

Tol, Richard S. J. et al.

Working Paper

Metrics for aggregating the climate effect of different emissions: A unifying framework

ESRI Working Paper, No. 257

Provided in Cooperation with:

The Economic and Social Research Institute (ESRI), Dublin

Suggested Citation: Tol, Richard S. J. et al. (2008) : Metrics for aggregating the climate effect of different emissions: A unifying framework, ESRI Working Paper, No. 257, The Economic and Social Research Institute (ESRI), Dublin

This Version is available at:

<https://hdl.handle.net/10419/50162>

Standard-Nutzungsbedingungen:

Die Dokumente auf EconStor dürfen zu eigenen wissenschaftlichen Zwecken und zum Privatgebrauch gespeichert und kopiert werden.

Sie dürfen die Dokumente nicht für öffentliche oder kommerzielle Zwecke vervielfältigen, öffentlich ausstellen, öffentlich zugänglich machen, vertreiben oder anderweitig nutzen.

Sofern die Verfasser die Dokumente unter Open-Content-Lizenzen (insbesondere CC-Lizenzen) zur Verfügung gestellt haben sollten, gelten abweichend von diesen Nutzungsbedingungen die in der dort genannten Lizenz gewährten Nutzungsrechte.

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.



Working Paper No. 257

September 2008

Metrics for Aggregating the Climate Effect of Different Emissions: A Unifying Framework

Richard S.J. Tol^{a,b,c,d*}, Terje K. Berntsen^e, Brian C. O'Neill^f, Jan S. Fuglestedt^e, Keith P. Shine^g, Yves Balkanski^h and Laszlo Makraⁱ

Abstract: Multi-gas approaches to climate change policies require a metric establishing “equivalences” among emissions of various species. Climate scientists and economists have proposed four classes of such metrics and debated their relative merits. We present a unifying framework that clarifies the relationships among them. We show that the Global Warming Potential, used in international law to compare greenhouse gases, is a special case of the Global Damage Potential, assuming (1) a finite time horizon, (2) a zero discount rate, (3) constant atmospheric concentrations, and (4) impacts that are proportional to radiative forcing. We show that the Global Temperature change Potential is a special case of the Global Cost Potential, assuming (1) no induced technological change, and (2) a short-lived capital stock. We also show that the Global Cost Potential is a special case of the Global Damage Potential, assuming (1) zero damages below a threshold and (2) infinite damage after a threshold. The UN Framework Convention on Climate Change uses the Global Warming Potential, a simplified cost-benefit concept, even though the UNFCCC frames climate policy as a cost-effectiveness problem and should therefore use the Global Cost Potential or its simplification, the Global Temperature Potential.

Key words: Climate change; multi-gas climate policy; Global Warming Potential; equivalences between greenhouse gases

Corresponding Author: Richard.Tol@esri.ie

^a Economic and Social Research Institute, Dublin, Ireland

^b Institute for Environmental Studies, Vrije Universiteit, Amsterdam, The Netherlands

^c Department of Spatial Economics, Vrije Universiteit, Amsterdam, The Netherlands

^d Department of Engineering and Public Policy, Carnegie Mellon University, Pittsburgh, PA, USA

^e CICERO – Center for International Climate and Environmental Research – Oslo, P.O. Box 1129 Blindern, N-0318 Oslo, NORWAY

^f Institute for the Study of Society and Environment, National Center for Atmospheric Research P.O. Box 3000 Boulder, CO 80307 USA

^g Department of Meteorology, University of Reading, Earley Gate, Reading RG6 6BB, UK

^h LSCE/IPSL, Laboratoire CEA-CNRS-UVSQ, 91191 Gif-sur-Yvette, France

ⁱ SZTE, University of Szeged, Hungary, 6722 Szeged, Hungary

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.

Metrics for Aggregating the Climate Effect of Different Emissions: A Unifying Framework

1. Introduction

Human activity puts many substances in the atmosphere that can force climate change. They have widely varying characteristics. Some species stay in the atmosphere for a few days, some for tens of thousands of years. Some exert a forcing globally, while others cause a forcing in limited regions. Some species are emitted in large amounts, others in tiny quantities. Some species have a powerful warming effect per gram, others a much smaller effect, and yet other species cool the atmosphere. Some species influence the climate directly, while others have primarily an indirect effect by affecting the concentrations of other species. And emissions of some species have multiple impacts which themselves have widely varying characteristics. Different as these emissions may be, it is important that their climate effects be added up in order to answer questions about the various contributions of countries and sectors to climate change, and about the priorities in emission reduction. Climate scientists and economists have proposed four classes of “equivalences” between climate changing species, and there are occasionally heated debates about which “metric” is the better one (1-31). The classes are:

- *Global Warming Potential (32, 33);*
- *Global Damage Potential (7);*
- *Global Cost Potential (21); and*
- *Global Temperature change Potential (27, 29).*

Here we show that these “exchange rates” are special cases of a single, unifying framework. This clarifies the relationships between them. The paper shows that some metrics require more knowledge than others while others make more stringent assumptions than some. It also argues that some metrics are appropriate in certain contexts but not in others.

Adding together the climate impact of species that have different characteristics is a bit like adding apples and oranges. There is no single unique way that this can be done. However, sometimes one just has to. If one transports things, then one would add apples and oranges by their weight or volume. This is not because “weight” is the only attribute that makes an apple an apple and an orange an orange. Rather, this is because weight is the main thing that matters in transport. Similarly, a nutritionist would add apples and oranges by their nutrient content. A grocer might add apples and oranges by their selling prices. To put it abstractly, the metric of aggregation depends on the purpose of aggregation.

This may be unsettling. There is no universal way of aggregation. There is no best method. There are multiple truths, or rather: there are multiple perspectives on the same reality. Transporters and nutritionists have different viewpoints. As apples are rich in vitamin A, and oranges in vitamin C, nutritionists would differ too – or rather, a nutritionist would give different recommendations to clients with different problems. Adding emissions is like adding apples and oranges: different problems require different solutions. And there are pragmatic considerations too. A transporter would not weigh every single box of apples and oranges, but rather use an average weight. The same holds for aggregating different emissions. The theoretically preferred option may be impractical.

One may argue for a metric that averages across several properties. However, the average of weight, vitamin C content, and selling price is meaningless to the transporter, the nutritionist and the grocer. Trying to serve different purposes at once in fact may mean that no purpose is served. Adding the climate impact of emissions is similar. Different stakeholders and different policies will require different metrics. There is no one size that fits all and the average size might fit no one.

In the context of climate change it is the very different time and spatial scales of both removal of the different forcing agents and the potential damages of warming that cause the problems. Thus a climate policy designed to mitigate long term sea level rise would

put more emphasis on mitigation of long lived forcing agents, than a policy that considers short term rate-of-change impacts (e.g. ability of biological systems to adapt) as the main potential damage. The decision regarding what constitutes a “dangerous anthropogenic interference with the climate system” involves value judgements and thus cannot be solved by scientists alone. However, once this has been determined (e.g. the EU’s goal of restricting global temperature increase to 2°C above pre-industrial levels), metrics can be designed based on objective, scientific methods.

In the next section, we start with a *cost-benefit* framework for assigning the appropriate weights to different emissions. These ratios are called *Global Damage Potentials*. We show that with three additional assumptions, the *Global Damage Potential* is equivalent to the *Global Warming Potential* as used in the implementation of the Kyoto Protocol. We argue that these assumptions are simplistic, but also that more realistic assumptions are uncertain and even controversial.

In Section 3, we show that the more commonly used *cost-effectiveness* framework is a special case of cost-benefit analysis, although it reflects a completely different policy perspective. We derive the appropriate metric for comparing emissions in a cost-effectiveness analysis (*Global Cost Potentials*), and show under what circumstances this is equivalent to the purely physical concept of *Global Temperature change Potentials*. We do this for targets on the level of climate change. Section 4 concludes the paper.

2. Cost-Benefit Analysis: Global Warming Potentials and Global Damage Potentials

Consider a decision-maker who wants to minimize the net losses due to climate change and climate policy. If emissions of only one component contribute to climate change, the problem to be solved is¹

$$(1) \quad \min_R \sum_{t=0}^{\infty} \frac{L(R_t, D_t)}{(1 + \rho)^t}$$

¹ The derivations assume that policy and time progress in discrete steps of equal length. This assumption is not necessary, but it greatly reduces the complexity of the exposition.

where L is the net loss function, say in monetary units, which depends on emission reduction R and damages D , with $\partial L/\partial R > 0$ and $\partial L/\partial D > 0$; ρ is the discount rate. Damages depend on climate change; let's use global-average surface temperature T as an indicator. Similarly, we use the total costs of emission reduction and the total impacts of climate change as high level indicators, abstracting from distributional issues of costs and impacts. The global mean temperature T depends on the full history of the emissions. The complex interactions and the various time scales of the climate system imply that a simulation with a comprehensive 3-D global climate model is required to estimate the full effect on T over time. This is certainly not feasible for a metric that is intended for policy use. To simplify the evaluation, radiative forcing F is often used to give a first-order estimate of the impacts of different emissions (33). Radiative forcing F , in turn depends on concentration C , and hence on a scenario of assumed emissions E and possible emission reductions R , so that the actual emissions are given by $E-R$. Although a system of difference equations is the most convenient way of computing Equation (1), it can also be expressed as:

$$(1) \quad \min_R \sum_{t=0}^{\infty} \frac{L(R_t, D_t(T_t(F_t, F_{t-1}, \dots, F_0)))}{(1+\rho)^t}$$

where the radiative forcing at any given time is a function of concentrations at that time, which in turn are a function of the history of reference emissions and reductions (E and R), that is:

$$(2) \quad F_t = f(C_t(E_t, \dots, E_0, R_t, \dots, R_0)).$$

The first order conditions are

$$(3a) \quad \frac{\partial L}{\partial R_t} (1+\rho)^{-t} = - \sum_{s=t}^{\infty} \frac{\partial L}{\partial D_s} \frac{\partial D_s}{\partial T_s} \frac{\partial T_s}{\partial R_t} (1+\rho)^{-s} \forall t$$

where

$$(3b) \quad \frac{\partial T_s}{\partial R_t} = \sum_{\tau=t}^s \frac{\partial T_s}{\partial F_\tau} \frac{\partial F_\tau}{\partial C_\tau} \frac{\partial C_\tau}{\partial R_t}.$$

This means that, in the optimum, the marginal costs of emission reduction are equal to the future stream of damages of climate change avoided by that emission reduction. The right hand side of (3) is typically referred to as the marginal damages cost of greenhouse gas emissions, the Pigou tax, or the social cost of carbon (34, 35).

Now suppose that there are J different emissions (i.e. different gases and aerosols) that affect the climate. The aim is then to solve

$$(4) \quad \min_{R^1, R^2, \dots, R^J} \sum_{t=0}^{\infty} \frac{L(R_t^1, R_t^2, \dots, R_t^J, D_t)}{(1 + \rho)^t}.$$

Following standard methods for optimization (e.g., Sundaram, 1996), the first-order conditions are

$$(5) \quad \frac{\partial L}{\partial R_t^j} (1 + \rho)^{-t} = - \sum_{s=t}^{\infty} \frac{\partial L}{\partial D_s} \frac{\partial D_s}{\partial T_s} \frac{\partial T_s}{\partial R_t^j} (1 + \rho)^{-s} \forall t, j.$$

That is, the discounted marginal abatement cost for emission j should equal the marginal damage cost of emission j . The marginal cost of damage given by (5) is per mass unit of emission. Due to large difference in the physical properties of different climate agents (e.g. lifetimes and radiative efficiencies) the marginal costs of damage will be very different.

A global climate policy based on (5) demands full knowledge about damages as well as mitigation costs. If these were known this framework would give global reductions for each component as a function of time. The optimal mitigation could be achieved either by giving out quotas for each component to each single emitter according to their known mitigation costs, or by assigning emission metrics to each component and letting each emitter decide how best to achieve their total emission constraint. To assign the appropriate weights for different emissions, we normalize with respect to emissions of C^R , a reference gas (usually carbon dioxide). We can then rewrite Equation (5) to

$$(6) \quad \frac{\frac{\partial L}{\partial R_t^j}}{\frac{\partial L}{\partial R_t^{C^R}}} = \frac{\sum_{s=t}^{\infty} \frac{\partial L}{\partial D_s} \frac{\partial D_s}{\partial T_s} \frac{\partial T_s}{\partial R_t^j} (1+\rho)^{-s}}{\sum_{s=t}^{\infty} \frac{\partial L}{\partial D_s} \frac{\partial D_s}{\partial T_s} \frac{\partial T_s}{\partial R_t^{C^R}} (1+\rho)^{-s}} \quad \forall t, j.$$

This is unity for $j=C^R$. The ratio of marginal abatement costs should equal the ratio of marginal damage costs. In principle, the marginal abatement cost should equal the tax on greenhouse gas emissions, or the price of tradable permits. Therefore, Equation (6) specifies how much higher the tax on j should be relative to the tax on C^R . Alternatively, Equation (6) specifies how many (climate) equivalent tonnes of emissions of C^R there are in a tonne of emissions of j . That is, Equation (6) establishes equivalence between emissions of different climate species. The right-hand side of Equation (6) is the *Global Damage Potential*.² Note that the equivalence established by Equation (6) is valid for a pulse emission reduction at time t and as such will be different for emission reductions at different points in time.

One may argue that discounting is unethical, or that choosing an appropriate discount rate is too controversial and set $\rho=0$ and at the same time capping the time horizon at H by the argument that the far future is very uncertain.³ One may argue that climate change damage estimates are controversial and uncertain, and instead use the temperature as an indicator of climate impacts – or assume that impacts are proportional to temperature. Then (6) reduces to

$$(7) \quad \frac{\frac{\partial L}{\partial R_t^j}}{\frac{\partial L}{\partial R_t^{C^R}}} = \frac{\sum_{s=t}^H \frac{\partial T_s}{\partial R_t^j}}{\sum_{s=t}^H \frac{\partial T_s}{\partial R_t^{C^R}}} = \frac{\sum_{s=t}^H \sum_{\tau=t}^s \frac{\partial T_s}{\partial F_\tau} \frac{\partial F_\tau}{\partial C_\tau} \frac{\partial C_\tau}{\partial R_t^j}}{\sum_{s=t}^H \sum_{\tau=t}^s \frac{\partial T_s}{\partial F_\tau} \frac{\partial F_\tau}{\partial C_\tau} \frac{\partial C_\tau}{\partial R_t^{C^R}}} \quad \forall t, j.$$

A further simplification is to assume that the climate change damage is linear in radiative forcing (rather than in temperature), or alternatively to assume that the temperature

² Eckaus (1992) first suggested this. Kandlikar (1995) coined the term.

³ Note that a finite time horizon is equivalent to an infinite discount rate at the final year of analysis.

change is linear in radiative forcing⁴. Either of these assumptions lead (directly from Equation (6) or via Equation (7)) to

$$(8) \quad \frac{\frac{\partial L}{\partial R_t^j}}{\frac{\partial L}{\partial R_t^{C^R}}} = \frac{\sum_{s=t}^H \frac{\partial F_s}{\partial C_s} \frac{dC_s}{dR_t^j}}{\sum_{s=t}^H \frac{\partial F_s}{\partial C_s^R} \frac{dC_s^R}{dR_t^{C^R}}} \forall t, j.$$

The right-hand side of Equation (8) is the (pulse) *Global Warming Potential* as defined by the IPCC (32) and applied in the Kyoto Protocol where the (absolute) *Global Warming Potential* (the numerator of Equation (8)) for emission j and a time horizon of H is defined by

$$(9) \quad AGWP_j(H) = \int_0^H a_j c_j(t) dt.$$

Here a_j is the specific radiative forcing (e.g. in units of $\text{Wm}^{-2}\text{kg}^{-1}$) and so is equivalent to the $\partial F_s / \partial C_s$ term in Equation (8), while $c_j(t)$ is the concentration at time t due to a unit pulse emission at time $t=0$ and is equivalent to the $\partial C_s / \partial R_t$ term in Equation (8). Obviously, Equation (8) is a discrete sum in time-steps of one year, while Equation (9) uses infinitesimally small times steps and is thus written as an integral. Note that in standard IPCC usage of the *Global Warming Potential*, the background concentrations of all gases other than j are taken to be constant, thereby ignoring radiative saturation effects (CO_2 , CH_4 and N_2O) and adjustment time changes (CO_2 and CH_4) in the case of increasing background concentrations.

Hence, the *Global Warming Potential* can be viewed as a special case of the *Global Damage Potential* in Equation (6), and consequently can be viewed, subject to the validity of the assumptions leading to its derivation, as a cost-benefit analysis tool. The

⁴ The assumption of linearity between forcing and temperature is with respect to magnitude of forcing, time development of forcing and forcing mechanism. This assumption implicitly makes the metric independent of uncertainty in the climate sensitivity.

Global Warming Potential was designed as a purely physical indicator of the relative climate impact of different emissions, and so this interpretation may seem surprising to some. However, this has been known amongst economists; it was noted by Fankhauser (1994). Nevertheless, given the difficulties in defining damage functions and the difficulties in reaching consensus over whether, or to what extent, discounting should be applied, the *Global Warming Potential* is arguably a robust and transparent version of the *Global Damage Potential*.

3. Cost-Effectiveness Analysis: Global Temperature change Potentials and Global Cost Potentials

In Section 2, we approached climate policy through cost-benefit analysis. Cost-benefit analysis is controversial for issues such as climate change because costs of both mitigation and adaptation are difficult and controversial to quantify. Instead one may define a target for emissions, concentrations, or temperatures and try to meet that target at the least cost. Indeed, the United Nations Framework Convention on Climate Change is phrased in such terms, commonly referred to as cost-effectiveness analysis. Article 2 states that policies and measures to address a human-induced climate change shall stabilise atmospheric concentrations of greenhouse gases “at a level that would prevent dangerous anthropogenic interference with the climate system”, and that the measures should be “comprehensive” and “cost-effective” (Article 3.3).

Note that cost-effectiveness analysis is a special case of cost-benefit analysis. For convenience, let us assume that the target is formulated as a temperature threshold, T_H . If $D_t = \infty$ for $T_t > T_H$ and $D_t = 0$ for $T_t \leq T_H$, then (4) becomes

$$(10) \quad \min_{R^1, R^2, \dots, R^J} \sum_{t=0}^{\infty} \frac{L(R_t^1, R_t^2, \dots, R_t^J)}{(1+\rho)^t} \text{ s.t. } T_t(T_{t-1}, F_t(C_t(C_{t-1}, R_t, R_{t-1}, \dots, R_0))) \leq T_H.$$

The first-order conditions are

$$(11) \quad \frac{\partial L}{\partial R_t^j} (1+\rho)^{-t} = \sum_{s=t}^{\infty} \lambda_s \frac{\partial T_s}{\partial R_t^j} (1+\rho)^{-s} \forall t, j$$

where λ_t is the LaGrange multiplier (or shadow price in economic jargon) of the temperature constraint at time t . If the constraint does not bite, $\lambda_t=0$. This is obviously the case for the earlier years. One may argue that the dynamics of the carbon cycle, the energy system and climate policy are such that the temperature is likely to touch the threshold and then fall (slightly) below it. Atmospheric stabilisation would require the commercialisation of carbon-neutral or even carbon-negative energy technology, and once that is achieved, CO₂ emissions would fall to a level at which concentrations would decline. Even if carbon-neutral energy requires taxes or subsidies, there would be lobby in place (either treasury or industry) to keep them even after the target will be met.⁵ If that is the case, $\lambda_t=0$ in later years too. Left with a single period $t=b$ in which the constraint bites, (11) simplifies to

$$(12) \quad \frac{\partial L}{\partial R_t^j} (1+\rho)^{-t} = \lambda_b \frac{\partial T_b}{\partial R_t^j} (1+\rho)^{-b} \forall t, j.$$

Normalising this with emissions C^R , this becomes

$$(13) \quad \frac{\frac{\partial L}{\partial R_t^j}}{\frac{\partial L}{\partial R_t^{C^R}}} = \frac{\frac{\partial T_b}{\partial R_t^j}}{\frac{\partial T_b}{\partial R_t^{C^R}}} \forall t, j.$$

The right-hand side is again an equivalence. It is the ratio of the shadow prices; that is, the relative force with which the different gases would break the constraint. Note again that the metric value for gas j relative to the reference gas C^R as established by the ratio on the right hand side of Equation 13 (as for equation 6) is valid for a pulse emission reduction at time t , and as such will change over time. Interestingly, the penalty of breaking the constraint, λ_b , drops out of Equation (12). That implies that the shadow price ratio is a purely physical concept (albeit grounded in economics).⁶ It in fact equals the (pulse) *Global Temperature change Potential* (27, 29). A key uncertainty in climate

⁵ Note that such reasoning would not hold if Equation (10) had a constraint on the rate of warming, rather than its level.

⁶ When the constraint does not bind, the ratio of marginal costs in the least cost solution can be expressed as a purely physical ratio (36).

research is the limited knowledge about the sensitivity of the climate system, i.e. the temperature response to a given radiative forcing (33). It may appear from Equation (13) to be of less importance since the right hand side of Equation (13) is the ratio of the temperature changes, and thus the climate sensitivity apparently cancels – but only if forcing efficacy is the same (27). Furthermore, the time until the constraint bites ($t=b$) will be shorter the higher the climate sensitivity. Thus the metric value for short-lived species increases with increasing climate sensitivity (29).

The ratio of shadow prices and the *Global Temperature change Potential* coincide, but only under the assumption that there is no capital stock turnover or technological effects in abatement. Power generation is an example. If one decides to build a gas-fired power plant rather than a coal-fired one, the plant is still there several decades later. If one invests in R&D to reduce the costs of photovoltaic power, it will be cheaper forever.

If we add that current abatement costs depend on past abatement, (10) becomes

$$(14) \quad \min_{R^1, R^2, \dots, R^J} \sum_{t=0}^{\infty} \frac{L_t(R_t^1, R_t^2, \dots, R_t^J, R_{t-1}^1, R_{t-1}^2, \dots, R_{t-1}^J, \dots, R_0^1, R_0^2, \dots, R_0^J)}{(1+\rho)^t} \text{ s.t. } T_t \leq T_H.$$

The first-order conditions are

$$(15) \quad \sum_{s=0}^{\infty} \frac{\partial L_{t+s}}{\partial R_t^j} (1+\rho)^{-t-s} = \lambda_b \frac{\partial T_b}{\partial R_t^j} (1+\rho)^{-b} \forall t, j$$

where s is time after t .⁷ Rearranging and normalising, this yields

$$(16) \quad \frac{\frac{\partial L_t}{\partial R_t^j}}{\frac{\partial L_t}{\partial R_t^{C^R}}} = \frac{\lambda_b \frac{\partial T_b}{\partial R_t^j} - \sum_{s=1}^{\infty} \frac{\partial L_{t+s}}{\partial R_t^j} (1+\rho)^{-t-s}}{\lambda_b \frac{\partial T_b}{\partial R_t^{C^R}} - \sum_{s=1}^{\infty} \frac{\partial L_{t+s}}{\partial R_t^{C^R}} (1+\rho)^{-t-s}} \forall t, j.$$

⁷ Note that the left-hand side sums to infinite on the assumption that climate policy will have to be maintained forever. If climate policy can be abandoned after a certain date, the partial derivatives are zero after then.

Equation (13) is clearly a special case of Equation (16). While the right hand side of Equation (13) is purely physical, the right hand side of Equation (16) combines physics and economics, by including terms that account for future economic gains from emission reduction.

Capital stock turnover is probably the most important reason why emission reduction costs are not independent between periods. In Reference (21), it is the only dynamic effect. This implies that Equation (13) and (16) are close if the temperature constraint is relatively far in the future. Power plants have a lifetime of some forty years, so Equation (13) can be used to approximate Equation (16) if the temperature threshold is not expected to be reached in the next forty years. If the target is closer, the purely physical metric of Equation (13) is insufficient, and one would need to use Equation (16), which can be computed using existing detailed models of energy infrastructure.

4. Discussion and conclusion

We derive a series of alternative metric concepts to quantify the trade-offs between reducing different climate-changing emissions. Each alternative metric establishes equivalence between emissions, or an exchange rate. We show that the alternative metrics proposed in the literature are special cases of the *Global Damage Potential*, the metric based on cost-benefit analysis. The *Global Damage Potential* is equal to the ratio of the marginal damage costs of emissions. If one assumes that climate impacts are proportional to radiative forcing, assumes a finite horizon and a zero discount rate, the *Global Damage Potential* becomes the *Global Warming Potential*, the metric currently used in international climate policy. However, none of these ifs is valid.

Cost-effectiveness analysis is a special case of cost-benefit analysis (although again under incredible assumptions), but it is more usually seen as an alternative. In a cost-benefit analysis, the policy target and least-cost trajectory to meet that target are simultaneously derived. In a cost-effectiveness analysis, the policy target is based on a political process, and only the least-cost trajectory is derived. We show that, in a cost-

effectiveness analysis, the appropriate metric is the ratio of the shadow prices of the constraint on total radiative forcing, the *Global Cost Potential*. The shadow price consists of two components: (1) the effect of emission reduction in one period on emission reduction costs in a later period; and (2) the contribution to temperature increase with which the constraint is broken. If the first were zero (it is not), the *Global Cost Potential* is a purely physical concept and, if the constraint is binding for a short time only, coincides with the *Global Temperature change Potential*, that is, the ratio of the marginal effects on global warming at the time of the constraint.

We hope that establishing the relationships between the different concepts for equivalences will allow for a more constructive discussion between the proponents of the different metrics. We also identify the crucial parameters that drive the different estimates of the numerical values between and within metrics. The above framework can readily be replicated for alternative indicators (e.g., impacts driven by precipitation) or alternative thresholds (e.g., the rate of warming), or indeed, given its generality, for impacts beyond climate change. Also in these cases, there is a physico-economic metric that can be approximated with a purely physical metric – and that approximation can be more or less accurate. As policy makers seem to prefer purely physical metrics,⁸ estimates of the approximation accuracy are desirable, although perhaps impractical to provide.

There is one immediate policy implication. The UN Framework Convention on Climate Change is phrased in terms of cost-effectiveness analysis – there is a target (i.e., avoiding dangerous climate change) that is to be met at minimum cost. Yet, the Kyoto Protocol, the first step towards meeting the long-term target, uses *Global Warming Potentials*, a cost-benefit concept, as the tool for implementation of a multi-gas approach. This is inconsistent. If a target-based policy is technologically and politically feasible and if it can be taken for granted that it will be possible to stay below the target after the target year, changing the metric of equivalence between emissions could be a way of resolving this inconsistency between the adopted regime and adopted tool. This needs further

⁸ One can also argue that the IPCC has not granted policy makers the option of choice.

considerations and dialog between policymakers and scientist from several disciplines is required (37).

Acknowledgements

This research was supported by the European Union's Sixth Framework Program Project QUANTIFY.

Reference List

1. Lashof, D. A. & Ahuja, D. R. (1990) Relative contributions of greenhouse gas emissions to global warming. *Nature* **344**: 529-531.
2. Eckaus, Richard S. (1992) Comparing the Effects of Greenhouse Gas Emissions on Global Warming. *Energy Journal* **13**: 25-35.
3. Harvey, L. D. D. (1993) A guide to global warming potentials (GWPs). *Energy Policy* **21**: 24-34.
4. Reilly, J. M. and Richards, K. R. (1993) Climate Change Damage and the Trace Gas Index Issue. *Environmental and Resource Economics* **3**: 41-61.
5. Schmalensee, R. (1993) Comparing Greenhouse Gases for Policy Purposes. *Energy Journal* **14**: 245-255.
6. Fankhauser, S. (1994) (Centre for Social and Economic Research on the Global Environment, University College London and University of East Anglia, London and Norwich), pp. 1-48.
7. Kandlikar, M. (1995) The Relative Role of Trace Gas Emissions in Greenhouse Abatement Policies. *Energy Policy* **23**: 879-883.
8. Kandlikar, M. (1996) Indices for Comparing Greenhouse Gas Emissions: Integrating Science and Economics. *Energy Economics* **18**: 265-281.
9. Hammitt, J. K., Jain, A. K., Adams, J. L., and Wuebbles, D. J. (1996) A Welfare-Based Index for Assessing Environmental Effects of Greenhouse-Gas Emissions. *Nature* **381**: 301-303.
10. Wallis, M. K. & Lucas, N. J. D. (1994) Economic global warming potentials. *International Journal of Energy Research* **18**: 57-62.
11. Wigley, T. M. L. (1998) The Kyoto Protocol: CO₂, CH₄ and Climate Implications. *Geophysical Research Letters* **25**: 2285-2288.

12. Reilly, J. M., Prinn, R., Harnisch, J., Fitz-Maurice, J., Jacoby, H. D., Kicklighter, D. W., Melillo, J. M., Stone, P., Sokolov, A. P., and ng, C. (1999) Multi-gas assessment of the Kyoto Protocol. *Nature* **401**: 549-555.
13. Smith, Steven J. and Wigley, T. M. L. (2000) Global Warming Potentials: 1. Climatic Implications of Emissions Reductions. *Climatic Change* **44**: 445-457.
14. Smith, Steven J. and Wigley, T. M. L. (2000) Global Warming Potentials: 2. Accuracy. *Climatic Change* **44**: 459-469.
15. O'Neill, B. C. (2000) The jury is still out on global warming potentials. *Climatic Change* **44**: 427-443.
16. O'Neill, B. C. (2003) Economics, Natural Science, and the Costs of Global Warming Potentials -- An Editorial Comment. *Climatic Change* **58**: 251-260.
17. Godal, O. and Fuglestvedt, J. S. (2002) Testing 100-year global warming potentials: Impacts on compliance costs and abatement profile. *Climatic Change* **52**: 93-127.
18. Fuglestvedt, J. S., Berntsen, T. K., Godal, O., Sausen, R., Shine, K. P., and Skodvin, T. (2003) Metrics of Climate Change: Assessing Radiative Forcing and Emission Indices. *Climatic Change* **58**: 267-331.
19. Smith, Steven J. (2003) The Evaluation of Greenhouse Gas Indices -- An Editorial Comment. *Climatic Change* **58**: 261-265.
20. Tol, R. S. J. (1999) The Marginal Costs of Greenhouse Gas Emissions. *Energy Journal* **20**: 61-81.
21. Manne, A. S. and Richels, R. G. (2001) An alternative approach to establishing trade-offs among greenhouse gases. *Nature* **410**: 675-677.
22. Bradford, D. F. (2001) Time, money and tradeoffs. *Nature* **410**: 649-650.
23. Godal, O. (2003) The IPCC's Assessment of Multidisciplinary Issues: The Case of Greenhouse Gas Indices. *Climatic Change* **58**: 243-249.
24. Johansson, D. J. A., Persson, U. M., and Azar, C. (2006) The Cost of Using Global Warming Potentials: Analysing the Trade-off between CO₂, CH₄ and N₂O. *Climatic Change* **77**: 291-309.
25. Forster, P. M. D., Shine, K. P., and Stuber, N. (2006) It Is Premature to Include non-CO₂ Effects of Aviation in Emission Trading Schemes. *Atmospheric Environment* **40**: 1117-1121.
26. Shine, K. P., Berntsen, T. K., Fuglestvedt, J. S., and Sausen, R. (2005) Scientific Issues in the Design of Metrics for Inclusion of Oxides of Nitrogen in Global

- Climate Agreements. *Proceedings of the National Academy of Science* **102**: 15768-15773.
27. Shine, K. P., Fuglestedt, J. S., Hailemariam, K., and Stuber, N. (2005) Alternatives to the global warming potential for comparing climate impacts of emissions of greenhouse gases. *Climatic Change* **68**: 281-302.
 28. Hope, Chris W. (2006) The Marginal Impacts of CO₂, CH₄ and SF₆ Emissions. *Climate Policy* **6**: 537-544.
 29. Shine, K. P., Berntsen, T. K., Fuglestedt, J. S., Bieltvedt Skeie, R., and Stuber, N. (2007) Comparing the Climate Effect of Emissions of Short- and Long-Lived Climate Agents. *Philosophical Transactions of the Royal Society A* **365**: 1903-1914.
 30. Michaelis, P. (1992) Global Warming: Efficient Policies in the Case of Multiple Pollutants. *Environmental and Resource Economics* **2**: 61-77.
 31. Gottinger, H. W. (1999) (Fondazione Eni Enrico Mattei, Milan), pp. 1-13.
 32. Shine, K. P., Derwent, R. G., Wuebbles, D. J., & Morcrette, J.-J. (1990) in *Climate Change - The IPCC Scientific Assessment*, eds. Houghton, J. T., Jenkins, G. J., & Ephraums, J. J. (Cambridge University Press, Cambridge), pp. 41-68.
 33. Forster, P., Ramaswamy, V., Artaxo, P., Berntsen, T. K., Betts, R. A., Fahey, D. W., Haywood, J., Lean, J., Lowe, D. C., Myhre, G. *et al.* (2007) in *Climate Change 2007: The Physical Science Basis -- Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, eds. Solomon, S., Qin, D., Manning, M., Marquis, M., Averyt, K., Tignor, M. M. B., LeRoy Miller, H., Jr., & Chen, Z. (Cambridge University Press, Cambridge), pp. 129-234.
 34. Tol, R. S. J. (2005) The marginal damage costs of carbon dioxide emissions: an assessment of the uncertainties. *Energy Policy* **33**: 2064-2074.
 35. Tol, R. S. J. (2008) The Social Cost of Carbon: Trends, Outliers and Catastrophes. *Economics -- the Open-Access, Open-Assessment E-Journal* **2**: 1-24.
 36. Michaelis, P. (1999) Sustainable greenhouse policies: The role of non-CO₂ gases. *Structural Change and Economic Dynamics* **10**: 239-260.
 37. UNFCCC (2008) (United Nations Framework Convention on Climate Change, Bonn).

Year	Number	Title/Author(s) ESRI Authors/Co-authors <i>Italicised</i>
2008	256	Intra-Union Flexibility of Non-ETS Emission Reduction Obligations in the European Union <i>Richard S.J. Tol</i>
	255	The Economic Impact of Climate Change <i>Richard S.J. Tol</i>
	254	Measuring International Inequity Aversion <i>Richard S.J. Tol</i>
	253	Using a Census to Assess the Reliability of a National Household Survey for Migration Research: The Case of Ireland <i>Alan Barrett and Elish Kelly</i>
	252	Risk Aversion, Time Preference, and the Social Cost of Carbon David Anthoff, <i>Richard S.J. Tol</i> and Gary W. Yohe
	251	The Impact of a Carbon Tax on Economic Growth and Carbon Dioxide Emissions in Ireland <i>Thomas Conefrey, John D. Fitz Gerald, Laura Malaguzzi Valeri and Richard S.J. Tol</i>
	250	The Distributional Implications of a Carbon Tax in Ireland <i>Tim Callan, Sean Lyons, Susan Scott, Richard S.J. Tol and Stefano Verde</i>
	249	Measuring Material Deprivation in the Enlarged EU <i>Christopher T. Whelan, Brian Nolan and Bertrand Maitre</i>
	248	Marginal Abatement Costs on Carbon-Dioxide Emissions: A Meta-Analysis Onno Kuik, Luke Brander and <i>Richard S.J. Tol</i>
247	Incorporating GHG Emission Costs in the Economic Appraisal of Projects Supported by State Development Agencies <i>Richard S.J. Tol and Seán Lyons</i>	

- 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
- 238 Immigrants and Welfare Programmes: Exploring the Interactions between Immigrant Characteristics, Immigrant Welfare Dependence and Welfare Policy
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 Maitre
- 234 Managing Capital Flows: Experiences from Central and Eastern Europe
Jürgen von Hagen and Iulia Siedschlag
- 233 ICT Diffusion, Innovation Systems, Globalisation and Regional Economic Dynamics: Theory and Empirical Evidence
Charlie Karlsson, Gunther Maier, Michaela Trippel, 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 Maitre
- 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

- 213 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
- 211 Where do MNEs Expand Production: Location Choices of the Pharmaceutical Industry in Europe after 1992
Frances P. Ruane, Xiaoheng Zhang
- 210 Holiday Destinations: Understanding the Travel Choices of Irish Tourists
Seán Lyons, Karen Mayor and Richard S.J. Tol
- 209 The Effectiveness of Competition Policy and the Price-Cost Margin: Evidence from Panel Data
Patrick McCloughan, *Seán Lyons* and William Batt
- 208 Tax Structure and Female Labour Market Participation: Evidence from Ireland
Tim Callan, A. Van Soest, J.R. Walsh
- 207 Distributional Effects of Public Education Transfers in Seven European Countries
Tim Callan, Tim Smeeding and Panos Tsakloglou