Tol, Richard S. J.

Working Paper
The feasibility of low concentration targets: An application of FUND

ESRI Working Paper, No. 285

Provided in Cooperation with:
The Economic and Social Research Institute (ESRI), Dublin


This Version is available at:
http://hdl.handle.net/10419/50083

Terms of use:
Documents in EconStor may be saved and copied for your personal and scholarly purposes.
You are not to copy documents for public or commercial purposes, to exhibit the documents publicly, to make them publicly available on the internet, or to distribute or otherwise use the documents in public.

If the documents have been made available under an Open Content Licence (especially Creative Commons Licences), you may exercise further usage rights as specified in the indicated licence.
The Feasibility of Low Concentration Targets: 
An Application of FUND

Richard S.J. Tol*

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

Corresponding Author: Richard.Tol@esri.ie

*Economic and Social Research Institute, Dublin, Ireland
Institute for Environmental Studies, Vrije Universiteit, Amsterdam, The Netherlands
Department of Spatial Economics, Vrije Universiteit, Amsterdam, The Netherlands

ESRI working papers represent un-refereed work-in-progress by members who are solely responsible for the content and any views expressed therein. Any comments on these papers will be welcome and should be sent to the author(s) by email. Papers may be downloaded for personal use only.
The Feasibility of Low Concentration Targets: 
An Application of $FUND$

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:

\[ \text{Box}_{i,t} = \rho_i \text{Box}_{i,t-1} + 0.000471 \alpha_i E_t \]

with

\[ C_t = \sum_{i=1}^{5} \alpha_i \text{Box}_{i,t} \]

where \( \alpha_i \) denotes the fraction of emissions \( E \) (in million metric tonnes of carbon) that is allocated to \( \text{Box} \ i \) (0.13, 0.20, 0.32, 0.25 and 0.10, respectively) and \( \rho \) the decay-rate of the boxes (\( \rho = \exp(-1/\text{lifetime}) \), 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 (Hammit 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:

\[ E_t^B = \beta (T_t - T_{2000}) \frac{B_t}{B_{\text{max}}} \]

with

\[ B_t = B_{t-1} - E_{t-1}^B \]
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); $B_{\text{max}}$ is the total stock of potential emissions; $B_{\text{max}} = 1,900$ gigatonnes of carbon; $\beta$ is a parameter; $\beta = 2.6 \text{ GtC}$, 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 21$^{\text{st}}$ 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 21$^{\text{st}}$ 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 21\(^{st}\) 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 3.5°C. This can be kept below 2.0°C (in the 21\(^{st}\) 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 21\(^{st}\) 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.

**Acknowledgements**

Previous versions of this paper were presented at the EMF22 meetings in Dublin, Vienna, and U Maryland; and various participants had welcome suggestions. The Electric Power Research Institute and the Ireland Environmental Protection Agency provided welcome financial support.
References


Tol, R.S.J. (2007), 'Biased Policy Advice from the Intergovernmental Panel on Climate Change', *Energy & Environment, 18*, (7+8), 929-936.


<table>
<thead>
<tr>
<th>Year</th>
<th>Number</th>
<th>Title/ Author(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2009</td>
<td>284</td>
<td>Policy Options to Reduce Ireland’s GHG Emissions Instrument choice: the pros and cons of alternative policy instruments Thomas Legge and <em>Sue Scott</em></td>
</tr>
<tr>
<td></td>
<td>283</td>
<td>Accounting for Taste: An Examination of Socioeconomic Gradients in Attendance at Arts Events <em>Pete Lunn</em> and <em>Elish Kelly</em></td>
</tr>
<tr>
<td></td>
<td>281</td>
<td>Assessing the impact of biodiversity on tourism flows: A model for tourist behaviour and its policy implications Giulia Macagno, Maria Loureiro, Paulo A.L.D. Nunes and <em>Richard S.J. Tol</em></td>
</tr>
<tr>
<td></td>
<td>280</td>
<td>Advertising to boost energy efficiency: the Power of One campaign and natural gas consumption <em>Seán Diffney, Seán Lyons</em> and <em>Laura Malaguzzi Valeri</em></td>
</tr>
<tr>
<td></td>
<td>279</td>
<td>International Transmission of Business Cycles Between Ireland and its Trading Partners <em>Jean Goggin</em> and <em>Iulia Siedschlag</em></td>
</tr>
<tr>
<td></td>
<td>278</td>
<td>Optimal Global Dynamic Carbon Taxation <em>David Anthoff</em></td>
</tr>
<tr>
<td></td>
<td>277</td>
<td>Energy Use and Appliance Ownership in Ireland <em>Eimear Leahy</em> and <em>Seán Lyons</em></td>
</tr>
<tr>
<td></td>
<td>276</td>
<td>Discounting for Climate Change <em>David Anthoff, Richard S.J. Tol</em> and Gary W. Yohe</td>
</tr>
<tr>
<td></td>
<td>275</td>
<td>Projecting the Future Numbers of Migrant Workers in the Health and Social Care Sectors in Ireland <em>Alan Barrett</em> and Anna Rust</td>
</tr>
<tr>
<td></td>
<td>274</td>
<td>Economic Costs of Extratropical Storms under Climate Change: An application of FUND</td>
</tr>
</tbody>
</table>
Daiju Narita, *Richard S.J. Tol, David Anthoff*

273 The Macro-Economic Impact of Changing the Rate of Corporation Tax
*Thomas Conefrey and John D. Fitz Gerald*

272 The Games We Used to Play
An Application of Survival Analysis to the Sporting Lifecourse
*Pete Lunn*

2008

271 Exploring the Economic Geography of Ireland
*Edgar Morgenroth*

270 Benchmarking, Social Partnership and Higher Remuneration: Wage Settling Institutions and the Public-Private Sector Wage Gap in Ireland
*Elish Kelly, Seamus McGuinness, Philip O’Connell*

269 A Dynamic Analysis of Household Car Ownership in Ireland
*Anne Nolan*

268 The Determinants of Mode of Transport to Work in the Greater Dublin Area
*Nicola Commins and Anne Nolan*

267 Resonances from *Economic Development* for Current Economic Policymaking
*Frances Ruane*

266 The Impact of Wage Bargaining Regime on Firm-Level Competitiveness and Wage Inequality: The Case of Ireland
*Seamus McGuinness, Elish Kelly and Philip O’Connell*

265 Poverty in Ireland in Comparative European Perspective
*Christopher T. Whelan and Bertrand Maître*

264 A Hedonic Analysis of the Value of Rail Transport in the Greater Dublin Area
*Karen Mayor, Seán Lyons, David Duffy and Richard S.J. Tol*

263 Comparing Poverty Indicators in an Enlarged EU
*Christopher T. Whelan and Bertrand Maître*

262 Fuel Poverty in Ireland: Extent, Affected Groups and Policy Issues
Sue Scott, Seán Lyons, Claire Keane, Donal McCarthy and Richard S.J. Tol

261 The Misperception of Inflation by Irish Consumers
David Duffy and Pete Lunn

260 The Direct Impact of Climate Change on Regional Labour Productivity

259 Damage Costs of Climate Change through Intensification of Tropical Cyclone Activities: An Application of FUND
Daiju Narita, Richard S. J. Tol and David Anthoff

258 Are Over-educated People Insiders or Outsiders? A Case of Job Search Methods and Over-education in UK
Aleksander Kucel, Delma Byrne

257 Metrics for Aggregating the Climate Effect of Different Emissions: A Unifying Framework
Richard S.J. Tol, Terje K. Berntsen, Brian C. O’Neill, Jan S. Fuglestvedt, Keith P. Shine, Yves Balkanski and Laszlo Makra

256 Intra-Union Flexibility of Non-ETS Emission Reduction Obligations in the European Union
Richard S.J. Tol

255 The Economic Impact of Climate Change
Richard S.J. Tol

254 Measuring International Inequity Aversion
Richard S.J. Tol

253 Using a Census to Assess the Reliability of a National Household Survey for Migration Research: The Case of Ireland
Alan Barrett and Elish Kelly

David Anthoff, Richard S.J. Tol and Gary W. Yohe

251 The Impact of a Carbon Tax on Economic Growth and Carbon Dioxide Emissions in Ireland
Thomas Conefrey, John D. Fitz Gerald, Laura Malaguzzi
Valeri and Richard S.J. Tol

250 The Distributional Implications of a Carbon Tax in Ireland
    Tim Callan, Sean Lyons, Susan Scott, Richard S.J. Tol and Stefano Verde

249 Measuring Material Deprivation in the Enlarged EU
    Christopher T. Whelan, Brian Nolan and Bertrand Maître

248 Marginal Abatement Costs on Carbon-Dioxide Emissions: A Meta-Analysis

247 Incorporating GHG Emission Costs in the Economic Appraisal of Projects Supported by State Development Agencies
    Richard S.J. Tol and Seán Lyons

246 A Carton Tax for Ireland
    Richard S.J. Tol, Tim Callan, Thomas Conefrey, John D. Fitz Gerald, Seán Lyons, Laura Malaguzzi Valeri and Susan Scott

245 Non-cash Benefits and the Distribution of Economic Welfare
    Tim Callan and Claire Keane

244 Scenarios of Carbon Dioxide Emissions from Aviation
    Karen Mayor and Richard S.J. Tol

243 The Effect of the Euro on Export Patterns: Empirical Evidence from Industry Data
    Gavin Murphy and Iulia Siedschlag

242 The Economic Returns to Field of Study and Competencies Among Higher Education Graduates in Ireland
    Elish Kelly, Philip O’Connell and Emer Smyth

241 European Climate Policy and Aviation Emissions
    Karen Mayor and Richard S.J. Tol

240 Aviation and the Environment in the Context of the EU-US Open Skies Agreement
    Karen Mayor and Richard S.J. Tol

239 Yuppie Kvetch? Work-life Conflict and Social Class in Western Europe
    Frances McGinnity and Emma Calvert
*Alan Barrett* and Yvonne McCarthy

237 How Local is Hospital Treatment? An Exploratory Analysis of Public/Private Variation in Location of Treatment in Irish Acute Public Hospitals
*Jacqueline O’Reilly* and Miriam M. Wiley

236 The Immigrant Earnings Disadvantage Across the Earnings and Skills Distributions: The Case of Immigrants from the EU’s New Member States in Ireland
*Alan Barrett, Seamus McGuinness* and Martin O’Brien

235 Europeanisation of Inequality and European Reference Groups
*Christopher T. Whelan* and Bertrand Maître

234 Managing Capital Flows: Experiences from Central and Eastern Europe
Jürgen von Hagen and *Iulia Siedschlag*

Charlie Karlsson, Gunther Maier, Michaela Trippl, *Iulia Siedschlag*, Robert Owen and Gavin Murphy

232 Welfare and Competition Effects of Electricity Interconnection between Great Britain and Ireland
*Laura Malaguzzi Valeri*

231 Is FDI into China Crowding Out the FDI into the European Union?
Laura Resmini and *Iulia Siedschlag*

230 Estimating the Economic Cost of Disability in Ireland
John Cullinan, Brenda Gannon and *Seán Lyons*

229 Controlling the Cost of Controlling the Climate: The Irish Government’s Climate Change Strategy
Colm McCarthy, *Sue Scott*

228 The Impact of Climate Change on the Balanced-Growth-Equivalent: An Application of *FUND*
*David Anthoff, Richard S.J. Tol*
227 Changing Returns to Education During a Boom? The Case of Ireland
Seamus McGuinness, Frances McGinnity, Philip O’Connell

226 ‘New’ and ‘Old’ Social Risks: Life Cycle and Social Class Perspectives on Social Exclusion in Ireland
Christopher T. Whelan and Bertrand Maître

225 The Climate Preferences of Irish Tourists by Purpose of Travel
Seán Lyons, Karen Mayor and Richard S.J. Tol

224 A Hirsch Measure for the Quality of Research Supervision, and an Illustration with Trade Economists
Frances P. Ruane and Richard S.J. Tol

223 Environmental Accounts for the Republic of Ireland: 1990-2005
Seán Lyons, Karen Mayor and Richard S.J. Tol

2007 222 Assessing Vulnerability of Selected Sectors under Environmental Tax Reform: The issue of pricing power
J. Fitz Gerald, M. Keeney and S. Scott

221 Climate Policy Versus Development Aid
Richard S.J. Tol

220 Exports and Productivity – Comparable Evidence for 14 Countries
The International Study Group on Exports and Productivity

219 Energy-Using Appliances and Energy-Saving Features: Determinants of Ownership in Ireland
Joe O’Doherty, Seán Lyons and Richard S.J. Tol

218 The Public/Private Mix in Irish Acute Public Hospitals: Trends and Implications
Jacqueline O’Reilly and Miriam M. Wiley

217 Regret About the Timing of First Sexual Intercourse: The Role of Age and Context
Richard Layte, Hannah McGee

216 Determinants of Water Connection Type and Ownership of Water-Using Appliances in Ireland
Joe O’Doherty, Seán Lyons and Richard S.J. Tol

215 Unemployment – Stage or Stigma?
Being Unemployed During an Economic Boom
Emer Smyth

214 The Value of Lost Load
Richard S.J. Tol

Adolescents’ Educational Attainment and School Experiences in Contemporary Ireland
Merike Darmody, Selina McCoy, Emer Smyth

212 Acting Up or Opting Out? Truancy in Irish Secondary Schools
Merike Darmody, Emer Smyth and Selina McCoy

Where do MNEs Expand Production: Location Choices of the Pharmaceutical Industry in Europe after 1992
Frances P. Ruane, Xiaoheng Zhang

Holiday Destinations: Understanding the Travel Choices of Irish Tourists
Seán Lyons, Karen Mayor and Richard S.J. Tol

The Effectiveness of Competition Policy and the Price-Cost Margin: Evidence from Panel Data
Patrick McCloughan, Seán Lyons and William Batt

Tax Structure and Female Labour Market Participation: Evidence from Ireland
Tim Callan, A. Van Soest, J.R. Walsh

Distributional Effects of Public Education Transfers in Seven European Countries
Tim Callan, Tim Smeeding and Panos Tsakloglou