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Economics vs. Physical-based Metrics for Relative Greenhouse Gas Valuations

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Abstract

A range of alternatives to the Global Warming Potential (GWP) have been suggested in the scientific literature. One of these alternative metrics that has received significant attention is the cost-effective relative valuation of greenhouse gases. However, this metric is based on complex optimising integrated assessment models that are far from transparent to the general scientist or policymaker. Here we present a new analytic metric, the Cost-Effective Temperature Potential (CETP) which is based on an approximation of the cost-effective relative valuation. We show that this metric shares many similarities with the purely physical metric, Global Temperature change Potential (GTP), but that the CETP performs much better as an approximation to the cost-effective relative valuation.

Keywords: *GWP, GTP, cost-effectiveness, stabilization, climate change*
JEL: Q54, Q58

1 Introduction

Policy discussions concerning mitigation of climate change have mainly focused on abatement of CO_2 emissions. However, substantial economic gains can be achieved if other greenhouse gases are included in the policy portfolio as in the Kyoto protocol (Reilly, 1999; Hayhoe, 2000; Van Vuuren et al, 2006, Weyant et al, 2006).

Different greenhouse gases have different physical properties, both in terms of their effect on the radiative balance and in terms of atmospheric lifetimes. Therefore, to facilitate the implementation of the multigas approach, reductions in emissions of different greenhouse gases (GHGs) have to be made commensurable. To compare the different greenhouse gases, the Intergovernmental Panel on Climate Change (IPCC) and the United Nations Framework Convention on Climate Change (UNFCCC) have adopted the use of Global Warming Potentials (GWP). Basically, the GWP is constructed to ensure equivalence in time-integrated radiative forcing of emissions impulses over a pre-specified time horizon, usually 20, 100, or 500 years. As the Kyoto protocol stands now, GWPs calculated over a time period of 100 years should be used to facilitate the trade-off between different GHGs (UNFCCC, 1997). However, the time horizon over which the GWPs are calculated is chosen rather arbitrarily; there is no clear reason why to choose one time horizon over another.

The GWP metric has been criticized by both climate scientists and economists. The choice to construct the GWP so as to ensure equivalence in time-integrated radiative forcing rules out equivalence for any other end-point, such as temperature change or sea level rise, which may be more relevant end-points (Reilly et al, 1999; Smith & Wigley, 2000a; O'Neill, 2000). Further, the radiative efficiency, i.e., the marginal change in radiative forcing due to an emissions pulse, and the atmospheric life times of the gases are assumed to be constant over time. In reality, these variables change over time, depending on the concentrations of the relevant greenhouse gases (Caldeira and Kasting, 1993; Wuebbles et al, 1995; Smith & Wigley, 2000b).

The GWP also lacks any consideration of economic efficiency or cost-effectiveness. It has been argued that climate damages, see for example Hammitt et al (1996), Schmalensee (1993), and Kandlikar (1996), or climate policy targets, see for example Manne & Richels, (2001), Michaelis (1992, 1999), and Kandlikar (1996), should be taken into account in the metric formulation.

Based on this critique of the GWP, a range of different metrics, purely physical-based metrics as well as metrics where economics is taken into account, have been proposed, see for example Michaelis (1992), Eckaus (1992), Schmalensee (1993), Manne & Richels (2001), Reilly (1993), Hammitt et al (1996), Kandlikar (1996), Wigley (1998), Shine et al (2005), and the review article by Fuglestvedt et al (2003).

The two alternatives to the GWP that have gained most attention recently are:

(1) the Global Temperature change Potential (GTP) and
(2) the use of relative cost-effective prices on GHGs obtained from optimising climate-economy models; here we refer to this metric as the Global Cost Potential (GCP), as in Tol et al (2008).

Besides interest from the research community, there has been a renewed interest on the part of policymakers to reconsider the GWP approach and especially to evaluate the potential use of the GTP (UNFCCC, 2008).

The basic principle behind the GTP is to take the ratio of the temperature response in a specific year, here denoted $\hat{t}$, following an emissions pulse of a specific greenhouse gas X at year zero, to the temperature response in the year $\hat{t}$, of an emissions pulse of CO_2 at year zero, see Shine et al (2005) and Shine et al (2007). The GCP values are obtained by using optimising climate-economy models with exogenously set climate targets, such as the EU target of stabilising the global average surface temperature change at less than 2 ºC above the pre-industrial level. The GCP is defined as the ratio of the cost-effective price on emissions (i.e., the shadow price) of greenhouse gas X to the cost-effective price on carbon dioxide, see for example Manne & Richels (2001), O'Neill (2003) and Johansson et al (2006, 2008). Shine et al (2007) and later Tol et al (2008) argued that the GTP and the GCP share many traits.

The aim of this paper is two-fold:

-to show in a "simple" analytical framework that the GCP approach can be approximated with purely physical information plus the discount rate;
-to show that this approximation of GCP has, under idealised conditions, similarities with the GTP metric as suggested by Shine et al (2005), (2007) and the original formulation of GWP as suggested by Lashof and Ahauja (1990).

In section 2 we develop a simple analytical framework where the GCP is analysed and an approximation of it, the Cost-Effective Temperature Potential (CETP), is suggested. In section 3 we further analyse the CETP given idealised assumptions, i.e., assumptions in line with those used for calculating the GPW and GTP. In section 4 we present a simple climate-economy model that will be used to evaluate the CETP and the GTP with numerically obtained GCPs. In section 5 we present the results and further analyse the differences between the GCP, CETP, and GTP. In section 6 we discuss the policy implications of our results and conclude.

Independently, Tol et al (2008) have written a paper using similar reasoning but with a focus on how the standard GWP and the GTP can be interpreted from the view of economics, and on the relationships between the GTP and GCP. However, they do not suggest an explicit metric that approximates the GCP under more general circumstances, as we do here.

2 General Model used to find an approximation of the GCP

To be able to analyse the GCP approach and make an approximation of it we use an integrated climate-economy model. In order to increase the accessibility of this analytical model and the results obtained from it we try to avoid economic jargon as much as possible.

The starting point of the model is that a temperature stabilisation target[1] should be met at the lowest possible cost (in economic jargon this is a social planning model). We consider only two greenhouse gases, carbon dioxide and a generic gas denoted X. A generalisation to incorporate a range of different greenhouse gases and even particles would be straightforward. However, it would not change the nature of the results we are after, but it would make the model messier. We leave that for future work.

Given the aim of cost-minimization and a stabilisation target, a general, although simple, model can be expressed as the following constrained optimisation problem:

$$\mathrm{Min}\sum_{t=0}^{\tilde{t}}\frac{\sum_{i}C_{CO_2,i,t}\left(a_{CO_2,i,0},\ldots,a_{CO_2i,t}\right)+\sum_{j}C_{j,X,t}\left(a_{X,j,0},\ldots,a_{X,j,t}\right)}{(1+r)^t} \tag{1}$$

$s.t.$

$$T(t)=f\left(\sum_{i}a_{CO_2,i,0},\ldots,\sum_{i}a_{CO_2,i,t,},\sum_{j}a_{X,j,0},\ldots,\sum_{j}a_{X,j,t,},E_{CO_2,0},\ldots,E_{CO_2,t},E_{X,0},\ldots,E_{X,t,}S^0_{CO_2},S^0_X,T_0\right) \tag{2}$$

$$T(t)\le\hat{T} \tag{3}$$

$C_{CO2,i,t}$ and $C_{,X\,i,t}$ refer to the cost functions for reducing CO_2 and gas X in time step *t*, respectively, by using technology *i* or *j*, whereas $a_{CO2,i,t}$ and $a_{CH4,j,t}$ refer to the level of abatement by using technology *i* and *j*, respectively, in time step *t*. Note that the cost functions in equation (1) depend on the abatement level history. This assumption is made

[1] In the numerical modelling presented below we use the EU's target of keeping the global annual mean surface temperature increase below 2 ºC above the pre-industrial level.

to capture effects such as learning-by-doing and the degree of sunkenness of abatement capital. The function *f*, shown in equation (2), is a black-box temperature model where the temperature in time *t* is dependent on the history of baseline emissions (E_{t,CO_2} and $E_{t,X}$) and abatement levels, the initial atmospheric stocks ($S^0_{CO_2}$ and $S^0_{CH_4}$) of the greenhouse agents, and initial global average surface temperature above the pre-industrial level (T_0). Decay rates, radiative impacts of stock changes and the temperature response to changes in the radiative forcing are implicitly taken into account in *f*. Equation (3) is a policy constraint implying that the global annual mean surface temperature change has to be kept below $\hat{T}$ ºC above the pre-industrial level.

The cost functions for all *i*, *j*, *t* and for both gases are positive, increasing in in-period abatement, and convex, i.e., $C > 0$, $\frac{\partial C(a)}{\partial a} > 0$, $\frac{\partial^2 C(a)}{\partial a^2} \geq 0$. We do not make any explicit assumptions on the functional forms concerning the temporal interdependence of the abatement decisions and costs. Hence, abatement in one period can make future abatement costs both higher and lower. For example, depletion of low-cost and safe aquifers to store captured CO_2 would raise future abatement costs while learning-by-doing in the production of PhotoVoltaic (PV) cells would lower future abatement costs.

If we solve for the first order conditions of the constrained optimisation problem presented in (1)-(3) by stating the Lagrangian we get:

$$\frac{\partial C_{CO_2,i,t}}{\partial a_{CO_2,i,t}} = -\sum_{\tau=t}^{\tilde{t}} \frac{\eta_\tau}{(1+r)^{\tau-t}} \cdot \frac{\partial T_\tau}{\partial a_{CO_2,i,t}} - \sum_{\upsilon=t+1}^{\tilde{t}} \frac{1}{(1+r)^{\upsilon-t}} \cdot \frac{\partial C_{CO_2,i,\upsilon}}{\partial a_{CO_2,i,t}} \qquad \forall i,t \tag{4}$$

and

$$\frac{\partial C_{X,j,\tau}}{\partial a_{X,j,t}} = -\sum_{\tau=t}^{\tilde{t}} \frac{\eta_\tau}{(1+r)^{\tau-t}} \cdot \frac{\partial T_\tau}{\partial a_{X,j,t}} - \sum_{\upsilon=t+1}^{\tilde{t}} \frac{1}{(1+r)^{\upsilon-t}} \cdot \frac{\partial C_{X,j,\upsilon}}{\partial a_{X,j,t}} \qquad \forall j,t \tag{5}$$

where η_τ is the Lagrange multiplier associated with the constraint on the global annual mean surface temperature in equation (3).

Optimality conditions (4) and (5) imply that the optimal marginal abatement cost for each technology *i* and *j* in each time step equals the negative sum up to $\tilde{t}$ of the discounted (negative) temperature response of a marginal abatement perturbation multiplied with the Lagrange multiplier (shadow price) of the temperature constraint minus the sum up to $\tilde{t}$ of the discounted derivative of the subsequent periods' abatement costs for technology *i* and *j* with respect to the abatement in period *t*.

The Lagrange multiplier η_τ of the temperature constraint is zero as long as the constraint (3) is slack. This implies that the temperature response following an abatement unit (or emissions pulse) prior to the date the constraint starts to bite, let's denote this date $\bar{t}$, does not have any influence on the cost-effective price on the emissions nor on the optimal marginal abatement cost, presented in (4) and (5). Hence, it is only the temperature response of an abatement (or emissions) unit in time *t* post-stabilisation, i.e., at time $\bar{t}$ and beyond, that influences the magnitude of the cost-effective price on the emissions.

In order to continue the analysis we have to define what we mean by the cost-effective price on the emissions and of what this price consists. Is it equal to the right hand side of equations (4) and (5) or something else? We claim that it only includes the first term on the right hand side of equations (4) and (5), hence the cost-effective price on the emissions depends only on the policy constraint (3) and not on the technology dynamics[2].

It is rather easy to understand that the shadow prices (the first term on the right hand side of equations (4) and (5)), generated by the temperature constraint (3), warrants a corrective policy. Profit/utility maximising consumers/producers would never internalise such a price in their decisions if it were not for explicit corrective polices such as an emissions tax or an emissions permit trading scheme, see for example Baumol & Oates (1988) and Sterner (2003). Hence, the first term of the right hand side in equations (4) or (5) should be included in the cost-effective price on the emissions.

However, whether the temporal interdependence of abatement costs, i.e. the second term on the right hand side of equations (4) and (5) should be taken into account in the cost-effective price on the emissions and in a policy such as an emissions tax is not self-evident at all. In most cases it should not.

In general, policy intervention can only be justified on efficiency grounds if there are market failures. Consequently, corrective policies for the temporal interdependencies between abatement costs are only justified if the social returns to investments in abatement capital are higher than the private returns, hence there are adoption externalities involved, see for example Jaffe et al (2005), Rosendahl (2004) and Bramoullé & Olson (2005). Note that most of the temporal interdependencies considered in the cost functions do not involve problems with market failures, i.e., the private and social returns coincide and there are no adoption externalities. For example, under most

[2] The Lagrange multiplier η_τ will depend on the technology characteristics and abatement cost. Consequently, the cost-effective price on the emissions will indirectly (through η_τ) depend on the technology dynamics and the abatement cost.

circumstances an investment in a production facility with a long lifespan would result in equal private and social returns, hence long-lived capital as such is not a reason for a policy intervention even if the temporal interdependencies are strong. On the other hand, through learning-by-doing the social returns may be higher than the private returns on investments in abatement capital. For example, if one agent invests in an immature technology such as PV cells and thereby lowers the cost of investing in PV for all market agents, then a policy that subsidises investment in PV would be justified. However, for more mature technologies such as Natural Gas Combined Cycles (NGCC) such learning-by-doing effects would be close to negligible and no policies would be justified. Given this heterogeneity of the difference between private and social returns to investments in abatement capital the use of a single policy for all abatement technologies, such as raising the price on emissions, would be a very blunt policy instrument to use to correct for the potential market failures. On the other hand, more efficient corrective policies that are differentiated for each and every single technology and sector would be very unpractical and virtually impossible given all the information needed to implement such a policy. The elegant balance lies somewhere in between, see Sandén & Azar (2005) and Jaffe et al (2005).

Consequently, it is only the first term on the right hand side of equations (4) and (5) that should be taken into account in the cost-effective price on the emissions. Therefore, the cost-effective price (or the cost-effective tax) on CO_2 emissions (equivalent for emissions of *X)* is:

$$\text{Price}_{CO_2}(t) = \sum_{\tau=t}^{\tilde{t}} \frac{\eta_\tau}{(1+r)^{\tau-t}} \cdot \frac{\partial T_\tau}{\partial a_{CO_2,i,t}} \qquad \forall i,t \tag{6}$$

Hence, the GCP approach as suggested by Manne & Richels (2001) and many others can be summarised by the following ratio

$$GCP_X(t) = \frac{\text{Price}_{\text{X,t}}}{\text{Price}_{\text{CO}_2,t}} = \frac{\sum_{\tau=t}^{\tilde{t}} \frac{\partial T_\tau}{\partial a_{X,t}} \cdot \frac{\eta_\tau}{(1+r)^{\tau-t}}}{\sum_{\tau=t}^{\tilde{t}} \frac{\partial T_\tau}{\partial a_{CO_2,t}} \cdot \frac{\eta_\tau}{(1+r)^{\tau-t}}} \tag{7}$$

Since the temperature response does not depend on the abatement technology per se, we suppress indices *i* and *j* in equation (7).

Unfortunately the ratio in equation (7) does not make us much more content since we do not know η_τ. η_τ depends in a complex manner on a range of parameter assumptions, initial conditions, etc. and will not be dwelled upon in this paper.

As the aim is to find a simple metric that approximates the GCP we conjecture:

Conjecture 1. If there exists a simple trade-off metric, here called the Cost-Effective Temperature Potential (CETP), which closely resembles the GCP, it is owing ratio

$$CETP(t)=\frac{\int_{t}^{\tilde{t}}\frac{\Delta T_{\tau}^{E_{x,t}}}{\Delta E_{X,t}}e^{-r(\tau-t)}d\tau}{\int_{t}^{\tilde{t}}\frac{\Delta T_{\tau}^{E_{CO_2,t}}}{\Delta E_{CO_2,t}}e^{-r(\tau-t)}d\tau}\approx\frac{\sum_{\tau=t}^{\tilde{t}}\frac{\partial T_{\tau}}{\partial a_{X,t}}\cdot\frac{1}{(1+r)^{\tau-t}}}{\sum_{\tau=t}^{\tilde{t}}\frac{\partial T_{\tau}}{\partial a_{CO_2,t}}\cdot\frac{1}{(1+r)^{\tau-t}}} \qquad (8)$$

where $\Delta T_{\tau}^{E_{x,t}}$ is the temperature response following a small emissions pulse, $\Delta E_{X,t}$, of gas *X* at time *t* and where $\Delta T_{\tau}^{E_{CO_2,t}}$ is the temperature response at time τ following a small emissions pulse, $\Delta E_{CO_2,t}$, of CO_2 at time *t*.

Note that we in equation (8) went from discrete time to continuous time and that we analyse the temperature response of small positive emissions pulse instead of marginal abatement. This is done to enhance the tractability of the metric without losing anything essential.

The most important step between equation (7) and equation (8) is that we dropped η_τ when we went from the GCP to the CETP. Given the restrictive assumption that η_τ is a constant beyond the date of stabilisation, $\bar{t}$, the CETP would be identical to the GCP. In addition, in the simple model presented in section 3, the CETP would be identical to the GCP also in the case where η_τ is growing or declining exponentially with time beyond the date of stabilisation. However, dropping η_τ under more general circumstances still makes the CETP a decent approximation to the GCP as is illustrated in section 5 below. The reason why the simplification works well under more general circumstances is that η_τ takes a fairly steady value after the date of stabilisation if abatement cost functions are independent on time. Also, if exogenous technical change is assumed and implemented so that the abatement costs falls exponentially with a constant rate over time, η_τ would approximately decline exponentially.

This simplification of the GCP means that an approximation that only requires physical information, the date of stabilisation, and the discount rate can be obtained. Hence, the full integrated assessment model including the cost of abatement can be dropped when computing the approximated GCP.

In order to increase the transparency of the suggested CETP and elucidate its links with the GTP and GWP metrics, we will derive an explicit solution of the CETP in the next section.

3 Analytical solution of the CETP under linearized conditions

In order to be transparent we will first derive an expression for the Absolute CETP (ACETP). Since the aim is to find a metric at a similar level of complexity as the GWP and GTP we make similar assumptions concerning linearity in radiative efficiency, atmospheric decay functions of the greenhouse gases, and temperature response functions.

We use a simple, one-box energy balance model, see for example Shine et al (2005) and Andrews & Allen (2008), to assess the change in the global annual-mean surface temperature:

$$\Delta \dot{T}(t) = \frac{\Delta F(t)}{H} - \frac{\Delta T(t)}{\lambda H} \qquad (9)$$

where H is the equivalent heat capacity of the climate system, λ is the climate sensitivity, $\Delta F(t)$ the time dependent radiative forcing and $\Delta T(t)$ the temperature response. The solution of the differential equation (9) is:

$$\Delta T_t = \frac{1}{H}\int_0^t \Delta F_\tau e^{\frac{\tau - t}{\lambda H}} d\tau \qquad (10)$$

The temperature response of a unit emissions pulse of agent X with a constant atmospheric decay rate of δ_X and radiative efficiency of I_X can be described by, see Shine et al (2005):

$$\Delta T_\tau^{E_{x,t}} = \frac{I_X}{H\left(\frac{1}{\lambda H} - \delta_X\right)}\left(e^{-\tau\delta_X} - e^{\frac{-t}{\lambda H}}\right) \qquad (11)$$

By using the nominator in (8), assuming that $\Delta E_{X,t}$(t)=1 kg, and that the model time horizon, $\tilde{t}$, approaches infinity the $ACETP_X$ for the time period prior to the date of stabilisation is:

$$ACETP_X(t) = \lim_{\tilde{t}\to\infty} \int_{\bar{t}}^{\tilde{t}} \frac{\Delta T_{\tau}^{E_{x,t}}}{\Delta E_{X,t}} e^{-r(\tau-t)} e^{-r(\tau-t)} d\tau =$$
$$= \frac{I_X}{H\left(r + \frac{1}{\lambda H}\right)} \left[\frac{e^{-(\bar{t}-t)(r+\delta_X)} - e^{-(\bar{t}-t)\left(r+\frac{1}{\lambda H}\right)}}{\frac{1}{\lambda H} - \delta_X} + \frac{e^{-(\bar{t}-t)(r+\delta_X)}}{(r+\delta_X)} \right] \qquad \forall t < \bar{t} \tag{12}$$

and for the time period after stabilisation the $ACETP_X$ is:

$$ACETP_X(t) = \frac{I_X}{H\left(r + \frac{1}{\lambda H}\right)(r+\delta_X)} \qquad \forall t \geq \bar{t} \tag{13}$$

The ACETP for carbon dioxide is slightly more complex since the atmospheric perturbation lifetime of carbon dioxide cannot be described accurately by a simple exponential decay, instead several decay rates have to be considered for the impulse response, see for example Maier-Reimer & Hasselmann (1987) and Forster et al (2007). Accordingly, the ACETP for carbon dioxide prior to the date of stabilisation can be written as:

$$ACETP_{CO_2}(t) = \frac{I_{CO_2}}{H\left(r + \frac{1}{\lambda H}\right)} \left(\alpha_0 \left(\frac{1 - e^{-(\bar{t}-t)\frac{1}{\lambda H}}}{\frac{1}{\lambda H}} + \frac{1}{r} \right) + \sum_{i=1}^{3} \alpha_i \left(\frac{e^{-(\bar{t}-t)\delta_{CO_2}^i} - e^{-(\bar{t}-t)\frac{1}{\lambda H}}}{\frac{1}{\lambda H} - \delta_{CO_2}^i} + \frac{e^{-(\bar{t}-t)\delta_{CO_2}^i}}{\left(r + \delta_{CO_2}^i\right)} \right) \right)$$
$$\forall t < \bar{t} \tag{14}$$

and for the time period after the date of stabilisation the ACETP for carbon dioxide is:

$$ACETP_{CO_2}(t) = \frac{I_{CO_2}}{H\left(r + \frac{1}{\lambda H}\right)} \left(\frac{\alpha_0}{r} + \sum_{i=1}^{3} \frac{\alpha_i}{\left(r + \delta_{CO_2}^i\right)} \right) \qquad \forall t \geq \bar{t} \tag{15}$$

By combining equation (12) with equation (14) we get the CETP for agent *X* prior to the date of temperature stabilisation:

$$CETP_X(t) = \frac{ACETP_X(t)}{ACETP_{CO_2}(t)} =$$
$$= \frac{I_X}{I_{CO_2}} \frac{\frac{e^{-(\bar{t}-t)(r+\delta_X)} - e^{-(\bar{t}-t)\left(r+\frac{1}{\lambda H}\right)}}{\frac{1}{\lambda H} - \delta_X} + \frac{e^{-(\bar{t}-t)(r+\delta_X)}}{(r+\delta_X)}}{\alpha_0 \left(\frac{1 - e^{-(\bar{t}-t)\frac{1}{\lambda H}}}{\frac{1}{\lambda H}} + \frac{1}{r} \right) + \sum_{i=1}^{3} \alpha_i \left(\frac{e^{-(\bar{t}-t)\delta_{CO_2}^i} - e^{-(\bar{t}-t)\frac{1}{\lambda H}}}{\frac{1}{\lambda H} - \delta_{CO_2}^i} + \frac{e^{-(\bar{t}-t)\delta_{CO_2}^i}}{\left(r + \delta_{CO_2}^i\right)} \right)} \qquad \forall t < \bar{t} \tag{16}$$

While the CETP of agent X after the date of stabilisation is:

$$CETP_X(t) = \frac{I_X}{I_{CO_2}} \frac{\frac{1}{(r+\delta_X)}}{\frac{\alpha_0}{r} + \sum_{i=1}^{3} \frac{\alpha_i}{(r+\delta_i)}} = GWP_X \qquad \forall t \geq \bar{t} \tag{17}$$

Interestingly, as is seen in equation (17), GETP after stabilisation is identical to the original GWP with discounting as formulated by Lashof and Ahuja (1990). The response time of the energy balance model (which is equal to *λH*) is cancelled out in equation (17). Note that this would not be the case if we had used a more complex energy balance model in which the response time could not be represented by a single time constant as here.

The CETP prior to stabilisation as seen in equation (16) shares similarities with both Lashof and Ahuja's original GWP and the GTP as formulated by Shine et al (2005), (2007). GTP evaluated at time $\bar{t}$ is defined as:

$$GTP_X(t) = \frac{AGTP_X(t)}{AGTP_{CO_2}(t)} == \frac{I_X}{I_{CO_2}} \frac{\frac{e^{-(\bar{t}-t)(r+\delta_X)} - e^{-(\bar{t}-t)\left(r+\frac{1}{\lambda H}\right)}}{\frac{1}{\lambda H} - \delta_X}}{\alpha_0 \left(\frac{1-e^{-(\bar{t}-t)\frac{1}{\lambda H}}}{\frac{1}{\lambda H}} \right) + \sum_{i=1}^{3} \alpha_i \left(\frac{e^{-(\bar{t}-t)\delta_i} - e^{-(\bar{t}-t)\frac{1}{\lambda H}}}{\frac{1}{\lambda H} - \delta_i} \right)} \qquad \forall t < \bar{t} \tag{18}$$

By combining the GTP and GWP so that the AGTP is evaluated at the date of stabilisation $\bar{t}$, while the AGWP as suggested by Lashof and Ahuja is calculated for the remaining fraction of gas X and CO_2, respectively, in the atmosphere at year $\bar{t}$ of an initial emissions pulse in year 0, we get the CETP for agent *X*:

$$CETP_X(t) = \frac{AGTP_{CH_4,pulse}^{0,0\to\bar{t}} + AGWP_{CH_4}^{0,\bar{t}\to\infty}}{AGTP_{CO_2,pulse}^{0,0\to\bar{t}} + AGWP_{CO_2}^{0,\bar{t}\to\infty}} \qquad \forall t < \bar{t} \tag{19}$$

where $0,0 \to \bar{t}$ means an emissions pulse in year 0 and that the AGTP is calculated for time horizon $\bar{t}$ and where $0,\bar{t} \to \infty$ means an emissions pulse in year 0 and where the AGWP is calculated for the period $\bar{t} \to \infty$.

Finally, it is worth noting that the CETP, GTP and GCP would be identical in three special circumstances:

1. If the time horizon (i.e. $\tilde{t}$) of the optimisation problem was equal to $\bar{t}$ (and not approaching ∞ as assumed here in section 3), and the temperature target was met the last year of the modelling time horizon, the three metrics would coincide.
2. If the temperature peaks year $\bar{t}$ and then for some policy-independent reason declines after the peak, with the policy constraint only biting in year $\bar{t}$, the GCP and GTP metrics would coincide. This is assumed in Tol et al (2008) where the GCP and GTP are compared. The CETP would coincide with the other two metrics if $\tilde{t}$ were set to $\bar{t}$.
3. If the discount rate approaches infinity, the CETP would in the limit converge to the GTP. Whether this also holds for the GCP is not straightforward, and we leave that for future research, but as seen in section 5, an increase in the discount rate results in a convergence of the values of the three metrics prior to the date of stabilisation.

4 Numerical model assumptions

In order to compare the CETP and GTP with the GCP obtained from an optimising climate-economy model, we have used a simple dynamic climate-economy model with only three greenhouse gases, methane, nitrous oxide, and carbon dioxide. The numerical model is an updated and simplified version of the MiMiC model presented and used in Johansson et al (2006, 2007). The main difference between the model used here and the versions in Johansson et al (2006, 2007) is that the climate module has been linearised for the model runs presented in this paper. This assumption makes the cost-effective price on emissions, and consequently the GCP and CETP, commensurable with the GTP and the GWP, since linearity is assumed in these two latter metrics[3]. This is of course a very crude simplification of the real geophysical system, but it yields a model complicated enough to show the approximation made by the CETP in comparison with the “correct” GCP and to analyse the differences and similarities between the GCP, CETP and GTP.

The values for the constant radiative efficiency for each gas are taken from Forster et al (2007)**.** For methane we add 40 % extra radiative forcing per mole due to methane’s indirect effect on the level of tropospheric ozone and stratospheric water, in line with Forster et al (2007).

CO_2 concentrations are modelled by a linear pulse representation of the Bern carbon cycle model. CH_4 and N_2O concentrations are modelled by using global mean mass-balance equations with a single lifetime describing decay rates. We

[3] To be correct, a constant background atmosphere is assumed when calculating the GWP and the GTP. This, however, gives identical results as assuming linearity and a non-constant background atmosphere.

use the average atmospheric lifetime as the decay rate. For methane the perturbation lifetime is about 30 % greater than the average atmospheric life time. By assuming that the perturbation lifetime is equal to the average atmospheric lifetime we underestimate the GCP, CETP and GTP for methane, but we can keep the climate module linear.

For the time-discrete version of the one-box energy balance model shown in equation (9), we assume that the climate sensitivity is 3 ºC for a doubling of the CO_2 concentration and that the equivalent heat capacity of the ocean-land-atmosphere system is 1.2 G J $K^{-1}m^{-2}$. The equivalent heat capacity is set so as to give an e-folding time of the global annual mean surface temperature response to about 30 years. This is in line with the e-folding times obtained estimated in the simple climate model MAGICC for a climate sensitivity of 3 ºC, see Richels et al (2007), and in line with the e-folding times estimated from transient runs of large-scale AOGCMs (Andrews & Allen, 2008). Note that the calibration of the equivalent heat capacity and the choice of using or not using a more complicated and “correct” EBM, such as an upwelling diffusion energy balance model, are of importance for the results since these choices have an influence on the temperature response following an emissions pulse and on the date of stabilisation. Shine et al (2005, 2007) choose to calibrate their one-box EBM with a, from ours, radically different value for the equivalent heat capacity. Consequently our numerical GTP value for a rather short lived GHG like methane differs considerably from their value. However, the efficient heat capacity we choose is more in line with what is common in climate-economy models using one-box energy balance models, see for example Richels et al (2007).

The model runs between the years 2000-2300 with annual time-steps. Abatement of emissions is only allowed from the year 2011 and onward. Baseline emissions of the well-mixed GHGs in the period 2020-2100 are taken from the IPCC IS92a scenario (IPCC, 1992). Years up to 2006 are based on historical data, and emissions estimates for 2007 to 2019 are obtained by using linear interpolation. After 2100 the emissions are assumed to follow a path toward stabilisation, which occurs in the year 2150, see Johansson et al (2006) for details.

The model chooses abatement levels of the GHGs in order to minimize the net present value abatement cost to meet a stabilisation target for the global average surface temperature of 2°C above the pre-industrial level. Abatement costs are modelled with the aid of abatement cost functions, see Johansson et al (2006) for details.

The choice of discount rate for long-term analysis is a delicate matter. This issue has been at the centre of the climate debate for a long time and was recently amplified in the aftermath of the Stern Review. We will not here delve into the issue of what constitutes a proper long-term discount rate. Rather, we take note of the difficulties in choosing a long-term discount rate and analyse the model for different discount rates. Our base case uses a discount rate of 5 % per year. This value is chosen as our base case since it is a common assumption in long-term energy-economy-climate modelling. Two alternative discount rates are also tested for, 1 % per year and 10 % per year. The 10 % discount rate is well above what is defensible from an intergenerational-equity point of view, but is included for the sake of illustration.

To generate the results presented in section 5 we first run the numerical model where the stabilisation date is endogenously determined. This stabilisation date is then fed into the formulas for calculating the GTP, equation (18), and the CETP, equation (16). We also limit the results to the relative valuation of methane to carbon dioxide and leave the valuation of nitrous oxide and other gases for future analysis.

5 Results – comparison and illustration

5.1 Base discount rate case

Given a discount rate of 5 % per year the stabilisation target will be met in the model in 2090. As seen in figure 1, the CETP approximates the GCP rather well, especially up to about 2060-2070 and for the time after stabilisation of temperature, i.e., beyond year 2090. As can also be seen in figure 1, the GTP value is considerably higher than both the GCP and the CETP. The reason for this is that the GTP does not take into account the long-term temperature response of an emissions pulse that occur after the time of stabilisation, while this is reflected in the GCP and CETP. The temperature response beyond the date of stabilisation is relatively more important for CO_2 emission pulses than CH_4 emissions pulses, and consequently the metric value for CH_4 is lower if this is taken into account.

The reason why the GCP and CETP diverge in the decades just prior to stabilisation is that the shadow price (Lagrange multiplier) generated by the temperature stabilisation constraint, equation (3) above, takes on a high value the first date(s) the constraint bites and thereafter more or less stabilises. This relatively large initial shadow price of the temperature constraint is a result of the thermal inertia of the climate system[4]. A consequence of this large initial shadow price is that it pushes the relative emissions price upward prior to stabilisation and more so on short-lived GHGs than on long-lived GHGs. Consequently, the GCP becomes higher than the CETP close to the date of stabilisation.

[4] See den Elzen and Van Vuuren (2007) for a discussion of radiative forcing overshoots and temperature stabilisation, although they do not analyse shadow prices.

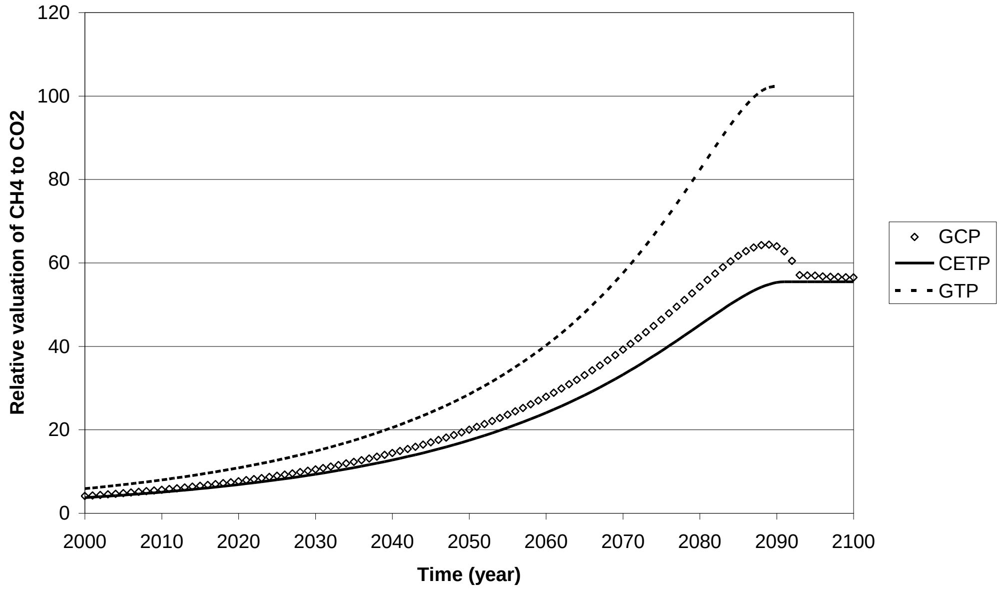

Figure 1. The figure shows the relative valuation of methane to carbon dioxide for three different metrics, i.e., GTP, GCP and CETP, as a function of time given a discount rate of 5% per year.

5.2 Low discount rate case

With a low discount rate such as 1 % per year the stabilisation target is not constraining until 2110. As a consequence of the later stabilisation time, the GCP, CETP, and GTP values for methane are all lower early this century than they are in the base case. As both GCP and CETP depend on the discount rate and the long-term temperature response beyond stabilisation, the difference in the valuation of methane using these metrics compared to using GTP are much more drastic than with a discount rate of 5 % , compare figure 1 and figure 2. This can be understood by comparing equations (16) and (18) where it is clear that the CETP diverges from the GTP as the discount becomes smaller. Note that the CETP approximates the GCP well under this assumption while the GTP does not.

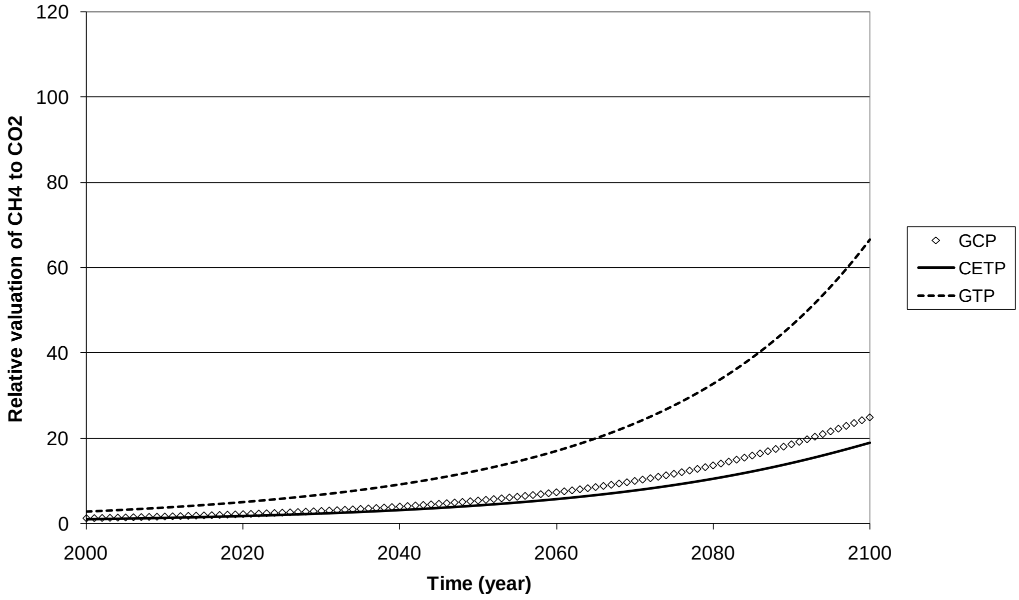

Figure 2. The figure shows the relative valuation of methane to carbon dioxide for three different metrics, i.e., GTP, GCP and CETP, as a function of time given a discount rate of 1% per year.

5.2 High discount rate case

With a high discount rate set to 10 % per year the stabilisation target is met 2080. As is discussed in the last paragraph of section 3 the CETP (and also the GCP) converges toward the GTP as the discount rate becomes large. This is clearly visible in figure 3, where relative valuation of methane to carbon dioxide is rather similar for GTP, CETP and GCP.

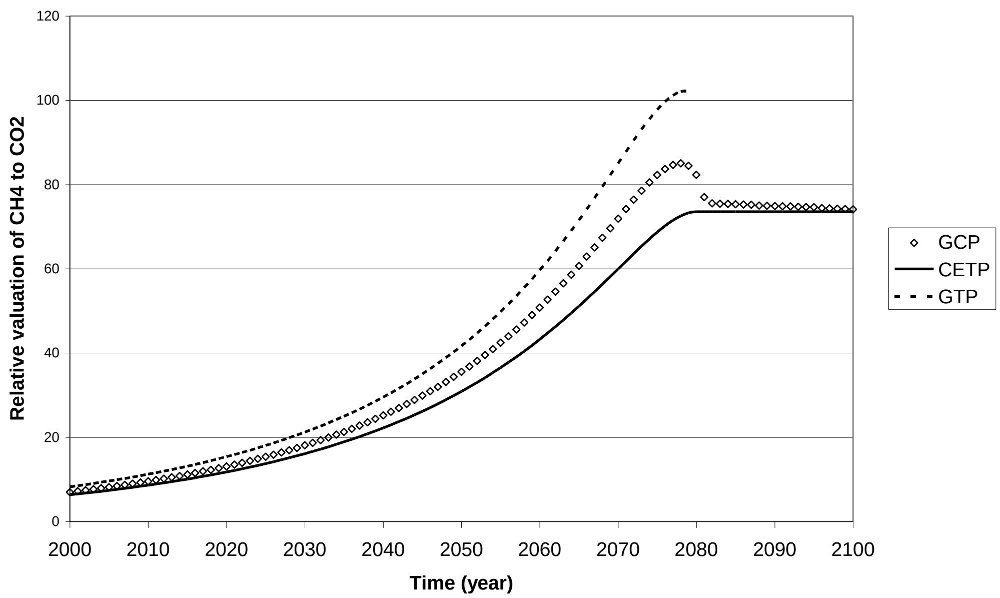

Figure 3. The figure shows the relative valuation of methane to carbon dioxide for three different metrics, i.e., GTP, GCP and CETP, as a function of time given a discount rate of 10% per year.

6 Discussion and Conclusion

Shine et al (2007) and Tol et al (2008) observed that the GTP shares many features with the GCP suggested by Manne & Richels (2001). The analysis in this paper substantiates those observations. However, given that cost-effectiveness is a clear goal of both the UNFCCC and the Kyoto protocol, we suggest a modification of the GTP resulting in a new metric, CETP. Not only does this metric provide a better approximation of the GCP than the GTP does, it also gives an estimate of a trade-off ratio after temperature stabilisation; GTP fails to do so. Besides, the CETP takes into account the very long-term temperature response (>1000-10 000 years) that follows from emissions of CO_2.

Furthermore, as is shown in the paper, the GCP and the CETP converge to the GTP as the discount rate increases. However, from the perspective of intergenerational equity, high discount rates are indefensible. Weather one chooses an ethical approach concerning discounting (Dasgupta, 2008) or a descriptive approach based on estimates of the return to capital (Nordhaus, 2007), one can argue on purely mathematical and statistical grounds that the long-term discount rate should progressively become lower and lower the farther away in the future, see Weitzman (1998, 2001), Gollier (2008) and Newell & Pizer (2004). This is a result of the uncertainty concerning what the long-term discount rate is, which in turn depends on the long-term overall technological progress of the economy. This implies that short-lived GHGs should have a low value relative to long-lived greenhouse gases, a value lower that you would get from the GTP or the GCP using a discount rate of 5% as is often used in integrated assessment models.

Finally, it is clear that the choice of metric is not only a scientific issue, but in the end a question of political choice and policy objective. The relevant end-points or policy targets are matters of value judgments, not science. However, policymakers have historically viewed the global warming potentials as a purely scientific issue and not an issue for policy (Schackley & Wynne, 1997; Smith, 2003). Nevertheless, a “perfect” metric cannot be constructed as long as the policy objectives are not clearly decided upon. The UNFCCC (1992) provides vague guidance on what the overall policy objective is. It is clear from the UNFCCC that “*stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system”* is the overall target. Further, it is stated that “*policies and measures to deal with climate change should be cost-effective so as to ensure global benefits at the lowest possible cost*.” Given these policy goals it is clear that the GCP and consequently the CETP are suitable tools to make emissions of different greenhouse gases commensurable. GTP may also do the job quite well due to the similarities with the GCP and the CETP, but as seen in section 5 this depends very much on the discount rate used.

However, the UNFCCC also states that the "*stabilization of greenhouse gas concentrations"* should be *"achieved within a time frame sufficient to allow ecosystems to adapt naturally to climate change.*" Hence to limit the rate of climate change is an aim in itself. All three metrics as they are presented here fail to incorporate any aspects of the rate of climate change. Rate of change constraints on, for example, the temperature can be taken into account in the construction of the GCP, but would depend on complex numerical models and much of the transparency gained with the analytical approach used for the CETP or the GTP would be lost. Also, even though the current GWP integrated over 100 years does not seem to be constructed with the policy goals of the UNFCCC in mind, it tends to perform quite well and is robust to a range of policy alternatives and socio-economic and climatic uncertainties, see Johansson et al (2006).

Whether changing metrics is worthwhile is consequently still an open question and our intention here was not to provide an answer concerning that. Rather, our intention was to clarify the relationship between the GCP and GTP and to suggest a transparent approximation of the GCP. The approximation that we call the Cost-Effective Temperature Potential (CETP) outperforms the GTP as an approximation of the GCP, but retains the analytical tractability of the GTP.

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