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The Feasibility of Low Concentration Targets: An Application of *FUND*

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Abstract: I study the feasibility of stringent targets for stabilizing ambient greenhouse gas concentrations. Climate policy has diminishing returns, and there is therefore a maximum to what can be achieved. The success of climate policy is hampered if the terrestrial biosphere turns from a carbon sink to a carbon source because of climate change. All major countries have to reduce their emissions in order to meet the more ambitious stabilization targets. The cost of climate policy would be lower if the stabilization target can be exceeded in the interim. The EU target of 2ºC warming above pre-industrial is infeasible under almost all assumptions. A cost-benefit analysis would endorse a target of 4.5 Wm^{-2} (but not much stricter than that) if all major emitters engage in abatement. Under the same condition, the median US voter would support a 3.7 Wm^{-2} target (but not much stricter than that). International permit trade would encourage large developing countries to reduce emissions, but the trade flows would be substantial relative to product trade and much larger than official development aid.

Key words: International climate policy; greenhouse gas emission reduction

JEL Classification: Q54

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1. Introduction

Politicians aspire to deep cuts in greenhouse gas emissions. The European Union has pledged to reduce 2050 emissions to 50% of their 2005 levels. President Obama has made a similar promise. The United Kingdom even wants to cut emissions by 80% by mid-century. These are aspirations only, but they do beg the questions whether such deep targets are desirable and even feasible. This paper, together with the other papers in this special issue, contributes to answering these questions.

Previous papers have studied the feasibility of stringent targets for climate policy (den Elzen et al. 2007;Edmonds et al. 2008b;Edmonds et al. 2008a;van Vuuren et al. 2006). Few studies, however, explicitly report on the potential infeasibility (van Vuuren, Eickhout, Lucas, & den Elzen 2006). The Fourth Assessment Report of the Intergovernmental Panel on Climate Change (Barker et al. 2007) suggests that deep emission cuts are feasible, but their summary unfortunately suffers from selection bias. That is, their cost estimates do not correct for the fact that some models do not report results for some policy targets because these targets cannot be met according to these models (Tol 2007). This special issue sheds some light on the matter by focusing on three targets for the stabilization of the concentrations of greenhouse gases, at least one of which is potentially infeasible. The current paper, however, considers a continuum of targets and spans the feasibility space – at least for a single model. I also show a range of sensitivity analyses. Furthermore, I go beyond technical feasibility and assess the political feasibility of climate policy targets, which are, after all, self-imposed.

The paper continues as follows. Section 2 sketches the model. The results are presented in two parts. In Section 3, we look at the effect of a range of carbon taxes in a range of circumstances, with regard to both the parameterization of the model and the timing of the imposition of the carbon tax. In Section 4, we compare the carbon taxes to the stated willingness to pay and the estimated social cost of carbon; and we assess the income transfers needed to sustain early involvement of non-OECD countries in climate policy. Section 5 concludes.

2. Model and scenarios

I use Version 2.9 of the Climate Framework for Uncertainty, Negotiation and Distribution (FUND). Version 2.9 of FUND has the same basic structure as previous versions (Tol 1999;Tol 2005;Tol 2006). The source code and a complete description of the model can be found at http://www.fund-model.org/.

Essentially, FUND is a model that calculates impacts of climate change and climate policy for 16 regions of the world by making use of exogenous scenarios of socioeconomic variables. The scenarios comprise of projected temporal profiles of population growth, economic growth, autonomous energy efficiency improvements and carbon efficiency improvements (decarbonization), emissions of carbon dioxide from land use change, and emissions of methane and of nitrous oxide. Carbon dioxide emissions from fossil fuel combustion are computed endogenously on the basis of the Kaya identity. The calculated impacts of climate change perturb the default paths of population and economic outputs corresponding to the exogenous scenarios. The model runs from 1950 to 2300 in time steps of a year, though the outputs for the 1950-2000 period is only used for calibration, and the years beyond 2100 are used for the approximating the social cost of carbon under low discount rates. The scenarios up to the year 2100 are based on the EMF14 Standardized Scenario, which lies somewhere in between IS92a and IS92f (Leggett et al. 1992). For the years from 2100 onward, the values are extrapolated from the pre-2100 scenarios. Radiative forcing is based (Shine et al. 1990). The global mean temperature is governed by a geometric buildup to its equilibrium (determined by the radiative forcing) with a half-life of 50 years. In the base case, the global mean temperature increases by 2.5˚C in equilibrium for a doubling of carbon dioxide equivalents.

FUND has elaborate modules for the impact of climate change (Tol 2002), but these are not used here.

FUND considers emission reduction of the three main greenhouse gases: carbon dioxide, methane, and nitrous oxide. For methane and nitrous oxide, simple abatement cost curves are used (Tol 2006). For carbon dioxide, the model is more elaborate. Initially, marginal abatement costs rise more than proportionally with abatement effort, but marginal costs become linear above \$100/tC. There are mild intertemporal spillovers between and within regions that reduce costs (Tol 2005). In the early decades, a 1% emission reduction from baseline would cost roughly 0.01% of GDP, and a 10% reduction would cost 1%.

The atmospheric concentration of carbon dioxide follows from a five-box model:

(1a) $Box_{i,t} = \rho_i Box_{i,t} + 0.000471 \alpha_i E_t$

with

(1b) $C_t = \sum_{i=1}^{5} \alpha_i Box_{i,t}$

where α_i denotes the fraction of emissions E (in million metric tonnes of carbon) that is allocated to *Box i* (0.13, 0.20, 0.32, 0.25 and 0.10, respectively) and ρ the decay-rate of the boxes (ρ = exp(-1/lifetime), with life-times infinity, 363, 74, 17 and 2 years, respectively). The model is due to (Maier-Reimer & Hasselmann 1987), its parameters are due to (Hammitt et al. 1992). Thus, 13% of total emissions remains forever in the atmosphere, while 10% is – on average – removed in two years. Carbon dioxide concentrations are measured in parts per million by volume.

There is a feedback from climate change on the amount of carbon dioxide that is stored and emitted by the terrestrial biosphere. Instead of modelling the full dynamics, I keep the uptake by the terrestrial biosphere as it is – that is, Equation (1) is not affected – and add emissions from the terrestrial biosphere. Emissions from the terrestrial biosphere follow:

(2a) $E_t^B = \beta\left(T_t - T_{2000}\right)\frac{B_t}{B_{\max}}$

with

(2b) $B_t = B_{t-1} - E_{t-1}^B$

where E^B are emissions (in million metric tonnes of carbon); t denotes time; T is the global mean temperature (in degree Celsius); B_t is the remaining stock of potential emissions (in million metric tonnes of carbon; B_{max} is the total stock of potential emissions; B_{max} = 1,900 gigatonnes of carbon; β is a parameter; β = 2.6 GtC, with a lower and upper bound of 0.6 and 7.5 GtC. The model is calibrated to (Denman et al. 2007).

The policy scenarios are described in Clarke et al. (this volume). To recap, there are three targets (2.6, 3.7 and 4.5 Wm^{-2}) for the radiative forcing of the gases regulated by the Kyoto Protocol. Note that FUND only considers carbon dioxide, methane, nitrous oxide, and sulfur hexafluoride, while there is no option to reduce SF_6. Emissions are reduced by imposing a carbon tax that rises with the discount rate. Implicitly, the stock of permissible emissions is treated as an exhaustible resource (Hotelling 1931), or unconstrained banking and borrowing is allowed. The targets can be met with and without overshoot, that is, we either consider radiative forcing in 2100 or the maximum radiative forcing over the 21st century. Emission reduction starts in 2013 in the countries of the OECD (in FUND: USA, Canada, Western Europe, Eastern Europe, Japan and South Korea, and Australia and New Zealand); in 2013 or 2030 in the BRIC countries (in FUND, South America, former Soviet Union, South Asia, and China); and in 2013 or 2050 in the rest of the world. Note that the delayed participation scenarios are irrational: Because of the slow turnover of the capital stock, any future emission reduction target should lead to immediate emission reduction. Note also that the delayed participation scenario also has a transition period, in which marginal abatement costs rise faster than the discount rate. Abatement is time inconsistent during this transition period. This implies that results are somewhat peculiar, as shown below.

3. Technical feasibility

Figure 1 shows target radiative forcing as a function of the initial carbon tax in 2013. All regions implement the same tax from 2013 onwards. The baseline scenario is FUND. The terrestrial carbon cycle feedback is set at its best guess. Three alternative targets are chosen. First, the target is the maximum radiative forcing in the 21st century. Second, the target is radiative forcing in the year 2100. This target allows for some overshoot, that is, radiative forcing may be higher before 2100. Third, the target is radiative forcing in the year 2200. This allows for considerable overshoot.

Figure 1 reveals that target radiative forcing declines rapidly for small carbon taxes. However, the incremental effect of a tax increase shrinks as the tax gets higher, and the curve goes almost flat for very high taxes. For low taxes, it does not make much of difference whether the target is the maximum radiative forcing or radiative forcing in 2100. For higher taxes, there is a difference. Specifically, the 2.5Wm^{-2} target cannot be met without overshoot (for an initial tax below \$1000/tC). If the radiative forcing target is for 2200, more can be achieved for the same tax, but of course at the price of greater global warming in the intermediate period.

Figure 2 shows radiative forcing in 2100 as a function of the initial carbon tax using the same definition as in Figure 1, that is, greenhouse gases only. Figure 2 also shows all radiative forcing – which matters for climate change. The qualitative pattern is similar, but the difference is about 1 Wm^{-2}. That is, the targets shown in Figure 1 (and Figures 3-6) are potentially misleading in that they suggest that deeper targets are feasible than is really the case. Figure 2 also shows radiative forcing in the very long term. In the carbon cycle model (Equation 1), some 13% of carbon dioxide stays in the atmosphere forever. If all greenhouse gas emissions are driven to zero, carbon dioxide concentrations will not revert to pre-industrial times. Figure 2 shows the committed radiative forcing, which much lower than radiative forcing in the 21st century. Policy can cut committed radiative forcing from 2.5 Wm^{-2} to 1.0 Wm^{-2}, and can come close to that for a relatively modest initial carbon tax. That is, really deep targets are feasible *in the very long run*. Finally, Figure 2 shows the global mean warming in 2100. Without climate policy, the world would warm some 3.5ºC. This can be kept below 2.0ºC (in the 21st century), but only for a carbon tax of \$1000/tC, starting in 2013 and rising with the rate of discount, and applied to all greenhouse gas emissions in all countries.

Figure 3 shows the maximum radiative forcing in the 21st century as a function of the initial carbon tax in 2013. The baseline scenario is FUND. The terrestrial carbon cycle feedback is set at its best guess. Four alternative targets are considered. First, all regions implement the same tax from 2013 onwards. Second, the OECD regions implement the same tax from 2013 onwards. China, the former Soviet Union, South America, and South Asia have a zero tax between 2013 and 2030, and then jump to the current OECD tax from 2031 onwards. The remaining regions have a zero tax between 2013 and 2050, and then jump to the OECD tax. Third, the non-OECD regions start taxing greenhouse gas emissions in 2030 and 2050, respectively, but approach the OECD tax level linearly in a 20 year transition period. Fourth, the non-OECD regions start taxing emission in 2050 and 2070, and linearly approach the OECD tax within 20 years.

Figure 3 reveals a general pattern that is similar to that in Figure 1. It also shows that any delay in non-OECD country participation comes at a substantial price. For any given tax, radiative forcing increases if fewer countries participate. Particularly, while the 2.6 Wm^{-2} target is infeasible (initial tax > \$1000/tC) with full participation, the 3.7 Wm^{-2} target becomes very expensive with a 20/40 year delay in non-OECD participation, and infeasible with a 40/60 year delay.

Figure 4 shows the maximum radiative forcing in the 21st century as a function of the initial carbon tax in 2013. All regions implement the same tax from 2013 onwards. The terrestrial carbon cycle feedback is set at its best guess. Five alternative baseline scenarios are considered: FUND, and the four IPCC SRES scenarios (IMAGE Team 2001).

Figure 4 reveals that the general pattern observed in Figures 1 and 3 is robust to the details of the baseline scenario. In scenarios with higher baseline emissions, it is more expensive to reach a given target. The difference is particularly pronounced for the 3.7 Wm^{-2} target, while the 2.6 Wm^{-2} is infeasible in all scenarios.

Figure 5 shows the maximum radiative forcing in the 21st century as a function of the initial carbon tax in 2013. All regions implement the same tax from 2013 onwards. The baseline scenario is FUND. Four alternative strengths of the terrestrial carbon cycle feedback are considered, including no feedback at all.

Figure 5 reveals that the general pattern observed in Figures 1, 3 and 4 is robust to the terrestrial carbon cycle feedback. If the terrestrial carbon cycle feedback is weaker than expected, meeting any target becomes cheaper, but the 2.6 Wm^{-2} target remains infeasible. However, if the terrestrial carbon cycle is stronger than expected, meeting any target becomes more expensive, and the feasibility of the 3.7 Wm^{-2} target becomes doubtful.

The feedback of the terrestrial carbon cycle has another effect, not shown in Figure 5. Without a carbon tax, the maximum radiative forcing is attained in 2100. Without the feedback of the terrestrial carbon cycle, a carbon tax reduces the maximum radiative forcing, and shifts it to an earlier year. For very high taxes, the maximum may be as early as 2017. However, with a terrestrial carbon cycle feedback, the maximum is not shifted in time. That is, the already committed warming is such that emissions from the terrestrial biosphere will lead to a steady increase in the concentration of carbon dioxide, regardless of climate policy.

Figure 6 shows the maximum radiative forcing in the 21st century as a function of the initial carbon tax in 2013. All regions implement the same tax from 2013 onwards. The baseline scenario is FUND. The terrestrial carbon cycle feedback is set at its best guess. The costs of emission reduction are halved, separately for carbon dioxide, methane, and nitrous oxide.

Figure 6 reveals that the general pattern observed in Figures 1 and 3-5 is robust to the assumptions about abatement costs. Lower abatement costs means that any given tax can be met at lower price. Figure 6 reveals that the costs of carbon dioxide emission reduction are most important, followed by methane. Halving the costs of emission reduction does not render the 2.6 Wm^{-2} feasible.

4. Political feasibility

Section 3 studies what target can be reached at what cost. It is unlikely, however, that climate policy will be implemented at any cost. Exactly what cost is acceptable is, of course, uncertain. I therefore consider two alternative ways of looking at this question: cost-benefit analysis and willingness to pay. Section 3 finds that climate policy would be considerably cheaper (for the same target) or more effective (for the same cost) if non-OECD countries reduce their emissions as well – but few of these countries have shown any willingness. I therefore also consider the capital flows that would be needed to ensure non-OECD participation. Before all that, however, I discuss the impact of the 9 feasible EMF22 policies.

4.1. Economic impact

Table 1 summarizes the costs of meeting the three radiative forcing targets of the EMF22 exercise, with and without overshoot, and with and without a delay in the participation of non-OECD countries. Figure 7 depicts the net present cost and the initial carbon tax. Table 2 shows the implications for carbon dioxide emissions.

Table 1 reveals moderate costs of emission reduction for the countries of the “OECD” for the less stringent target, and considerable costs for the 2.6 Wm^{-2} target. Still, the 20% drop in GDP in 2100 relative to the baseline scenario should be seen against an increase in GDP of 330% between 2010 and 2100 in the baseline scenario. Non-OECD countries register higher losses than the OECD because their economies are more carbon-intensive to start with. Yet, abatement costs are small relative to the projected economic growth. While a delay in climate policy would lead to lower (or zero) costs in the short-term, the long-term costs are higher because the carbon tax is disproportionally higher to make up for the decades without abatement.

Figure 7 reveals that the stabilization target is by far the most important driver of the cost of emission reduction, followed by the degree of participation. Whether overshoot is allowed or not is of secondary concern, particularly with full participation and less ambitious targets. Figure 7 also shows that, for any pairwise comparison of policies, the carbon tax accelerates faster than the net present cost if (a) the target is made more stringent; (b) participation is restricted; and (c) overshoot is disallowed.

Table 2 shows that, regardless of the target and the country, the economy is almost completely decarbonised by 2100: emissions are 90% or more below baseline, and 80% or more below 2000. Differences appear in 2050, but emission reduction (from baseline) is greater than 35% in all policies and regions, and greater than 70% in non-OECD regions. The difference between OECD and non-OECD underlines that abatement is cheaper outside the OECD. The carbon tax needs to be so high to achieve the lower targets because low targets cannot be met without emission reduction in the OECD. Indeed, for the 4.5 Wm^{-2} target with full participation, OECD emissions continue to increase (relative to 2000) until 2050, albeit more slowly than in the baseline scenario. The differences between policies and regions are even starker in 2020. Hardly any emission reduction is required in the OECD to meet the 4.5 Wm^{-2} target, while the 2.6 Wm^{-2} requires a 90% (from baseline) emission reduction in the Rest of the World.

4.2. Cost-benefit analysis

In a cost-benefit analysis, emission reduction is chosen such that the marginal abatement cost equals the marginal benefit, that is, the climate damage avoided. Figure 8 shows the survival function (one minus the cumulative density function) of the marginal benefit of emission reduction (Tol 2008). Figure 8 also shows the initial carbon tax for the 9 policies of Table 1.

Figure 8 reveals that there is almost a 60% chance that a 4.5 Wm^{-2} target would pass the cost-benefit test, if all countries participate from 2013 onwards. However, the probability of passing the cost-benefit test drops to below 40% if non-OECD regions delay abatement. With full participation, a 3.7 Wm^{-2} target has only a 30% chance of passing the cost-benefit test, and this drops to below 5% with delayed actions outside the OECD.

4.3. Willingness to pay

Cost-benefit analysis of climate change is controversial, and estimates of the marginal damage cost of climate change are uncertain. Instead, one could directly estimate the willingness to pay for climate policy. Figure 9 shows the results of the three studies that have done this (Lee & Cameron 2008;Li et al. 2004;Viscusi & Zeckhauser 2006), each of which estimates the fraction of the US population who would be willing to sacrifice a given share of their income in return for reduced greenhouse gas emissions. As in Figure 7, this is compared to the costs of selected policies from Table 1.

Figure 9 reveals that the median US household would support a 3.7 Wm^{-2} target, perhaps without immediate action outside the OECD. This is in contrast to the results shown in Figure 8. Figure 9 also reveals that more aggressive targets would be supported by a minority of US households only; and that more lenient targets would gather widespread support.

4.4. International transfers

The results above reveal that climate policy would be substantially cheaper (for a given target) or that policy targets could be substantially more ambitious (for a given willingness to pay) if all countries agree to reduce emissions. To date, only OECD countries have shown the political will to abate greenhouse gas emissions, and key non-OECD countries have explicitly ruled this out in the short and medium term. Therefore, some form of side payment would be necessary to induce non-OECD countries to reduce their emissions.

Table 3 shows one form of side payment. The results in Table 3 assume that there is a worldwide market for greenhouse gas emission permits. The emission allocation of the BRIC countries equals their emissions in the baseline scenario until 2030, and their emissions in the “delayed participation” between 2030 and 2050. The emission allocation of the Rest of the World equals their emissions in the baseline scenario. The emission allocation of the OECD is such that the global emission cap equals that in the “full participation” scenario – that is, the OECD makes good the shortfall in emission reduction in the non-OECD countries. Under these assumptions (and abstracting from the impact of permit trade on economic growth), the permit price equals the carbon tax in the "full participation" scenario, and the trade volume is the difference in emissions between the "full participation" and the "delayed participation" scenarios. Table 3 shows the trade volume, the price, and the trade value relative to GDP.

The trade volume is rather substantial. As shown in Table 2, countries in the Rest of the World would see a decarbonisation of 70% by 2050 for the 4.5 Wm^{-2} target, and a 90% decarbonisation for the 3.7 Wm^{-2} target. As these countries have no targets, all of this is covered by permit trade. Relative to the baseline emissions of the OECD, the trade volume rises from slightly over 15% in 2020 to slightly under 50% in 2050 for the 4.5 Wm^{-2} target. For the 3.7 Wm^{-2} target, it starts around 50% in 2020, exceeds 100% in 2030 and then falls to around 50% in 2050 again. These are large numbers. For instance, the European Union has proposed a limit on the use of the Clean Development Mechanism of 3% of EU emissions for the period 2013-2020.

The trade value is substantial too. The value of imported permits ranges between 0.1 and 3.3% of GDP for the OECD. These numbers are very high if permit trade were seen as development aid, as it is at present (Michaelowa & Michaelowa 2007). Official development aid has been in the range of 0.1 to 0.3% of GDP in the last 40 years. If permit trade were seen as trade, the numbers are not as large. On average, OECD countries imported some 20% of total final expenditure on goods and services. Of course, most OECD imports are from other OECD, so there would be a substantial shift in trade. Permit exports could rise to almost 20% of GDP for the Rest of the World, an unprecedented commercial opportunity for some of these countries.

Figure 10 shows the net present value of the consumer and producer surplus of permit trade. The OECD has a consumer surplus only, and the Rest of the World has a producer surplus only, while the BRIC countries shift from exporters to importers of emission permits. Figure 10 shows the net present value because interregional trade interacts with intertemporal trade (aka banking and borrowing).

Figure 10 reveals substantial gains from permit trade for the developing countries, in the order of 10 trillion US dollar. This should be sufficient for developing countries to want to partake in full permit trade rather than the more restricted trade under the Clean Development Mechanism. This would require a cap on emission. The gains of trade may be such that developing countries could even accept a target that is slightly below their projected emissions, and still be better off (Tol & Rehdanz 2008).

For the 3.7 Wm^{-2} target, the OECD also benefits from permit trade. This is not the case for the 4.5 Wm^{-2} target. The consumer surplus is negative. The explanation lies in the interaction between interregional and intertemporal trade. Without interregional trade, the countries of the OECD have more stringent emission reduction targets. However, so do non-OECD countries albeit delayed. For the 4.5 Wm^{-2} target, stringent abatement is postponed till mid-century. It is therefore in the self-interest of the OECD to wait for the non-OECD targets to take effect, instead of paying them for earlier emission reduction.[1] Bosetti et al. (this issue) reach the same conclusion.

5. Discussion and conclusion

I use the integrated assessment model FUND to analyze the feasibility of ambitious targets for the stabilization of the atmospheric concentration of greenhouse gases. Climate policy would reduce the maximum radiative forcing in the 21st century, but incremental climate policy has a diminishing impact on radiative forcing. This is independent of the baseline scenario. More ambitious targets can be met if more countries reduce their emissions. The same tax would achieve more if abatement costs are lower. Targets that are formulated in terms of the eventual radiative forcing can be more stringent than targets formulated in terms of the maximum radiative forcing. Carbon dioxide emissions from the impact of climate change on the terrestrial biosphere hamper the success of climate policy. A target of 2.6 Wm^{-2}, or 2ºC warming above pre-industrial times, is infeasible under any but the most advantageous of assumptions.

[1] Note that this is a result of the somewhat contrived construction of the EMF22 policy scenarios. Of course, at any point in time, the OECD would benefit from achieving some of its abatement targets in non-OECD countries. This result is well-established, and this policy is not analysed here.

A target of 4.5 Wm^{-2} may well pass the cost-benefit test, but only if all major emitters adopt a meaningful emission reduction policy in the coming decade. The median US voter may well be willing to pay the cost of meeting a 3.7 Wm^{-2}, but participation of all major emitters is again a prerequisite. International trade in emission permits may bring about the participation of large developing countries, but the trade flows would be substantial compared to product trade and very large compared to official development aid.

These results have the following caveats. The findings are from a single model, and may not be robust to differences in model structure and parameterization. Particularly, FUND does not have energy sources that sequester carbon, such as biomass with carbon capture and sequestration. On the other hand, the policy scenarios are fairly optimistic, assuming full when and how flexibility and where flexibility in a number of cases. The assessment of the political feasibility borders on the speculative. Estimates of the willingness to pay for climate policy are in their infancy, while it is not obvious whether international permit trade should be compared to trade or aid.

That said, the qualitative results are reasonably robust to variations within the FUND model. Deep emission reduction costs are technically, economically, and politically feasible on the time-scale of a century. However, it is probably not possible to reduce emissions fast enough to meet the more ambitious targets proposed in the policy arena.

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Table 3. Carbon permit trade for the "OECD" (USA, Canada, Western Europe, Eastern Europe, Japan and South Korea, and Australia and New Zealand), the "BRIC" (South America, former Soviet Union, South Asia, and China), and the RoW (Rest of the World; Central America, Middle East, Southeast Asia, North Africa, Sub-Saharan Africa, Small Island States).

Panel A: Volume (in billion metric tonnes of carbon dioxide)

	No overshoot				Overshoot			
	2020	2030	2040	2050	2020	2030	2040	2050
Target: 3.7 Wm^{-2}								
"OECD"	-7.3	-17.6	-8.3	-9.4	-7.2	-17.3	-12.0	-9.7
"BRIC"	5.3	12.4	-0.1	-1.3	5.2	12.3	3.6	-1.0
RoW	2.1	5.1	8.4	10.7	2.0	5.0	8.4	10.7
Target: 4.5 Wm^{-2}								
"OECD"	-2.4	-8.4	-11.7	-9.6	-2.4	-8.2	-11.7	-9.8
"BRIC"	1.8	6.2	7.1	1.3	1.7	6.0	7.2	1.7
RoW	0.6	2.2	4.6	8.3	0.6	2.2	4.5	8.1

Panel B: Price (in dollar per tonne of carbon dioxide)

	No overshoot				Overshoot			
	2020	2030	2040	2050	2020	2030	2040	2050
Target: 3.7 Wm^{-2}								
World	52	84	137	223	51	82	134	218
Target: 4.5 Wm^{-2}								
World	20	33	54	88	20	32	52	85

Panel C: Value (in percent of GDP in the reference scenario)

	No overshoot				Overshoot			
	2020	2030	2040	2050	2020	2030	2040	2050
Target: 3.7 Wm^{-2}								
"OECD"	-0.9	-3.0	-2.0	-3.2	-0.9	-2.9	-2.8	-3.3
"BRIC"	3.2	8.9	-0.1	-1.4	3.1	8.6	3.0	-1.0
RoW	2.3	6.7	12.9	19.8	2.3	6.4	12.6	19.4
Target: 4.5 Wm^{-2}								
"OECD"	-0.1	-0.6	-1.1	-1.3	-0.1	-0.5	-1.1	-1.3
"BRIC"	0.4	1.7	2.4	0.5	0.4	1.6	2.3	0.7
RoW	0.3	1.1	2.8	6.0	0.3	1.1	2.6	5.7

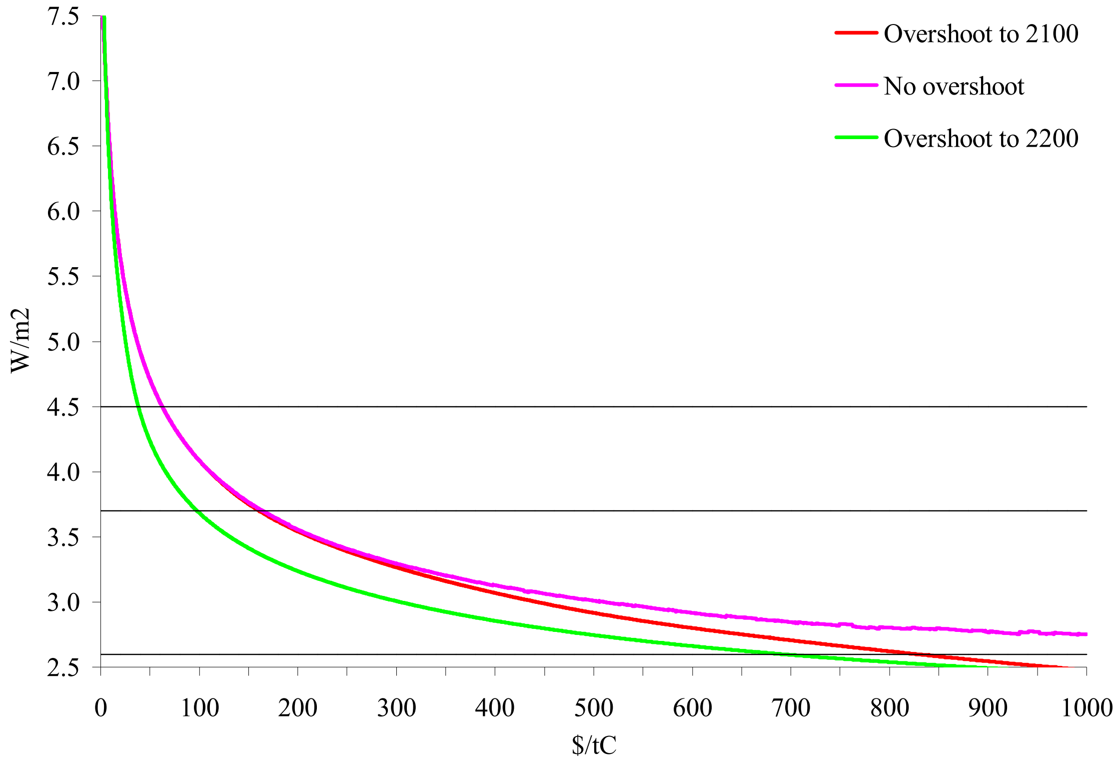

Figure 1. Radiative forcing (greenhouse gases only) as a function of the initial (2013) carbon tax for three alternative measures: radiative forcing in 2100 ("overshoot to 2100"), radiative forcing in 2200 ("overshoot to 2200"), and maximum in the 21st century ("no overshoot"); all countries implement the same tax in 2013.

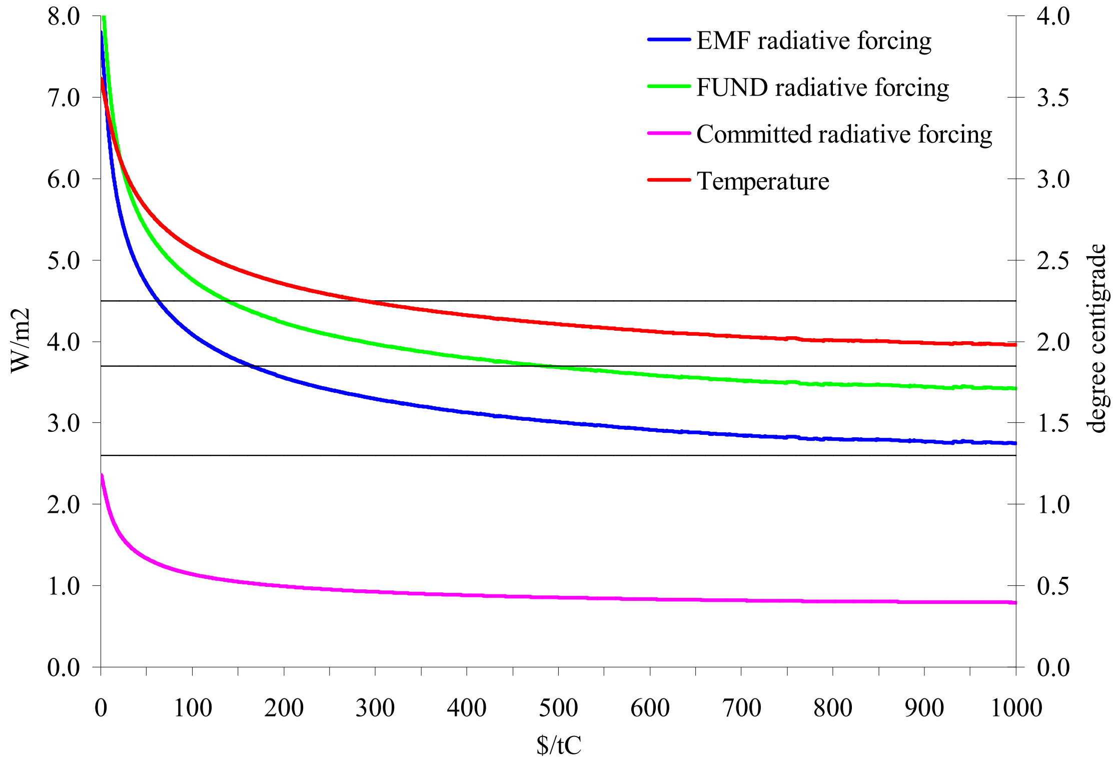

Figure 2. Radiative forcing (EMF: greenhouse gases only; FUND: all substances; Committed: Permanent carbon dioxide only) in the year 2100 and the global mean surface air temperature in 2100 as a function of the initial (2013) carbon tax. All countries implement the same tax in 2013.

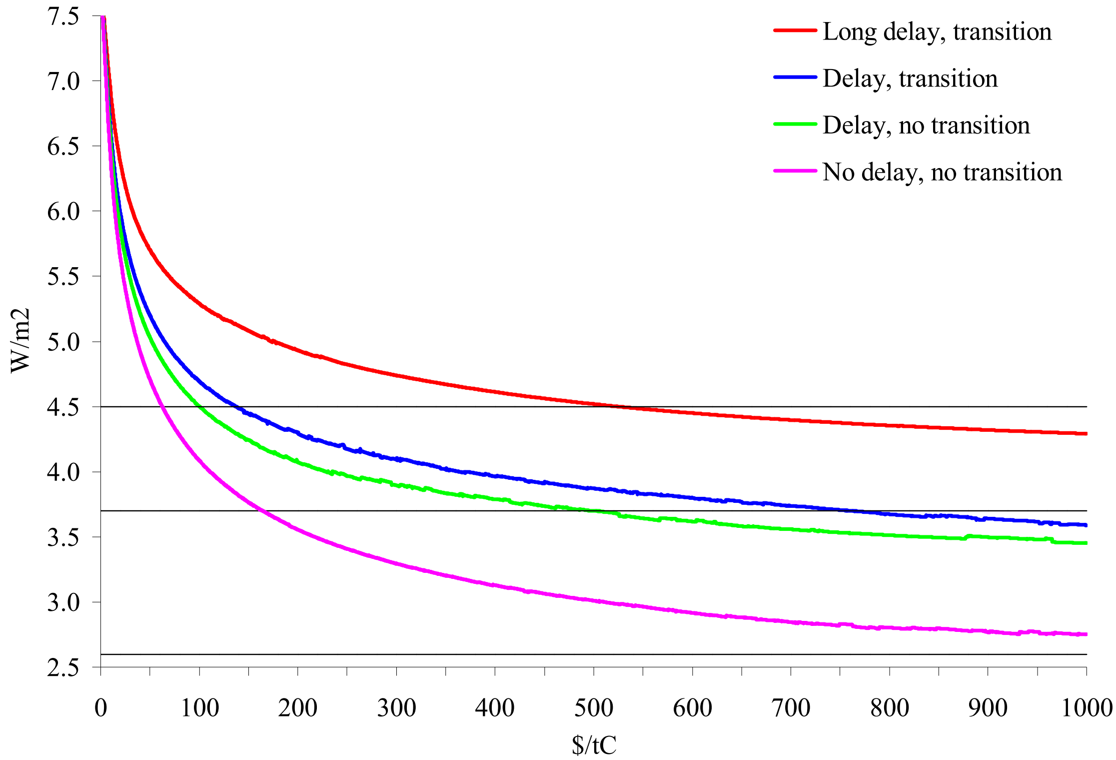

Figure 3. The maximum radiative forcing (greenhouse gases only) in the 21st century as a function of the initial (2013) carbon tax for four alternative policies: full participation ("no delay, no transition") as of 2013; an 18 year delay in participation for East Asia, South Asia, the former Soviet Union, and South America, and a 38 year delay for the other regions ("delay, no transition"); the same delay plus a 20 year transition period ("delay, transition"); and a 38 and 58 year delay plus a 20 year transition ("long delay, transition").

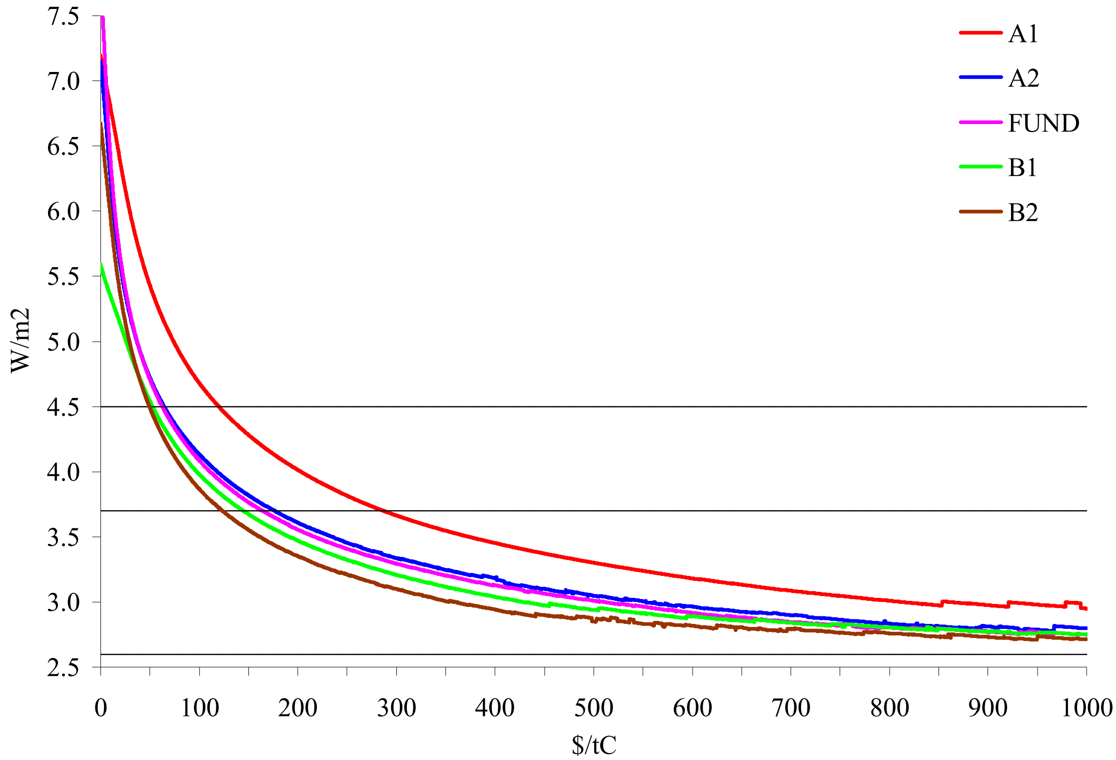

Figure 4. The maximum radiative forcing (greenhouse gases only) in the 21st century as a function of the initial (2013) carbon tax for five alternative baseline scenarios: FUND (the baseline in the Figures 1, 2, 4 and 5); A1, A2, B1 and B2; all countries implement the same tax in 2013.

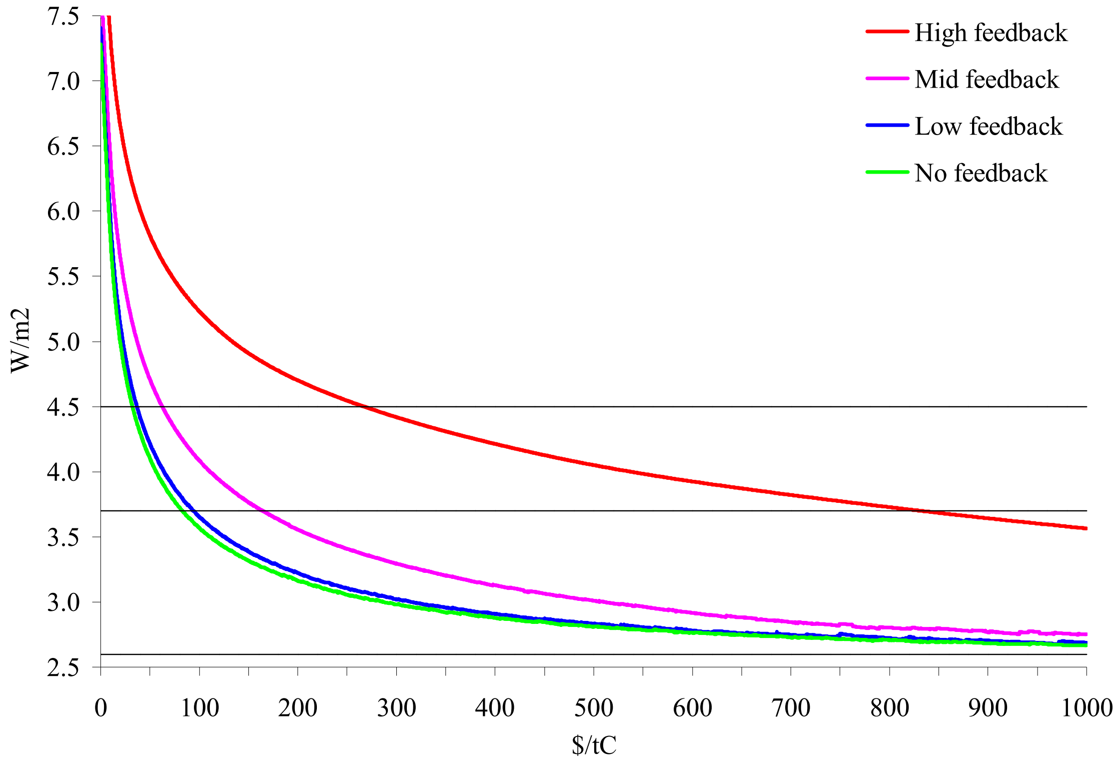

Figure 5. The maximum radiative forcing (greenhouse gases only) in the 21st century as a function of the initial (2013) carbon tax for four alternative sensitivities of the terrestrial carbon cycle to climate change; all countries implement the same tax in 2013.

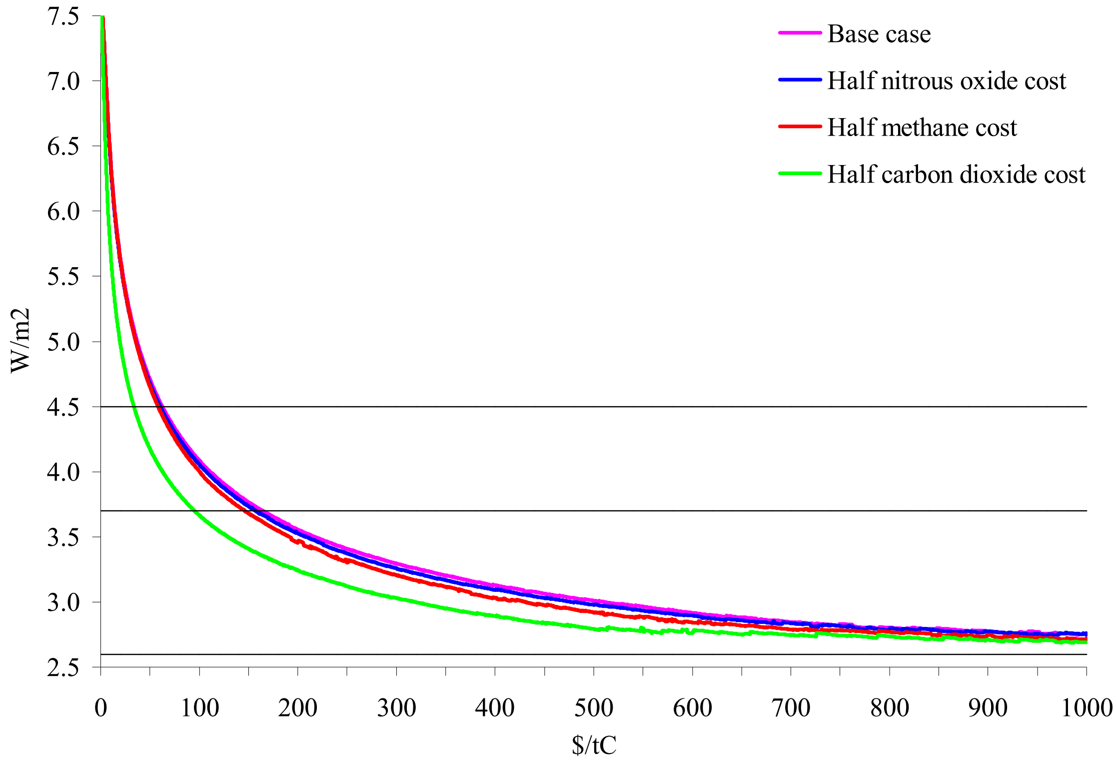

Figure 6. The maximum radiative forcing (greenhouse gases only) in the 21st century as a function of the initial (2013) carbon tax for four alternative assumptions about abatement cost; all countries implement the same tax in 2013.

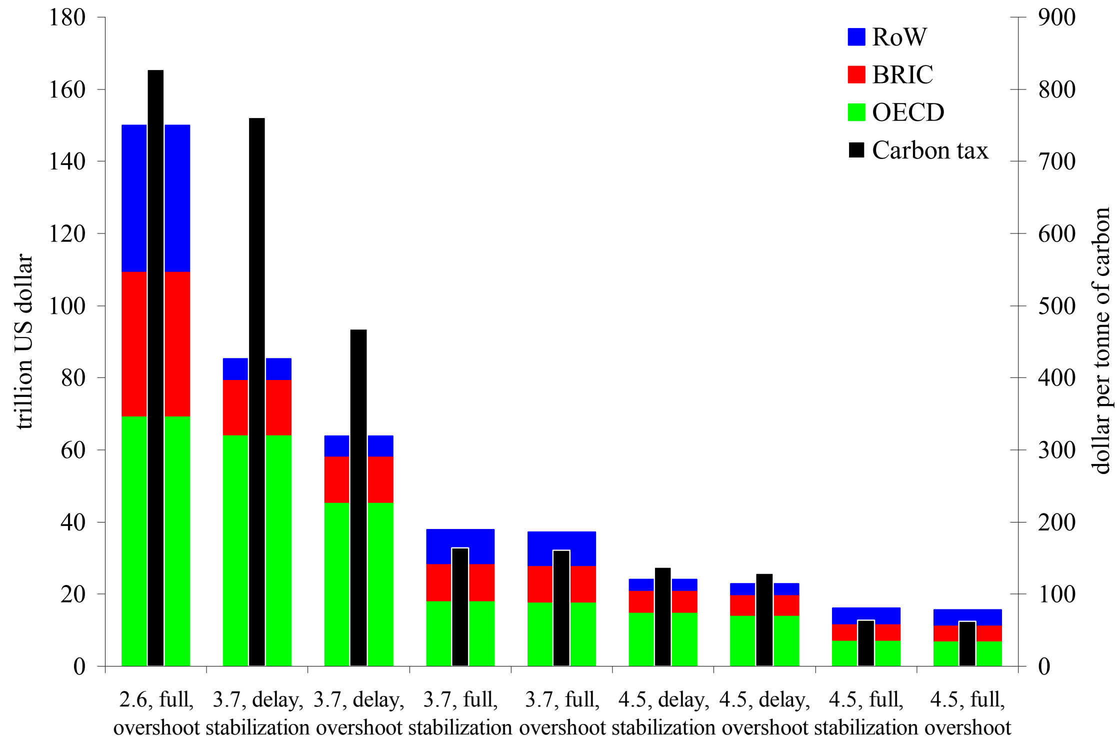

Figure 7. The net present value of the cost (as measured by the difference in gross domestic product) and the 2013 carbon tax in the OECD for nine alternative policies.

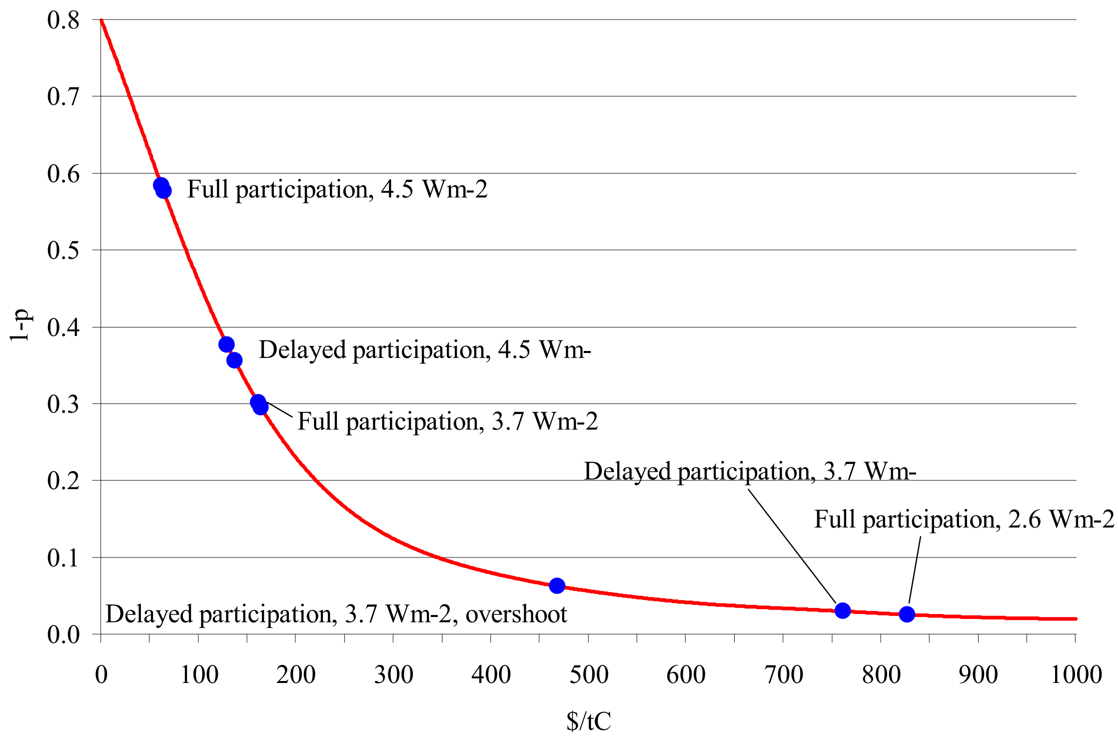

Figure 8. The survival function of the social cost of carbon (continuous line) and the initial (2013) carbon tax for nine alternative policies. Note that carbon taxes for full participation with a target of 3.7 and 4.5 Wm^{-2} with and without overshoot, and for delayed participation with a target of 4.5 Wm^{-2} with and without overshoot lie very close together.

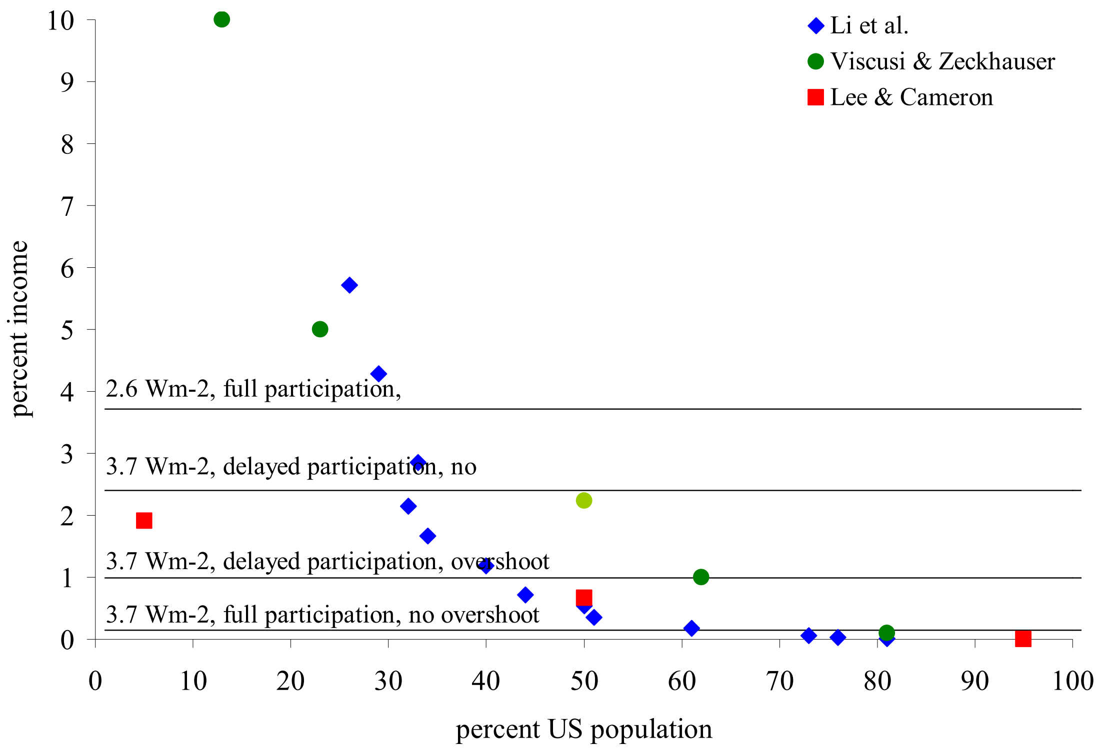

Figure 9. Three alternative estimates of the cumulative density function of the willingness to pay of US residents for climate policy, and the estimated costs of four alternative climate polices.

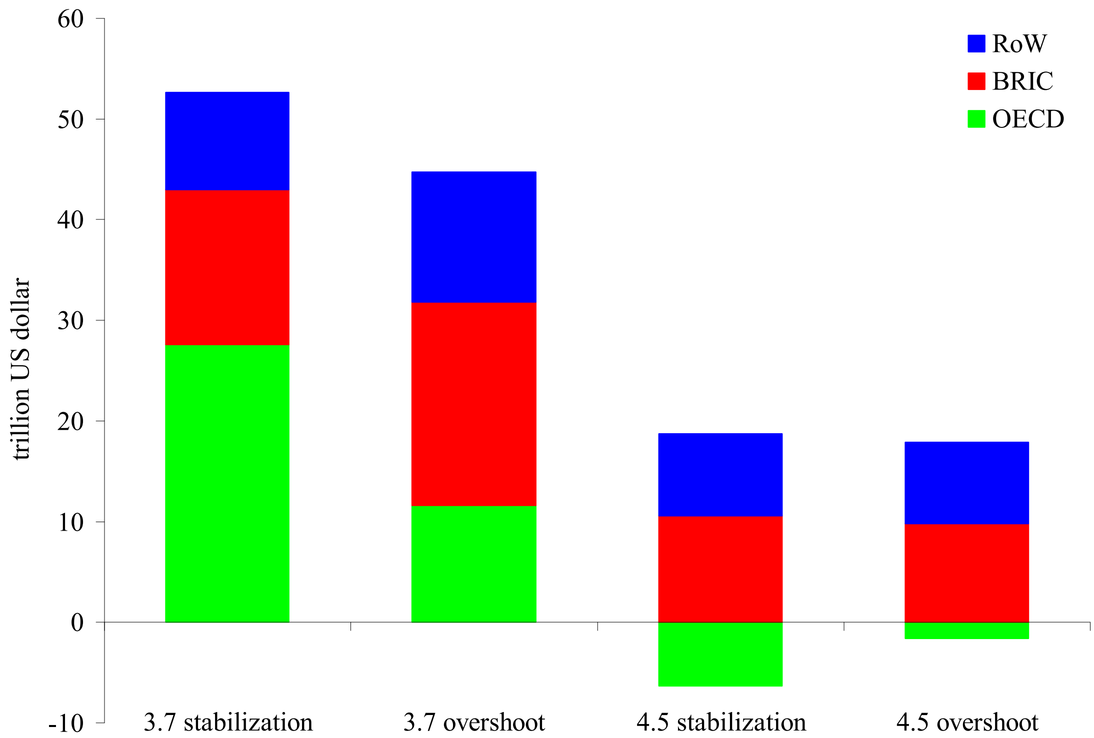

Figure 10. The net present value of the consumer and producer surplus of international permit trade for the three major world regions for four alternative targets.

Table 1. The impact of alternative climate policies on the economy of the "OECD" (USA, Canada, Western Europe, Eastern Europe, Japan and South Korea, and Australia and New Zealand), the "BRIC" (South America, former Soviet Union, South Asia, and China), and the RoW (Rest of the World; Central America, Middle East, Southeast Asia, North Africa, Sub-Saharan Africa, Small Island States).

Target	Overshoot	Delay	Tax	CO_2	ΔGDP, %, 2020			ΔGDP, %, 2050			ΔGDP, %, 2100		
Wm^{-2}			$/tC, 2013	ppm, 2100	OECD	BRIC	RoW	OECD	BRIC	RoW	OECD	BRIC	RoW
-	-	-	0	896.5	40.7[a]	8.5[a]	4.6[a]	64.3[a]	21.3[a]	12.0[a]	109.3[a]	77.3[a]	46.7[a]
2.6	No	Yes	>1000										
2.6	Yes	Yes	>1000										
2.6	No	No	>1000										
2.6	Yes	No	827.3	414.5	-2.0	-14.7	-13.3	-6.6	-21.2	-19.5	-20.0	-41.0	-49.3
3.7	No	Yes	761.2	474.9	-1.3	0.0	0.0	-7.3	-8.9	0.0	-15.5	-24.5	-21.7
3.7	Yes	Yes	467.6	483.0	-0.5	0.0	0.0	-5.4	-7.6	0.0	-15.2	-24.9	-22.1
3.7	No	No	164.1	466.2	-0.1	-1.6	-1.2	-1.9	-6.6	-6.1	-6.9	-11.8	-11.2
3.7	Yes	No	160.7	467.0	-0.1	-1.5	-1.2	-1.9	-6.5	-6.0	-6.9	-12.0	-11.2
4.5	No	Yes	137.4	528.9	-0.1	0.0	0.0	-1.2	-4.2	0.0	-6.6	-12.9	-10.8
4.5	Yes	Yes	129.1	531.0	0.0	0.0	0.0	-1.1	-3.9	0.0	-6.6	-12.5	-10.7
4.5	No	No	64.4	521.0	0.0	-0.3	-0.2	-0.5	-3.2	-2.7	-4.4	-6.8	-6.7
4.5	Yes	No	62.4	523.2	0.0	-0.3	-0.2	-0.4	-3.1	-2.5	-4.3	-6.6	-6.6

[a] Trillion dollar.

Table 2. The impact of alternative climate policies on the carbon dioxide emissions (excl. land use) of the "OECD" (USA, Canada, Western Europe, Eastern Europe, Japan and South Korea, and Australia and New Zealand), the "BRIC" (South America, former Soviet Union, South Asia, and China), and the RoW (Rest of the World; Central America, Middle East, Southeast Asia, North Africa, Sub-Saharan Africa, Small Island States).

Target	Overshoot	Delay	Tax	CO_2	ΔEmission, %, 2020			ΔEmission, %, 2050			ΔEmission, %, 2100		
Wm^{-2}			$/tC, 2013	ppm, 2100	OECD	BRIC	RoW	OECD	BRIC	RoW	OECD	BRIC	RoW
-	-	-	0	896.5	14.6[a]	14.8[a]	7.1[a]	20.2[a]	26.5[a]	11.6[a]	28.9[a]	59.5[a]	27.8[a]
2.6	No	Yes	>1000										
2.6	Yes	Yes	>1000										
2.6	No	No	>1000										
2.6	Yes	No	827.3	414.5	-45.3	-91.5	-90.4	-95.1	-97.5	-97.3	-99.1	-99.7	-99.7
3.7	No	Yes	761.2	474.9	-28.9	0.0	0.0	-95.0	-98.7	0.0	-97.5	-99.2	-98.4
3.7	Yes	Yes	467.6	483.0	-18.5	0.0	0.0	-90.1	-97.3	0.0	-98.0	-99.5	-99.3
3.7	No	No	164.1	466.2	-7.8	-35.6	-29.3	-69.8	-93.7	-92.3	-97.8	-99.1	-98.4
3.7	Yes	No	160.7	467.0	-7.7	-35.1	-28.8	-69.1	-93.5	-92.1	-97.4	-99.5	-99.1
4.5	No	Yes	137.4	528.9	-6.1	0.0	0.0	-43.9	-73.7	0.0	-95.9	-98.6	-98.3
4.5	Yes	Yes	129.1	531.0	-5.8	0.0	0.0	-41.5	-71.1	0.0	-96.7	-97.4	-98.8
4.5	No	No	64.4	521.0	-2.2	-12.1	-9.2	-35.8	-78.7	-71.7	-93.7	-97.8	-97.2
4.5	Yes	No	62.4	523.2	-2.1	-11.7	-8.8	-34.5	-77.4	-70.2	-93.6	-97.8	-97.1

[a] Billion metric tonnes of carbon dioxide.

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