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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. Fuglestvedt[e], Keith P. Shine[g], Yves Balkanski[h] and Laszlo Makra[i]

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 radiactive 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

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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 Potential*s. 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 Potential*s), 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 is[1]

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

[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:

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

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:

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

The first order conditions are

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

where

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

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

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

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

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

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

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

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 ρ=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

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

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

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[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 forcing[4]. Either of these assumptions lead (directly from Equation (6) or via Equation (7)) to

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

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

$$(9) \qquad AGWP_j(H) = \int_O^H a_j c_j(t)dt\,.$$

Here a_j is the specific radiative forcing (e.g. in units of $Wm^{-2}kg^{-1}$) 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 economics; 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) $$\min_{R^1,R^2,\ldots,R^J} \sum_{t=0}^{\infty} \frac{L(R_t^1,R_t^2,\ldots,R_t^J)}{(1+\rho)^t} \text{ s.t. } T_t(T_{t-1},F_t(C_t(C_{t-1},R_t,R_{t-1},\ldots,R_0))) \leq T_H \,.$$

The first-order conditions are

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

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, λ_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, CO_2 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, λ_t=0 in later years too. Left with a single period t=b in which the constraint bites, (11) simplifies to

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

Normalising this with emissions C^R, this becomes

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

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

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

The first-order conditions are

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

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

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

[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 Potential*s, 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.

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