 observations of key variables 2000-2100 for 3 stabilization scenarios for CO_2 concentrations by 2100[2] (Edenhofer *et al*., 2006).
2) **The Post-SRES study** by Barker *et al.* (2002) covered 6 modelling studies for a range of scenarios linked to the SRES[3] marker scenarios reported by Morita *et al.* (2000).
3) The **World Resources Institute study** (WRI) by Repetto and Austin (1997) assessed studies from 16 models of the costs for the US economy of CO_2 mitigation. The study concentrates on economy-wide top-down models, using econometric regression techniques to assess the role of assumptions in determining the projected GDP costs.

Figure 1, reproduced in the Stern review, shows the CO_2 reductions from baseline and the associated changes in GDP also as difference from baseline for the three datasets. Note that the WRI data covers US mitigation only. The higher variance in the IMCP results comes from the increasing returns and other non-linear properties of models including induced technological change (ITC). The higher variance in the WRI study comes from the wider range of modelling approaches and assumptions covered. The range of GDP effects for deep mitigation approaching total decarbonisation of the global economy is between a cost of 15% and a gain of 5%, both in relation to a baseline or reference case[4].

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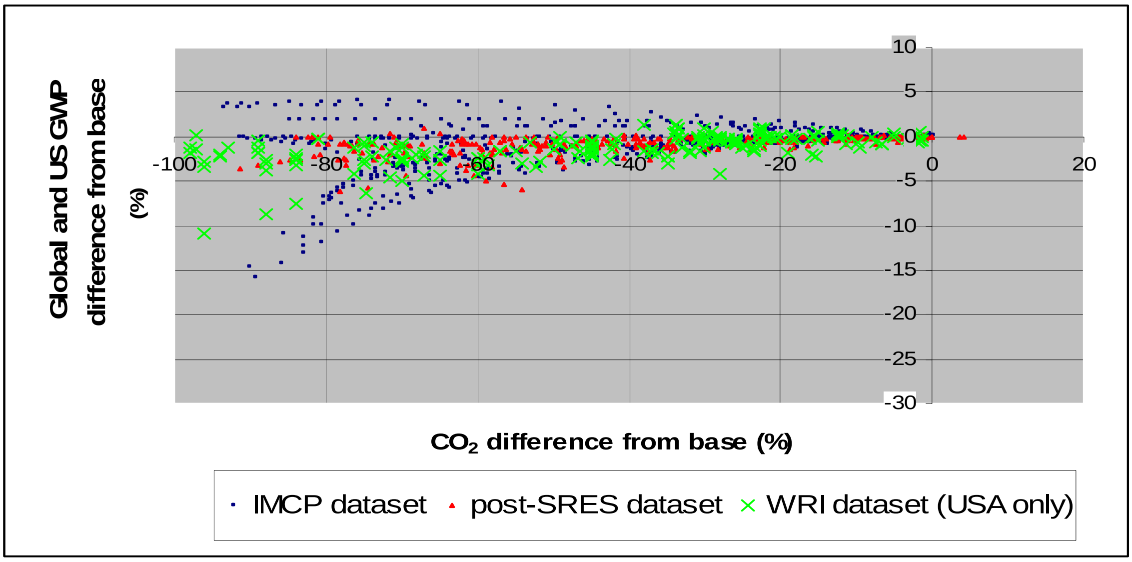
[2] The IMCP study is for CO_2-only stabilisations targets, although some of the models also include other GHGs in the analysis. The optimising models in the study are doing so for CO_2 abatement costs alone. The EMF19 studies (van Vuuren *et al*., 2006) explicitly cover multi-gas optimisation.

[3] SRES: IPCC Special Report on Emissions Scenarios (Nakicenovic *et al.,* 2000). The modelling teams involved with the SRES have run their models to achieve a series of different levels of stabilisation of GHG concentrations in the atmosphere: these are referred to as the “post-SRES” scenarios.

[4] The analysis in this paper covers studies adopting a very wide range of baseline assumptions for global population and GDP growth 2000-2100. We allow for the different baselines by analysing the differences for baseline and by checking to ensure that any factors associated with the absolute values in the baseline (such as stabilization levels) are included in the explanations.

Figure 1: GDP and CO_2 in the WRI-post-SRES-IMCP combined dataset for all years 2000-2100



Source: (Barker *et al*, 2006).
Notes: (1) Each point refers to one year's observations from a particular model.
(2) The IMCP data shown excludes those from IMACLIM-R at the request of the modellers, since these model results are experimental and are not to be considered realistic for policy implications.

The Annex reports the details of a parsimonious specification of the equation explaining the GDP costs from 1471 observations from the combined IMCP-post-SRES-WRI studies. This equation will be used for the detailed analysis below[5]. The effects are illustrated for the 450ppm CO_2-only stabilisation scenario in Table 2. The summary is for 2030 and is done by solving the equation for 2030 using the average CO_2 reduction in the 450ppm CO_2-only stabilisation scenario from the IMCP results. The table shows the parameters estimated and the effects of the parameters on GDP determined by the equation as % difference from base. All the parameters except the constant and the fixed effect for 2030 are highly significant (see Annex). The effects on GDP of adopting the worst case assumptions in the equation solution are presented in the top 6 lines of numbers and indicate a cost of some 3.3% of GDP. The various assumptions and effects that reduce this cost are then included one by one in the main body of the table, with the net outcome shown as best case assumptions in the last line of numbers.

It was notable from the study that the computable general equilibrium (CGE), recycling and ITC effects are not completely robust to the inclusion of model dummies. The reason is that it is very difficult to identify effects of model characteristics from those of model dummies; effectively there is multicollinearity between the two sets of parameters. There is also a problem of outliers in the regressions. Some models, especially when they are experimental, yield estimates that are significantly different from the average, and the effects can be substantial. These outliers were identified by interaction terms using MDs, picking those which are most significant and including them in the specification of the equation.

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[5] Note that the equation we use here is the parsimonious version of the equation quoted in the Stern Review (2006).

Table 2: Meta-analysis on combined dataset:
Effect on global GDP in 2030 for 450ppm CO_2-only

Observations		1471	
Rsq		0.79	
Source of effect	Variable name	parameter	effect (%)
Constant	_cons	-0.09747	-0.1
CO_2	co2	0.06596	-2.1
CO_2*CO_2	co2square	-0.00025	-0.3
450ppmv	d450ppmv_co2	0.02566	-0.8
year 2030	yr2030	0.00000	0.0
Total worst case assumptions (% differences from base)			**-3.3**
CGE model	cge_co2	-0.02476	0.8
Kyoto Mechanisms	km_co2	-0.02699	0.9
Backstop technology	bst_co2	-0.01542	0.5
Climate benefit	cben_co2	-0.01549	0.5
Non-climate benefit	ncbens_co2	-0.03034	1.0
ITC	with_itc_co2	-0.06327	2.0
Active recycling	recy_co2	-0.10329	3.3
	total of above		9.0
Total best case assumptions (% differences from base)			**5.7**

Source: Parsimonious equation in Barker *et al.* (2006).

The factors reducing the costs are considered one by one.

1) Adoption of static CGE models

Table 1 shows that the adoption of static CGE modelling assumptions leads to a 0.8pp or more reduction in GDP costs, compared to use of econometric model results, confirming the earlier WRI result. This result can be interpreted as suggesting that the CGE results assume efficient responses (Repetto and Austin, 1997) or, more likely, that they show long-run responses often for undefined dates in the future, whereas the econometric models allow for time of adjustment, with higher short term costs e.g. as in the US EIA (1998) results and other US studies (Barker and Ekins, 2004, Lasky, 2003).

2) Use of the Kyoto Mechanisms

The use of one or more of the Kyoto Mechanisms in the modelling, usually the stylised modelling of international trade in emission permits (see Special Issue of the *Energy Journal* (Weyant and Hill, 1999)) was assessed in the TAR and found to reduce the costs of Kyoto for OECD countries by 0.1pp to 0.9pp by 2010 (p. 10). The meta-analysis confirms the scale of this result with a 0.9pp reduction in global costs by 2030 for about 30% reduction in GHGs.

3) Introduction of a backstop technology

The use of a backstop technology allows for unlimited substitution at high enough carbon prices. This is an assumption purely for modelling convenience, since it implies no further technological change, and where it is introduced costs are 0.5pp lower.

4) Allowing for climate benefits

Some models have allowed for climate benefits in a cost-benefit framework in which the benefits of mitigation in the form of avoided climate change are monetised and discounted, an approach developed by Nordhaus (1994). The WRI result, repeated here, is a modest 0.5pp or less by 2030, largely due to the effect of the discount rates chosen (Downing et al., 2005).

5) Allowing for non-climate benefits

GHG reductions are associated with reductions in other emissions from burning fossil fuels, such as SO_2, NOx, black carbon, CO, and fine particulates. These other co-benefits of mitigation account for a further 1.0pp reduction in costs. They are normally excluded from the economic cost calculations.

6) Introduction of induced technological change (ITC)

The transition toward including ITC in the models has been one of the most far reaching methodological developments in recent years (Köhler *et al.*, 2006). It appears to be comparable in scale in its effects on costs to the recycling assumption adopted in models (Barker *et al.*, 2006).

7) Use of active recycling of government revenues

Finally there are substantial reductions in costs from the active use of carbon tax or auction revenues to reduce distorting taxes or to provide incentives for low-carbon innovation. This effect was extensively discussed in the TAR (section 8.2.2, p. 512), and depends on the model approach and of course the existence of revenues to recycle (free allocation of permits yields no direct revenues to government). It is further discussed in section 5.2 below.

3.2 Effects on the Carbon Price in the WRI-post-SRES-IMCP Models

Table 3: Effect of Model Assumptions on Carbon Prices in 2030 for 450ppm CO_2-only

Source of effect	Variable name	parameter	Effect (%)	Effect (US$1995)
Observations			861	
Rsq			0.82	
Constant	_cons	2.48455	2.5	3
CO_2	co2	-0.02780	0.9	8
CO_2*CO_2	co2square	-0.00057	-0.6	4
450ppmv	d450ppmv_co2	-0.08734	2.8	74
year 2030	yr2030	-0.05718	-0.1	70
Worst case assumptions			5.5	70
10 more sectors	sectors_co2	0.00070	-0.2	54
Backstop technology	bst_co2	0.03983	-1.3	15
ITC	with_itc_co2	0.00666	-0.2	12
	total of above		-1.7	12
Best case assumptions			3.8	12

Source: Parsimonious equation in Barker *et al.* (2006).

The parsimonious specification of the equation for carbon prices is reported in Table 3 in a similar form to Table 2. It reports the solution of equations to illustrate the various effects on the permit prices and tax rates that are required to achieve a 32% reduction in global CO_2-eq by 2030 for 450ppmCO2-only, the average requirement in the IMCP modelling study. Only three assumptions proved robust enough for parsimonious specification. In the worst case, the price has to be some 70 US$(1995)/t$CO_2$, and this is reduced by about 20% with moderate sectoral disaggregation (10 more sectors) to 54$ and collapses to $15 with backstop technologies and than to $12 with ITC. The effects of the cost-reduction from backstop technologies are not robust to the introduction of model dummies, indicating that there is strong interaction between the modelling approaches and the assumption of a backstop technology. However, it is not surprising that this assumption should have a strong effect on costs, since studies of advanced technologies and GHG mitigation, show cost reductions approaching 100% (Placet *et al*., 2004).

3.3 Summary

The review and summary of the quantitative literature on the costs of greenhouse gas mitigation provides estimates of the GDP costs and the required carbon prices at different levels of atmospheric stabilization. The review (technically a meta-analysis) concludes that the differences between the estimates are primarily the outcome of the assumptions made by the modellers. The lowest stabilization level that has been studied widely is that for 550ppm CO2-eq, at the top end of the range considered by the Stern Review to be dangerous. For this level to be reached by 2100, feasible combinations of different assumptions can yield estimates ranging from a cost of 3% GDP by 2030 to a similar-sized gain of GDP. Carbon prices to achieve this level ranged from 70 US$(1995)/t$CO_2$, in the worst case scenario, to 12 US$(1995)/t$CO_2$ again by 2030, highlighting the importance of modelling assumptions when calculating costs.

4. Extrapolation of the Stern Review meta-analysis to estimate the effects of more stringent targets

This section reports the application of the meta-analysis equation to estimate the macroeconomic costs and associated carbon prices for more stringent targets (450ppmv CO_2-eq and below). This is done by solving the equations under a variety of assumptions, keeping the estimates within the bounds established in the literature. The main assumption required is the reduction in CO_2 emissions below baseline, 2000-2100. We have started with the reductions required for the 550ppmCO_2-eq, at the top end of the Stern review range to avoid dangerous climate change, but not nearly enough to reach the 2ºC target[6].

We find the average reductions in CO_2 from baseline for the 550ppmCO_2-eq for each year from the 18 studies in the IMCP and EMF21 model comparisons (Edenhofer et al., 2006, Weyant, 2004). The average reduction from each set of studies is shown in Figure 2. In order for the 550 target to be met, the CO_2-only results from both sets of studies must be interpreted *as if* they were multi-gas, i.e. as if the carbon prices are also applied, suitably adjusted for global warming potential, to the non-CO_2 greenhouse gases. The EMF21 studies average about 40% by 2050, with a wide range from the underlying studies as shown in the figure. The IMCP average is about 55% (also shown in Barker *et al.,* 2006, p. 22), higher than the EMF21 average, the reason for the greater abatement being the common adoption of a higher emission baseline in many of the studies.

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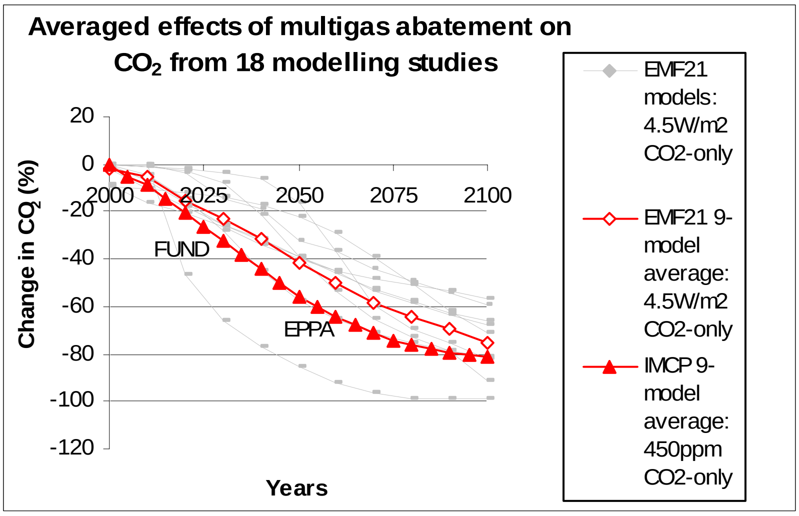
[6] The Stern Review (2006, p. 195) quotes the probabilities of 550ppmCO_2eq concentrations by 2100 leading to temperatures above the 2ºC as between 63% minimum and 99% maximum, with the Hadley Centre ensemble averaging 99%, i.e. it is very unlikely to be achieved. According to the Hadley Centre ensemble, even 3 ºC is likely to be exceeded at these concentrations.

Figure 2: Average reductions below baseline for global CO_2 emissions for 550ppmCO_2-eq concentrations



4.1 Results for Macroeconomic Costs

Table 4: Macroeconomic costs for 2030 in trajectories towards 550ppmCO_2-eq by 2100 for six feasible combinations of assumptions

(% point levels difference from base model run using parsimonious equation from the meta-analysis)

	Meta-analysis	CGE models with CO_2 permit trading		Growth model with CO_2 permit trading and back-stop technology		Econometric model with permit trading	
Assumptions	estimated effects	with lump-sum recycling of revenues	with non-climate benefit and revenue recycling	no ITC effect	with ITC	with lump-sum recycling of revenues	with ITC, env. tax reform and non-climate benefit
Number of reporting models	0	22	2 to 3	12	12	5	2 to 3
Worst-case assumptions	-3.3	-3.3	-3.3	-3.3	-3.3	-3.3	-3.3
Effects of approaches & assumptions:							
CGE model	0.8	0.8	0.8				
Kyoto mechanisms	0.9	0.9	0.9	0.9	0.9	0.9	0.9
‘Backstop’ technology	0.5			0.5	0.5		
Climate benefit	0.5						
Non-climate benefit	1.0		1.0				1.0
Induced technological change (ITC)	2.0				2.0		2.0
Active revenue recycling	3.3		3.3				3.3
Total extra assumptions	9.0						
Best-case assumptions	5.7						
Total difference from base GDP (%)		-1.6	2.7	-1.9	0.1	-2.4	3.9

Source: Barker *et al*., (2006), and this paper.

We solve the equation for costs for every 5-year period 2000-2100, removing the effects of outliers, and using the average reductions in CO_2 from baseline for each year calculated above as necessary to reach the 450ppm target. One other common assumption has been adopted, namely that Kyoto-style mechanisms, such as emission trading with full auctioning of permits, are in place globally from 2010 onwards. With this common assumption, the effects of a set of six combinations of the other assumptions on costs have been calculated.

The results for 2030 are shown in Table 4, taking the quantitative effects shown in Table 2 above and allocating them to form six combinations. The number of studies in the literature adopting similar sets of assumptions is shown in the third row of the table. Note that there are far fewer models showing the effects of active revenue recycling and hence GDP effects above base. Such results are considered in more detail below. A crucial feature of this table is that no models combine all the assumptions that reduce the costs. The reason is that several of the assumptions are either incompatible, or have not been combined in the underlying studies. The message from the table is that different combinations of assumptions yield a wide range of macroeconomic effects and costs, and that GDP can be above of below baseline, depending on the assumptions chosen.

Table 5: Macroeconomic costs for 2030 in trajectories towards 450ppmCO$_2$-eq by 2100 for six feasible combinations of assumptions

(% point levels difference from base model run using parsimonious equation from the meta-analysis)

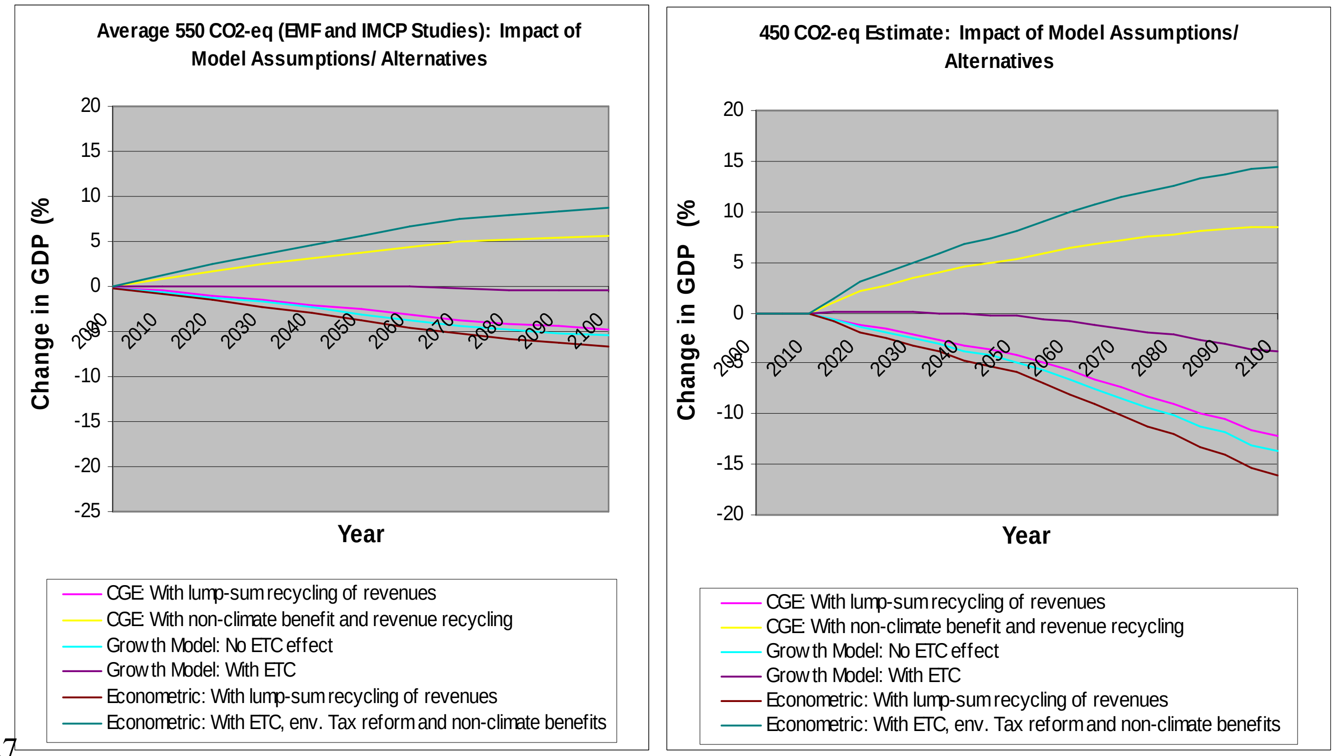
	Meta-analysis	CGE models with CO_2 permit trading		Growth model with CO_2 permit trading and back-stop technology		Econometric model with permit trading	
assumptions	estimated effects	with lump-sum recycling of revenues	with non-climate benefit and revenue recycling	no ITC effect	with ITC	with lump-sum recycling of revenues	with ITC, env. tax reform and non-climate benefit
Number of reporting models	0	22	2 to 3	12	12	5	2 to 3
Worst-case assumptions	-4.4	-4.4	-4.4	-4.4	-4.4	-4.4	-4.4
Effects of approaches & assumptions:							
CGE model	1.0	1.0	1.0				
Kyoto mechanisms	1.1	1.1	1.1	1.1	1.1	1.1	1.1
'Backstop' technology	0.6			0.6	0.6		
Climate benefit	0.6						
Non-climate benefit	1.3		1.3				1.3
Induced technological change	2.6				2.6		2.6
Active revenue recycling	4.3		4.3				4.3
Total extra assumptions	11.5						
Best-case assumptions	7.1						
Total difference from base GDP		-2.3	3.3	-2.7	-0.1	-3.3	4.9

Source: Barker *et al*., (2006), and this paper.

In order to compute the effects for the more stringent target of 450ppmCO_2-eq, a trajectory after 2010 involving much deeper reductions in CO_2 below baseline is assumed. Global CO_2 is taken to be 25% below baseline by 2020, 42% by 2030, 71% by 2050 and 156% by 2100, i.e. removal of 10 GtCO2-eq from the atmosphere by 2100. Table 5 presents the results of the calculations. Essentially both the costs and the benefits are greater. The benefits are greater because the higher carbon prices necessary raise more revenues, and if these are recycled the benefits in terms of more utilization of resources in developing countries is higher. Figure 3 shows the implications for the 550 and 450 ppmCO_2-eq concentrations by 2100 for global GDP. It shows the solutions of the six combinations of assumptions for the whole period, using the average IMCP-EMF21 18-model baseline, and illustrates the results for 2030 given in Tables 4 and 5, but generalizing them for the whole period 2010-2100. Avoiding dangerous climate change becomes more uncertain as the targets become more stringent, but not necessarily more expensive, depending on the approaches and assumptions made.

These estimated costs can be compared with those in the recent literature. The 2007 IPCC WG III Summary for Policymakers (SPM, p. 16) quotes a cost for achieving 445-535ppm CO2-eq stabilization of less than 3% GDP by 2030. This cost is the *highest* across all the post-Third-Assessment-Report modelling studies in the IPCC review. The result is from a CGE model (the US CCSP-IGSM model) with lump-sum recycling, and it does not allow for induced technological change. In fact, this is an outlier scenario, in which the carbon price rises to 1651 US\$/tCO_2 by 2100, partly due to the assumption of the limited substitution of fossil fuels by electricity as an energy source for transportation: 'In the IGSM scenarios, fuel demand for transportation, where electricity is not an option and for which biofuels supply is insufficient, continues to be a substantial source of emissions.' (US CCSP, 2006, p. 4–21).

Figure 3: Effect of six combinations of assumptions policies on GDP for 450 and 550 CO_2-eq



The IPCC 3% cost outlier is above the extrapolated cost of 2.3% in Table 5, column 2, given for the solution for average costs from similar models in the literature, although it is within the range to be expected from econometric models, with lump-sum recycling of tax/permit revenues. Apart from this study, the estimates of the highest GDP costs in the recent literature for the more stringent target (Rao and Riahi, 2006) of 3.9% of GDP by 2100 is well within the range of the estimates in Figure 3.

4.2 Results for Permit Prices and Carbon Tax Rates

The results for carbon prices in 2030 for trajectories towards 550 and 450ppm CO_2-eq stabilization by 2100 are shown in Table 6. Figure 4 illustrates the results for the global carbon price in 2030 from the parsimonious equation for the more stringent level of 450ppm CO_2-eq plus the three levels of stabilisation of the IMCP study. The very large, but unreliable, effect of the backstop technology assumption shown is outweighed by the effect of the targets on the price. For 450ppm CO_2-eq the global price in the worst case assumption is 173 \$US(2000)/tCO_2, falling to 131 \$US(2000)/tCO_2 and 127 \$US(2000)/tCO_2 with ITC and moderate sectoral disaggregation respectively. The effect of backstop technology causes the price to plummet to 24 \$US(2000)/tCO_2.

Table 6: Carbon prices for 2030 in trajectories towards stabilization by 2100 (\$(1995)/tCO_2-eq)

Assumptions	**550ppm CO_2-eq**	**450ppm CO_2-eq**
Worst-case assumptions	50	173
Effects of approaches & assumptions:		
‘Backstop’ technology	-28	-103
Induced technological change (ITC)	-9	-42
10 Sectors	-1	-4
Total extra assumptions	-38	-149
Best-case assumptions	17	24

Figure 4: Permit price/tax rate in 2030: effects of modelling assumptions

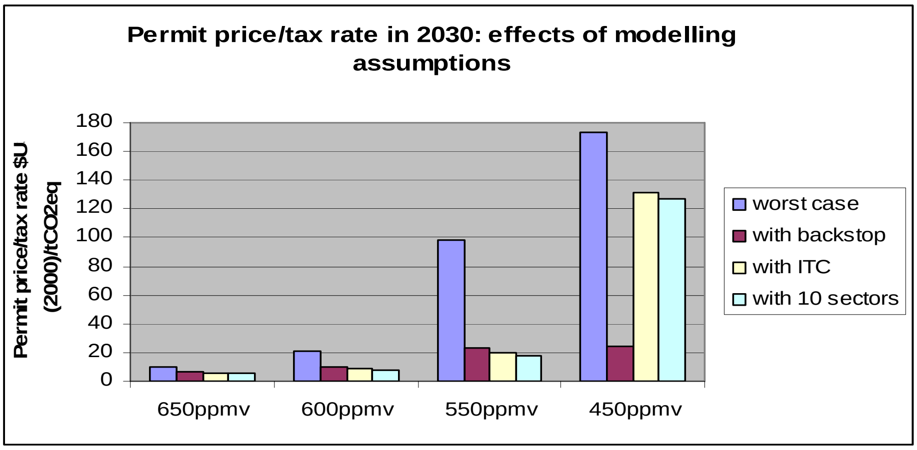
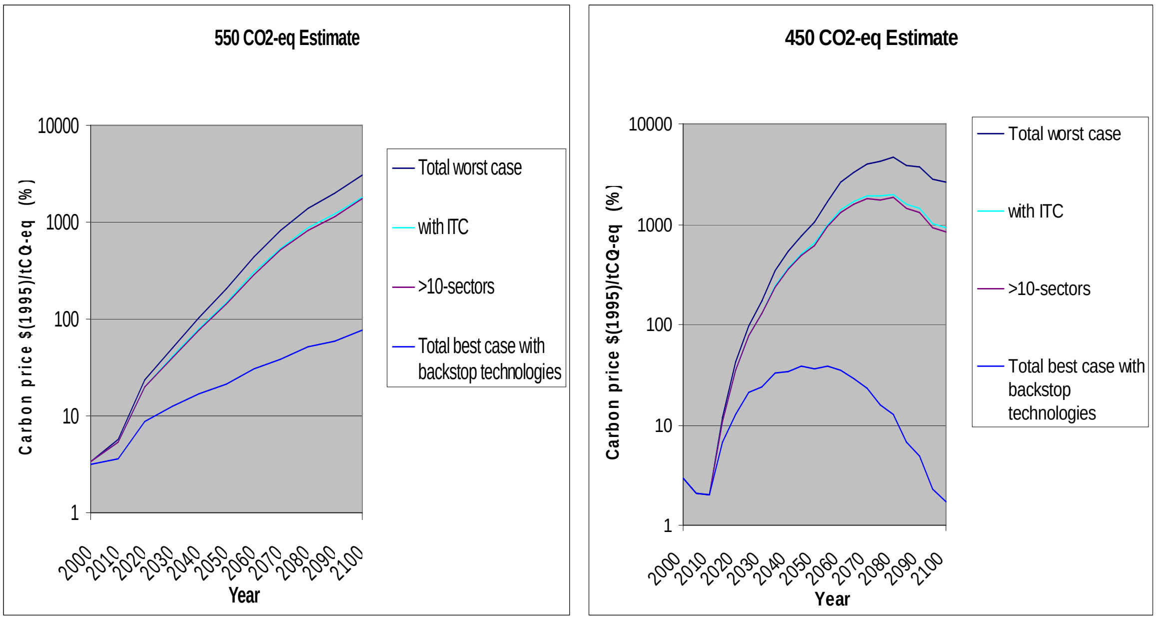


Table 6 and Figure 4 show some important features of the modelling of carbon prices for stabilization.

1. Carbon prices rise very sharply as the stringency of the target increases for the worst case set of assumptions.
2. The treatment of technology is critical to the estimated carbon prices from the modelling. The models have to allow for the response of technology to carbon prices in order to show modest carbon prices for stringent stabilization.
3. The effects of both backstop technology and induced technological change are also much larger as the target becomes more stringent. The high carbon prices in the early years bring backstop technologies into play in those models that have this treatment and the costs of lowered substantially. However, the effect is not robust to the specification of the meta-analysis equation, since the back-stop assumption cannot be reliably distinguished from the models that make the assumption. For the studies that allow for induced technological change, the high carbon prices accelerate change and also bring down the carbon price.
4. What is notable about these results is how small the carbon price being reported by the models has to be to achieve very large reductions in global GHG emissions, when technological change is induced. Global carbon prices to avoid dangerous climate change subsequently are about \$24/t CO_2-eq by 2030 for 450ppm CO_2-eq stabilization by 2100. However, the prices in the models are typically rising. These findings confirm those of other studies, e.g. EMF19 (Weyant, 2004) for 9 models, all of which report carbon tax rates less than 16\$US(2000)/tCO_2-eq in 2030 for 550ppm CO_2-only stabilization (650ppm CO_2-eq).

Figure 5 shows the implications for the 550 and 450 ppmCO_2-eq concentrations by 2100 for carbon prices. It shows the solutions of the three assumptions, including the total worst case, for the whole period, using the average IMCP-EMF21 18-model baseline. Figure 5 illustrates that the range of carbon prices become more uncertain as the target becomes more stringent. The rate of increase for the 450 ppmCO_2-eq target is more rapid than that of the 550 ppmCO_2-eq, however it peaks around 2090, and earlier at 2050 where the backstop technology assumption is included, and then declines until 2100, with the carbon price for the backstop technology assumption dropping to almost zero. This is a result of the non-linear terms in the equation and illustrates the very dramatic reductions in long-term costs when low-cost, low-carbon alternative technologies are assumed to respond to carbon prices. Economies of specialization and scale in the models eventually bring down the carbon price well below the levels required to stimulate the nascent technologies in the early years.

Figure 5: Carbon price 2000-2100: effects of modelling assumptions for 550 and 450 CO_2-eq



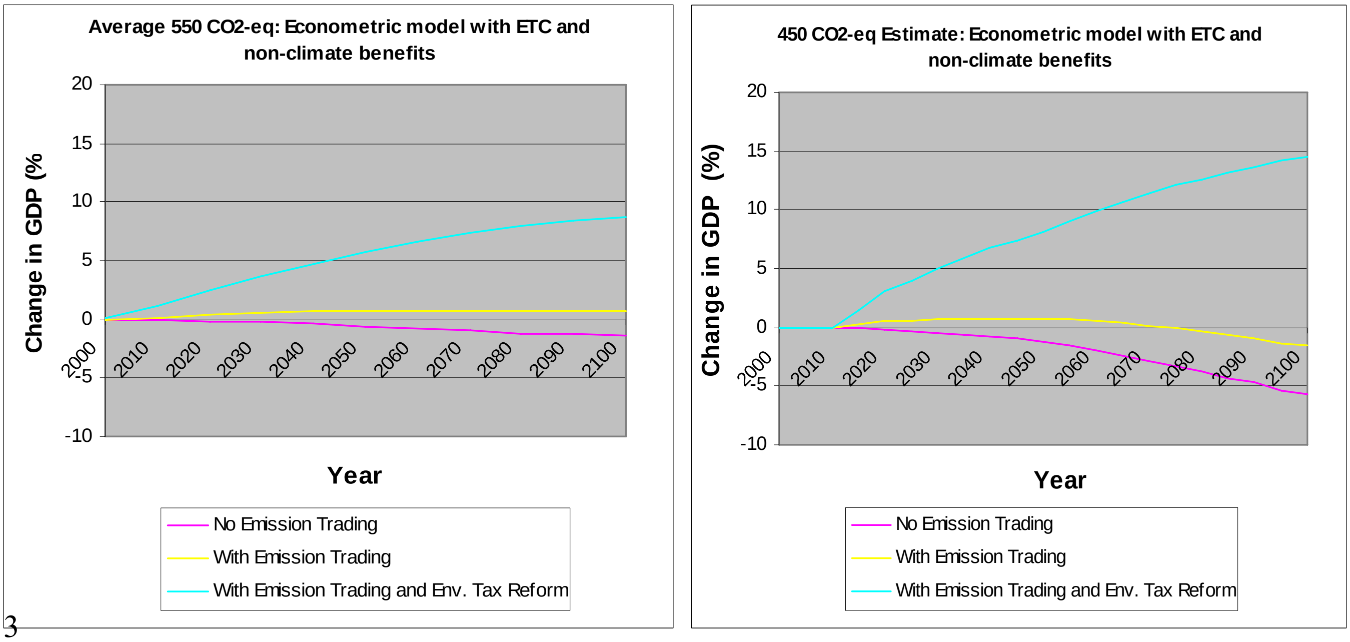
4.3 Summary

The explanation of the costs from the literature for stabilization at different levels can be extrapolated to provide an estimate for more stringent stabilization, more likely to reach the EU target of 2ºC increase above the pre-industrial temperatures. We have assumed a profile of greenhouse gas abatement 2000-2100 to achieve a 450ppm CO_2-eq target and calculated the implications for global GDP costs. The results show a wide range of costs, but depending on the assumptions costs may not necessarily be higher as the stringency of the target increases, although they are more uncertain. The benefits of technologies responding to carbon prices are substantial, with potential benefits for the global economy as well as for the environment.

5. Effective, efficient and equitable policies to avoid dangerous climate change

The results as shown above report costs from different modelling approaches, with different modelling assumptions. We now turn to the policy implications, assuming that the best approach to the modelling is to use econometric estimates of parameters directly estimated from data, rather than guess-estimates from the literature, and assuming that technological change responds to global carbon prices, rather than being fixed in the baseline. No climate benefits are assumed, but non-climate benefits are taken into account. Using this as the baseline, we then examine the effects first of international emission-permit trading, then national environmental tax reform in every country. This a speculative exercise, extrapolating from the results in the literature, but consistent with the studies that have been done for 2030 and earlier years on emission trading and recycling of revenues. Figure 6 shows the new baseline and the effects of emission trading and environmental tax reform for both concentration targets, showing the potential benefits of a global scheme and reforms of national tax systems.

Figure 6: Effect of emission trading and environmental tax reform on GDP for 450 and550 CO_2-eq



5.1 International emission-permit trading

The IPCC Third Assessment Report covered this issue in detail and concluded that trading would reduce mitigation costs substantially, effectively cutting the assessed macroeconomic costs in half. The treatment here is more general, but clearly costs come down when the most efficient options for mitigation are implemented wherever they are.

5.2 Use of revenues from auctioned permits and carbon taxes

Despite the fact that the models include carbon taxes and auctioned emission permit schemes, the use of the government revenues often goes unmentioned, although they are large scale, especially in earlier years with high emissions and high carbon prices. The most common treatment is simply not to have a government sector and ignore fiscal (and monetary) policy, other than to allow relative price changes through a carbon tax.

However, the use of these revenues can have a significant macroeconomic impact. Gaskins and Weyant (1993) report the results of the EMF12 comparison of modelling results on the macroeconomic costs of reducing US CO_2 emissions by up to 30% by 2010, compared with 1990 levels. Most of the 14 modelling teams used lump-sum payments to consumers as the means of recycling the carbon tax revenues. However, four of the modellers considered how costs might be reduced by the active use of the revenues to reduce taxes that discourage economic activity. They found that the costs of a 20% reduction in CO_2 for the US by 2010 were in the range 0.9 to 1.7% of GDP with lump-sum recycling. When the revenues were used to reduce taxes in the models, these costs were reduced substantially, by 35% to over 100%, particularly if the taxes on capital formation are reduced. Jorgensen and Wilcoxen, using the DGEM model covered by the EMF12 study, state: "Lump-sum recycling is probably not the most likely use of the revenue. ... Using the revenue to reduce a distortionary tax would lower the net cost of a carbon tax by removing inefficiency elsewhere in the economy." (Jorgensen and Wilcoxen, 1993, p.20). This is precisely the effect that they find when they reduce distortionary taxes to offset a carbon tax; a 1.7% GDP loss under lump-sum redistribution is converted to a 0.7% loss by reducing labour taxes or to a 1.1% gain by reducing capital taxes (1993, Table 5 p.22).

Goulder (1995) has also examined the effects of changing the recycling assumption. The GDP cost as a result of a carbon tax of $25/tC is reduced by 40-55% over the long run when the revenues are recycled via reductions in marginal rates of personal income tax rather than lump sum. The EIA (1998) finds that if the recycling assumption is changed from lump-sum so that revenues are used to reduce social security payments by employees and businesses, the costs fall from 4.1% to 1.9% of GDP in 2010 and then to a negligible 0.2% in 2020 (Table ES6). The IPCC Third Assessment Report reviewed this and other literature (2001, pp 514-519) and found many instances of improvement of national welfare associated with reductions in GHGs, when tax revenues are recycled through reductions in employment taxes, especially in Europe.

More recently, Barker *et al.*, 2002 and 2006 show that making a tax fiscally neutral, through reducing other taxes such as personal income tax or labour taxes can increase GDP compared with a baseline case. Köhler *et al.* (2007) show that this also occurs in the transport sector, where the estimated social costs of transport can be as high as 1-2% of GDP in e.g. European countries.

One of the most serious weaknesses in nearly all the models is the assumption that the world economy is at full employment in the base year and throughout the projection. This may be more or less true at the national level for some OECD countries, but it is not the case for many other countries, especially very low-income economies. If resources, such as underutilised labour in traditional industries, can be mobilised more or less effectively, then there is room for global climate policies to reduce unemployment and accelerate development. It is the availability of under-utilized resources that allows the recycling of tax revenues to increase output and employment so substantially.

5.3 Summary

Starting with a baseline projection of costs to avoid dangerous climate change, which includes an estimate of the co-benefits of reducing local air pollution, we have examined how international policy coordination can reduce these costs. We find that international emission-permit trading can reduce costs substantially, a finding that fits with the conclusions of the IPCC Fourth Assessment Report (2007). However when, in addition, national environmental tax reform is undertaken in every country, the costs turn into substantial benefits. This a speculative exercise, extrapolating from the results in the literature, but consistent with the IPCC studies that have been done for 2030 and earlier years on emission trading and recycling of revenues.

6. Conclusions

International action by many countries is necessary if dangerous climate change is to be avoided. Global emission trading and environmental tax reform are necessary if the costs are to be manageable and turned into benefits for social welfare and the market economies. In terms of previous policy co-operation, this is an unprecedented challenge, both in scale and duration. Fortunately it is not all or nothing, because even limited trading and tax reform will produce benefits for the countries implementing them. However, the largest gains come from global action, for two basic reasons. First, since one country's exports are another country's imports, the world economy being a closed economic system, environmental tax reform in one country will also benefit those countries that export to that country. The positive multiplier effects on employment and growth are re-enforced if the reform is coordinated internationally. Second, the world market (as opposed to the national market) provides the greatest scope for niche technologies, allowing economies of scale and specialization to reduce costs and encourage adoption of low-GHG products and processes.

The overall conclusion from the modelling literature is that even stringent stabilisation targets can be met without materially affecting world GDP growth, at low carbon tax rates or permit prices under several sets of feasible assumptions. The opportunity for so-called "deep green" growth comes from the potential offered by the auctioning of GHG permits to raise substantial revenues as contributions to national fiscal budgets. If these revenues are used to improve economic performance, by subsidising innovation, or improving the health and well-being of workers, or reducing inefficiencies in energy and other resource use, then the additional GDP growth could more than offset the costs of transforming the energy system. There are possibilities of global co-ordinated policy actions that benefit all participants, including fossil fuel producers.

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Annex

Table A1: Definitions of Variables

Variable	Description	Name
GDP change from Baseline	%	**GDP**
CO_2 change from Baseline	%	**CO_2**
Induced Technical Change (1=yes)	0 or 1 binary	**with_itc**
Recycling of revenues (=1) (not lump-sum)	0 or 1 binary	**recy**
Climate benefit (=1) eg less damage from climate change	0 or 1 binary	**cben**
Non-climate benefit (=1) eg reduction of pollution	0 or 1 binary	**ncbens**
Use of Kyoto mechanisms (=1) JI or ETS or CDM	0 or 1 binary	**km**
Computational General Equilibrium (=1)	0 or 1 binary	**cge**
Backstop technology (1 = yes)	0 or 1 binary	**bst**
Target: 450 ppm CO_2 (=1) or otherwise (=0)	0 or 1 binary	**d450ppmv**
Model dummy for Feemrice Bosetti et al. (2006)	0 or 1 binary	**feemrice**
Model dummy for Imaclim Crassous et al. (2006)	0 or 1 binary	**imaclim**
Model dummy for Demeter Gerlagh (2006)	0 or 1 binary	**demeter**

Table A2: The Equation used for Extrapolating GDP costs

```
-----------------------------------------------------
             |               Robust
         gdp |      Coef.   Std. Err.      t    P>|t|
-----------------------------------------------------
         co2 |   .0659585   .0056165    11.74   0.000
   co2square |  -.0002467   .0000801    -3.08   0.002
with_itc_co2 |  -.0632661   .0038994   -16.22   0.000
    recy_co2 |  -.1032893   .0052028   -19.85   0.000
    cben_co2 |  -.0154941    .001639    -9.45   0.000
  ncbens_co2 |  -.0303409   .0135219    -2.24   0.025
      km_co2 |  -.0269851   .0031972    -8.44   0.000
     cge_co2 |  -.0247622   .0027115    -9.13   0.000
     bst_co2 |  -.0154177   .0026445    -5.83   0.000
feemricefa~2 |  -.0502551   .0038374   -13.10   0.000
 imaclim_co2 |   .4827249   .0388887    12.41   0.000
demeter_co22 |   .0008234   .0000932     8.84   0.000
imaclim_co22 |   .0047035   .0004958     9.49   0.000
d450ppmv_co2 |    .025656   .0039061     6.57   0.000
       _cons |  -.0974674   .0450429    -2.16   0.031
Number of obs =    1471
F( 14,  1456) =  120.49
Prob > F      =  0.0000
R-squared     =  0.7860
Root MSE      =  1.8395
-----------------------------------------------------
Source: Barker et al. (2006), Equation B3, Parsimonious Specification for WRI-post-SRES-IMCP
Model Results for Changes in GDP with Model Characteristics and Outliers.
Note than calculations are done using the panel data package STATA, version 9.
```

Table A3: The Equation used for Extrapolating Tax/Permit Rates

```
------------------------------------------------------------------------------
             |               Robust
       lntax |      Coef.   Std. Err.      t    P>|t|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
         co2 |  -.0277956   .0072863    -3.81   0.000    -.0420975   -.0134937
   co2square |  -.0005673    .000085    -6.67   0.000    -.0007342   -.0004004
with_itc_co2 |   .0066628   .0011898     5.60   0.000     .0043275    .0089982
     bst_co2 |   .0398307   .0043778     9.10   0.000     .0312377    .0484237
d550ppmv_co2 |  -.0641544   .0055489   -11.56   0.000     -.075046   -.0532628
d500ppmv_co2 |  -.0773688   .0056183   -13.77   0.000    -.0883967   -.0663409
d450ppmv_co2 |   -.087339   .0056274   -15.52   0.000    -.0983847   -.0762933
 sectors_co2 |   .0007034   .0001244     5.65   0.000     .0004592    .0009476
feemricef~22 |  -.0004835   .0000818    -5.91   0.000     -.000644   -.0003231
feemrices~22 |   -.000368   .0000738    -4.98   0.000    -.0005129   -.0002231
imaclim_co22 |   -.000284   .0000657    -4.32   0.000     -.000413    -.000155
imaclim_wi~c |  -.4846085   .0856708    -5.66   0.000    -.6527676   -.3164495
    mind_co2 |  -.0745168   .0063549   -11.73   0.000    -.0869904   -.0620431
   mind_co22 |  -.0006003   .0000932    -6.44   0.000    -.0007832   -.0004173
mind_with_~c |  -.9613063   .1267167    -7.59   0.000    -1.210032   -.7125803
demeter_wi~c |  -1.204375   .1264238    -9.53   0.000    -1.452527   -.9562244
enticebr_co2 |  -.0164037    .002233    -7.35   0.000    -.0207869   -.0120206
       y2005 |  -.3225579   .3318059    -0.97   0.331    -.9738433    .3287274
       y2010 |  -.3766299   .3475635    -1.08   0.279    -1.058845    .3055854
       y2015 |  -.0021868   .3189684    -0.01   0.995    -.6282741    .6239004
       y2020 |   -.043784   .3302464    -0.13   0.895    -.6920084    .6044405
       y2025 |   .1230102   .3179403     0.39   0.699    -.5010592    .7470796
       y2030 |  -.0571846    .331025    -0.17   0.863    -.7069374    .5925681
       y2035 |   .0832063   .3205133     0.26   0.795    -.5459134    .7123261
       y2040 |  -.0191998   .3366588    -0.06   0.955    -.6800107    .6416111
       y2045 |   .0640452   .3254916     0.20   0.844    -.5748462    .7029366
       y2050 |   .0233812   .3336628     0.07   0.944    -.6315491    .6783114
       y2055 |   .1636431   .3220966     0.51   0.612    -.4685844    .7958706
       y2060 |   .3229551   .3241905     1.00   0.319    -.3133824    .9592925
       y2065 |   .4189956   .3183435     1.32   0.188    -.2058651    1.043856
       y2070 |   .5765812   .3226783     1.79   0.074     -.056788     1.20995
       y2075 |   .6878618   .3195991     2.15   0.032     .0605365    1.315187
       y2080 |   .8915317   .3276193     2.72   0.007     .2484639    1.534599
       y2085 |    .941165   .3239459     2.91   0.004     .3053076    1.577022
       y2090 |    1.11072   .3326768     3.34   0.001     .4577251    1.763715
       y2095 |   1.224558   .3336562     3.67   0.000     .5696411    1.879475
       y2100 |   1.433556   .3540804     4.05   0.000      .738549    2.128563
       _cons |   2.484546   .3005617     8.27   0.000     1.894588    3.074504
Number of obs =     861
F( 37,   823) =  136.10
Prob > F      =  0.0000
R-squared     =  0.8243
Root MSE      =  .69727

Source: Barker et al. (2006), Equation B7 Parsimonious Specification for WRI-post-SRES-IMCP
Model Results for Tax/Permit Rates with Model Characteristics and Outliers.
Calculations are done using the panel data package STATA, version 9
```