A unifying framework for metrics for aggregating the climate effect of different emissions

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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 kinds of such metrics and debated their relative merits. We present a unifying framework that clarifies the relationships among them. We show, as have previous authors, that the global warming potential (GWP), used in international law to compare emissions of greenhouse gases, is a special case of the global damage potential (GDP), assuming (1) a finite time horizon, (2) a zero discount rate, (3) constant atmospheric concentrations, and (4) impacts that are proportional to radiative forcing. Both the GWP and GDP follow naturally from a cost–benefit framing of the climate change issue. We show that the global temperature change potential (GTP) is a special case of the global cost potential (GCP), assuming a (slight) fall in the global temperature after the target is reached. We show how the four metrics should be generalized if there are intertemporal spillovers in abatement costs, distinguishing between private (e.g., capital stock turnover) and public (e.g., induced technological change) spillovers. Both the GTP and GCP follow naturally from a cost-effectiveness framing of the climate change issue. We also argue that if (1) damages are zero below a threshold and (2) infinitely large above a threshold, then cost-effectiveness analysis and cost–benefit analysis lead to identical results. Therefore, the GCP is a special case of the GDP. The UN Framework Convention on Climate Change uses the GWP, a simplified cost–benefit concept. The UNFCCC is framed around the ultimate goal of stabilizing greenhouse gas concentrations. Once a stabilization target has been agreed under the convention, implementation is clearly a cost-effectiveness problem. It would therefore be more consistent to use the GCP or its simplification, the GTP.

Keywords: climate change, multi-gas climate policy, global warming potential, equivalences between greenhouse gases

1. Introduction

Human activity puts many substances into 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 cause a cooling. 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 types of ‘equivalences’ between climate-changing species, and there are discussions (occasionally heated) about which ‘metric’ is the better one [1–36]. The types are:

- global warming potential (GWP) [37, 38];
- global damage potential (GDP) [27, 29];
- global cost potential (GCP) [21]; and
- global temperature change potential (GTP) [27, 29].

Recent work has addressed the development of additional metrics within these types, uncertainty in their values, and applications to short-lived gases and aerosols [39–44]. Here we focus on the conceptual framework for metrics in broad terms. We show that these ‘exchange rates’ are special cases of a single, unifying framework, as illustrated in figure 1. 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 and an orange. Rather, this is because weight is a major 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 judgments and thus cannot be solved by scientists alone. The UNFCCC Copenhagen Accord reaffirms the political goal of restricting global temperature increase to 2 °C above pre-industrial levels. However, once the goal has been determined, on whatever grounds, metrics can be designed based on objective, scientific methods.

In section 2, we start with a cost–benefit framework for assigning the appropriate weights to different emissions. These ratios are called global damage potential. We show

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**Figure 1.** The relationships between the four main types of metrics to compare different components of climate-changing emissions.
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), and show under what circumstances this is equivalent to the purely physical concept of global temperature change potential. We do this for targets on the level of climate change. Section 4 concludes the paper.

2. Cost–benefit analysis: global warming potential and global damage potential

Consider a decision maker who wants to minimize the net losses due to climate change and climate policy. If only one component of emissions (i.e., a particular gas or aerosol) contributes to climate change, the problem to be solved is:

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

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 \(\partial L / \partial D < 0\); \(\rho\) is the discount rate. Damages depend on climate change; let us 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. \(T\) depends on, but is not uniquely defined by, 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 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, and in any case, different comprehensive models would not agree on the evolution of \(T\). To simplify the evaluation, global-average radiative forcing \(F\) is often used to give a first-order estimate of the impacts of different emissions [38]. \(F\), 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:

\[
\min_R \sum_{t=0}^{\infty} L(R_t, D_t(T_t(F_t, F_{t-1}, \ldots, F_0))) \frac{1}{(1+\rho)^t} \quad (1')
\]

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

\[
F_t = f(C_t(E_t, \ldots E_0, R_t, \ldots, R_0)).
\]

Assuming that mitigation costs and damage costs are independent, the first-order conditions (that is, the conditions under which the derivative of the objective function with respect to the control variable \(R\) is equal to zero) are

\[
\frac{\partial L}{\partial R_t} (1+\rho)^{-t} = - \sum_{s=0}^{\infty} \frac{\partial L}{\partial D_s} \frac{\partial D_s}{\partial T_s} \frac{\partial T_s}{\partial R_t} (1+\rho)^{-s} \quad \forall t \quad (3a)
\]

where

\[
\frac{\partial T_s}{\partial R_t} = \sum_{j=1}^{J} \frac{\partial T_s}{\partial C_j} \frac{\partial C_j}{\partial R_t}.
\]

When these conditions hold, the solution is optimal. This means that, in the optimum, emissions should be set at a level such that the marginal cost of one additional unit of reduction is equal to the future stream of damages of climate change avoided by that emission reduction. The left-hand side of (3a) represents the marginal abatement cost of emissions, while the right-hand side is typically referred to as the marginal damage cost of emissions, the Pigou tax, or the social cost of carbon [45, 46].

Now suppose that there are \(J\) different emissions (i.e., a number of different gases or aerosols, or their precursors) that affect the climate. The aim is then to solve

\[
\min_{R^1, R^2, \ldots, R^J} \sum_{t=0}^{\infty} L(R^1_t, R^2_t, \ldots, R^J_t, D_t) \frac{1}{(1+\rho)^t}.
\]

Following standard methods for optimization [47], the first-order conditions are

\[
\frac{\partial L}{\partial R^j_t} (1+\rho)^{-t} = - \sum_{s=0}^{\infty} \frac{\partial L}{\partial D_s} \frac{\partial D_s}{\partial T_s} \frac{\partial T_s}{\partial R^j_t} (1+\rho)^{-s} \quad \forall t, j. \quad (5)
\]

That is, the optimal solution is one in which the emissions of each component \(j\) at a level, at any given point in time, such that the discounted marginal abatement cost for emission \(j\) should equal the marginal damage cost of emission \(j\). There is also some dependence of the optimum level for each component \(j\) on the other components of emissions built in, because in general the temperature response to a reduction in emissions of component \(j\) depends on the overall temperature and concentration pathways, and therefore on the history of emissions of all components.

The marginal cost of damage given by the right-hand side of equation (5) is per mass unit of emission. Due to large differences in the physical properties of different climate agents (e.g. lifetimes and radiative efficiencies) the marginal costs of damage can be very different.
A global climate policy based on (5) demands full knowledge about damages as well as mitigation costs.\textsuperscript{12} If these were known this framework would give the optimal global emission pathways for each component of emissions as a function of time. The optimal mitigation could be achieved either by giving out quotas for emissions of each component that were equal at each point in time to the optimal emissions implied by (5), or by assigning an emission metric to each component of emissions that establishes the equivalence between them and giving out quotas for total emissions at each point in time. Each emitter could then decide how best to achieve the total emission constraint. Alternatively, taxes could be levied. This would again require a metric that gives the tax on one component relative to another.

To assign the appropriate weights for different emissions, we normalize with respect to emissions of 1, the reference gas (usually carbon dioxide). We can then rewrite equation (5) as

\[ \frac{\partial L}{\partial R_i} = \sum_{s=1}^{\infty} \int_{t=0}^{\infty} \frac{\partial \tau_s}{\partial R_i} (1 + \rho)^{-s} \partial C_t \partial R_t \partial C_j \partial R_j \quad \forall t, j. \tag{6} \]

This is unity for \( j = 1 \). 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 gas 1. Alternatively, equation (6) specifies how many (climate) equivalent tonnes of emissions of 1 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 warming potential.\textsuperscript{13} 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.\textsuperscript{14} 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 of equation (6) reduce to

\[ \frac{\partial L}{\partial R_i} = \sum_{s=1}^{H} \int_{t=0}^{\infty} \frac{\partial \tau_s}{\partial R_i} (1 + \rho)^{-s} \partial C_t \partial R_t \partial C_j \partial R_j \quad \forall t, j. \tag{7} \]

Equation (7) is the integrated global temperature potential,\textsuperscript{48} which is equivalent to the mean global temperature potential,\textsuperscript{49} as shown by \textsuperscript{48}, and the sustained global temperature potential,\textsuperscript{27}, as shown by \textsuperscript{48}, \textsuperscript{50}.

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 change is linear in radiative forcing.\textsuperscript{15} Either of these assumptions leads (directly from equation (6) or via equation (7)) to

\[ \frac{\partial L}{\partial R_i} = \sum_{s=1}^{H} \int_{t=0}^{\infty} \frac{\partial \tau_s}{\partial R_i} (1 + \rho)^{-s} \partial C_t \partial R_t \partial C_j \partial R_j \quad \forall t, j. \tag{8} \]

In the very long run, (8) converges to (7), as shown by [50].

The right-hand side of equation (8) is the (pulse) global warming potential as defined by the IPCC \textsuperscript{37} and applied in the Kyoto Protocol where the (absolute) GWP (the numerator of equation (8)) for emission \( j \) and a time horizon of \( H \) is defined by

\[ \text{AGWP}_j(H) = \int_{0}^{H} a_c c_j(t) \, dt. \tag{9} \]

Here \( a_c \) is the specific radiative forcing (e.g. in units of W m\(^{-2}\) kg\(^{-1}\)) and so is equivalent to the \( \partial F_t / \partial C \) 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 \( \partial C_j / \partial R_t \) term in equation (8). Obviously, equation (8) is a discrete sum in time steps of one year, while equation (9) uses infinitesimally small time 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 further radiative saturation and changing overlap effects (CO\(_2\), CH\(_4\), and N\(_2\)O) and adjustment time changes (CO\(_2\) and CH\(_4\)) in the case of changing 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 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 simple and transparent version of the global damage potential.

\textsuperscript{12} Note that the framework still holds if the planner has full knowledge of the probability density functions of impacts and abatement costs. In equation (1), loss would be replaced by expected loss, and equation (5) would include some measure of the uncertainties, some of which would be generic to the climate problem and some of which would be species specific.

\textsuperscript{13} Reference [2] first suggested this. Reference [7] coined the term.

\textsuperscript{14} Note that a finite time horizon is equivalent to an infinite discount rate at the final year of analysis. The choice of the time horizon is arbitrary and controversial.

\textsuperscript{15} 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.
3. Cost-effectiveness analysis: global temperature change potential and global cost potential

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. This is commonly referred to as cost-effectiveness analysis. The United Nations Framework Convention on Climate Change is phrased in such terms. Article 2 states that policies and measures to address a human-induced climate change shall stabilize atmospheric concentrations of greenhouse gases ‘at a level that would prevent dangerous anthropogenic interference with the climate system’. Economic concerns may modulate the choice of target, but stabilization itself is beyond question. Article 3.3 has that the measures should be ‘cost-effective’.16

Cost-effectiveness analysis can be viewed as a special case of cost–benefit analysis. For example, let us begin with the cost–benefit problem described by (4) for multiple components of emissions. For convenience, let us assume that the target is formulated as a temperature threshold, \( \hat{T} \). If damages are assumed to be infinite beyond the threshold (\( D_t = \infty \) for \( T_t > \hat{T} \)), then the optimal solution will not exceed that threshold. If damages are assumed to be zero below the threshold (\( D_t = 0 \) for \( T_t \leq \hat{T} \)), then the loss function will depend only on emissions reduction costs. Under these two assumptions, (4) becomes

\[
\min_{R^1, R^2, \ldots, R^J} \sum_{t=0}^{\infty} \frac{L(R^1_t, R^2_t, \ldots, R^J_t)}{(1 + \rho)^t} \quad \text{s.t.} \quad T_t(T_{t-1}, F_t(C_{t-1}, R_t, R_{t-1}, \ldots, R_0)) \leq \hat{T} 
\]

(10)

where \( R_t \) and \( C_t \) also represent the various gases from 1 to \( J \). This equation now describes a cost-effectiveness problem. Temperature is constrained to not exceed the threshold, and the loss function \( L \) does not depend on damages; thus it is only abatement costs that are being minimized.

Assuming that the cost in time \( t \) is independent of emission reduction at time \( s \neq t \) (as was done in equation (5)), the first-order conditions are

\[
\frac{\partial L}{\partial R^j_t} (1 + \rho)^{-t} = \sum_{s=1}^{\infty} \lambda_s \frac{\partial T_s}{\partial R^j_t} (1 + \rho)^{-s} \quad \forall t, j
\]

(11)

where \( \lambda_t \) is the Lagrange multiplier (or shadow price in economic jargon) of the temperature constraint at time \( t \). Equation (11) says that in the optimal solution, emissions would be at a level such that the abatement cost of one additional unit of emissions reduction at time \( t \) (left-hand side) would be equal to the benefit that reduction would generate by reducing temperature change during periods when the constraint is binding (right-hand side).

To assign the appropriate weights for different emissions, we normalize with respect to emissions of reference gas 1. We can then rewrite equation (11) as

\[
\frac{\partial L}{\partial R^1_t} \sum_{s=1}^{\infty} \lambda_s \frac{\partial T_s}{\partial R^1_t} (1 + \rho)^{-s} = \frac{\lambda_t}{\sum_{s=1}^{\infty} \lambda_s} \frac{\partial T_t}{\partial R^1_t} (1 + \rho)^{-t} \quad \forall t, j.
\]

(12)

Equation (12) indicates that, in the cost-effective solution, the ratio of marginal abatement costs between component \( j \) and the reference gas should equal the ratio of benefits due to allowing more emissions at other time periods while maintaining the constraint. Because the marginal abatement cost should also equal the tax on greenhouse gas emissions, or the price of tradable permits, equation (12) specifies how much higher the tax on \( j \) should be relative to the tax on gas 1. Alternatively, it specifies how many (climate) equivalent tonnes of emissions of gas 1 there are in a tonne of emissions of \( j \). The equivalence this ratio establishes between emissions of different climate species is the global cost potential. It has been called the price ratio [21], calculated with an integrated climate–economy model in which ratios of marginal abatement costs found in the optimal solution are reported as the resulting index values.17

Equation (10) has a single constraint: temperature should stay below a certain threshold. This reflects the current thinking in international climate policy. In principle, there can be multiple constraints: ultimate temperature, rate of temperature change, sea level, ocean acidity and so on. In that case, the right-hand side of equation (11) become a double sum, over time and over constraints. Similarly, if there is a constraint as well as a concern about impacts below that constraint, then the right-hand side of equation (5) should be added to the right-hand side of equation (11).

The right-hand side of equation (11) is a sum of shadow prices times first partial derivatives. There is one shadow price per period because the constraint is imposed for every period. If, in a particular period, the constraint does not bite—i.e., if the temperature in the optimal solution is below the threshold temperature—then the shadow price is zero: \( \lambda_t = 0 \). This is obviously the case for the years before the threshold is reached, \( t < b \) where \( T_b = \hat{T} \). In the years after the threshold is reached \( t > b \), the temperature probably falls slightly below the target. If the temperature would stay exactly on target, it is as if had replaced a one-sided target (\( T_t \leq \hat{T} \)) with a two-sided one (\( T_t \leq \hat{T} \) and \( T_t \geq \hat{T} \)). Meeting two targets is necessarily more expensive as meeting a single target, so the optimal temperature almost always falls below the target temperature, if ever so slightly.18 Later still, climate-neutral technologies may have sufficiently matured to

17 Reference [33] proposes the cost-effective temperature potential, as an approximation of the global cost potential. The approximation is perfect if the marginal emission reduction costs are identical—for example, if it costs as much to reduce a tonne of methane as it does to reduce a tonne of carbon dioxide.

18 One may also 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 stabilization would require the commercialization of carbon-neutral or even carbon-negative energy technology, and once that is achieved, CO2 emissions would fall to
gain a 100% market penetration without policy support. Then the constraint does not bite anymore and shadow price is again zero: \( \lambda_t = 0 \). If that happens one period after the threshold is hit, then we are left with a single period \( t = b \) in which the constraint is reached: \( \lambda_b > 0 \) and \( \lambda_t = 0 \) if \( t \neq b \). Then, (12) simplifies to

\[
\frac{\partial L}{\partial R_t} = \frac{\partial T_b}{\partial R_t} \quad \forall t, j. \tag{13}
\]

The right-hand side is again an equivalence. It is the ratio of the temperature changes at the time the constraint is reached due to a unit additional reduction at time \( t \) of gas \( j \) relative to the reference gas at time \( t \). Interestingly, the shadow price \( \lambda_b \) in equation (12) has dropped out, so that the global cost potential is being approximated as a purely physical measure given by the right-hand side of equation (13). Physical measure in fact equals the (pulse) global temperature change potential [27, 29].

Note again that this 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.

A key uncertainty in climate research is the limited knowledge about the sensitivity of the climate system, i.e. the temperature response to a given radiative forcing [38]. 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 global cost potential and the global temperature change potential coincide in equation (13), but only under the additional assumption (implicit so far) that abatement costs across time periods are independent. This assumption would be violated if there were capital stock turnover or technological effects associated with abatement measures. Power generation is an example. If one decides to build a gas-fired power plant rather than a coal-fired one, the new plant is still there several decades later, affecting future as well as current mitigation costs. Similarly, if one invests in R&D to reduce the costs of photovoltaic power, it will be cheaper forever.

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

When the constraint does not bind, the ratio of marginal costs in the least-cost solution can be expressed as a purely physical ratio [51].

Reference [33] derives a variation of the GTP called the cost-effective temperature potential (CETP) that assumes the shadow price is constant once the constraint is reached, and therefore it also drops out of that metric. However the CETP includes the discount rate, so is still a combined physical-economic metric.

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

\[
\min_{R^1, R^2, \ldots, R_l} \sum_{t=0}^{\infty} \left[ L_t(R^1_t, R^2_t, R^3_t, \ldots, R^l_t)(1 + \rho)^{t-s} \right] \quad \text{s.t. } T_t \leq \hat{T} \quad \forall t. \tag{14}
\]

The first-order conditions are

\[
\sum_{s=0}^{\infty} \frac{\partial L_t}{\partial R^s_t} (1 + \rho)^{-t-s} = \lambda_t \frac{\partial T_b}{\partial R^s_t} (1 + \rho)^{-b} \quad \forall t, j \tag{15}
\]

where \( s \) is time after \( t \). Rearranging and normalizing, this yields

\[
\frac{\partial L_t}{\partial R^s_t} = \lambda_t \frac{\partial T_b}{\partial R^s_t} - \sum_{s=0}^{\infty} \frac{\partial L_{t+s}}{\partial R^s_t} (1 + \rho)^{-t-s} \quad \forall t, j \quad \tag{16}
\]

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.

There is an alternative way to rearrange and normalize equation (15). If cross-period spillovers are substantial and private, then they should not be included in the metric (which is a social preference) but rather they would be included in the decisions of individual agents making abatement decisions. In this case, it is better to rearrange equation (15) to move these spillover terms to the left-hand side, and then normalize:

\[
\frac{\partial L_t}{\partial R^s_t} + \sum_{s=1}^{\infty} \frac{\partial L_{t+s}}{\partial R^s_t} (1 + \rho)^{-t-s} = \lambda_t \frac{\partial T_b}{\partial R^s_t} \tag{17}
\]

In this case, the value of the GCP is once again approximated by a purely physical measure, the GTP (right-hand side). However, the GCP itself is no longer the ratio of marginal abatement costs, but rather it is the ratio of the shadow prices of emissions, which includes both marginal abatement costs of reductions at a given time as well as the cross-period costs associated with that reduction. Both must be taken into account by agents making abatement decisions.

Note that the reasoning to move from equation (13) to equations (16) and (17) also applies to equations (6)–(8) and (12). If intertemporal spillovers in emission reduction costs are substantial, then this should be reflected, either in the equivalence metric (equation (16)) or by applying the metric, be it GDP, GWP, GCP or GTP, to the net present costs rather than to the current costs (equation (17)). In both cases, foresight is required not only with respect to the climate system, but also with respect to the economic system.

Capital stock turnover is probably the most important reason why emission reduction costs are not independent.

21 Note that the left-hand side sums to infinity 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.
between periods. In [21], it is the only dynamic effect. This implies that equation (13) and (16) are close (and equation (17) less relevant) 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) or (17), 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. See figure 1. 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 in principle; in practice, their influence on the numerical value of the index is an empirical matter that depends on the particular application.

Cost-effectiveness analysis is a special case of cost–benefit analysis (although again under unrealistic 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 optimal marginal abatement costs, the global cost potential. This ratio 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, it 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 constructive discussion between the proponents of the different 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,22 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 the global warming potential, a cost–benefit concept, as the tool for implementation of a multi-gas approach. This is inconsistent [21, 29, 35, 36, 39]: The policy goal is formulated in terms of ultimate concentrations and ultimate concentrations only, but the measure used to evaluate progress towards that goal is based on integrated forcing, which is dominated by intermediate concentrations. Some might argue that the principle of cost-effectiveness is not necessarily incorporated within the objectives of the UNFCCC itself, but once a long-term stabilization target has been agreed under the convention, it aims for cost-effective implementation [52]. 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 considerations and dialog between policymakers and scientists from several disciplines is required [53].

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22 One can also argue [32] that the IPCC has not provided any alternatives.
