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# Physico-economic evaluation of climate metrics: A conceptual framework

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ABSTRACT

The design of multi-gas mitigation policies requires methods for comparing the climate impact of different forcing agents—so-called metrics. A multitude of climate metrics has been presented in the literature. Key characteristics of any metric are (a) its impact function, i.e. its functional relationship to physical climate parameters, and (b) the weighting of impacts over time. In view of these characteristics, we present a physico-economic framework which allows classifying climate metrics from the literature in a straight-forward manner. From the economics perspective, the Global Damage Potential can be considered as a first-best benchmark metric since it ensures that the trade-off between different forcing agents is efficient. The conceptual framework based on economic principles shows that virtually all climate metrics including Global Warming Potential and Global Cost Potential can be constructed as variants of the Global Damage Potential. The framework facilitates a structured discussion on climate metrics since it reveals normative assumptions and simplifications that are implicit to the choice of a climate metric. The evaluation of commonly used metric approaches in terms of uncertainties reveals that the choice of metric is largely characterized by trade-offs between different kinds of uncertainties: explicit ones which are directly linked to operational feasibility and implicit structural ones which reflect the degree of policy relevance. Based on our findings, we suggest as an alternative option for policy applications to base exchange rates between forcing agents on an explicit analysis of the value-based, scientific and scenario uncertainties in the context of a physico-economic metric, rather than eliminating the relevant uncertainties by the choice of a physical metric.



## 1. Introduction

Cost-effective and comprehensive multi gas mitigation strategies as stipulated by the United Nation Framework Convention on Climate Change require climate change metrics. These represent methods for quantitatively comparing climate impacts of different radiatively active substances (e.g. Fuglestvedt et al., 2010). A multitude of emission metrics have been presented in the literature. The choice of metric type is crucially

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*Abbreviations:* AM, absolute metric; C, concentration; $CO_2$, carbon dioxide; *D*, economic damage; $\delta$-function, Dirac Delta Function; *E*, emission; EGWP, Economic Global Warming Potential; FEI, Forcing Equivalent Index; *H*, time horizon; GCP, Global Cost Potential; GDP, Global Damage Potential; GTP, Global Temperature Potential; GWP, Global Warming Potential; I, impact function; *M*, metric; *MAC*, marginal abatement costs; *MDC*, marginal damage costs; *PI*, physical impact parameter; $PI_{thres}$, physical impact threshold; *r*, discount rate; ref, reference concentration pathway; *RF*, radiative forcing; *T*, temperature; $t_x$, end point; *TEMP*, Temperature Proxy Index; $\theta$-function, unit step function; *W*, weighting function.

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important for the numeric values of greenhouse gas exchange rates (e.g. Boucher, 2012; Fuglestvedt et al., 2010, see also Table 2). Identifying an appropriate metric approach for any mitigation strategy requires a clear definition and prioritization of policy objectives. Climate metric design involves physical, economic and politico-economic aspects and requires a thorough interdisciplinary perspective and understanding (Plattner et al., 2009; Shine, 2009; Godal, 2003; O'Neill, 2003; Smith, 2003). The physical sciences are indispensable in metric design for quantifying how emissions affect climate. In virtually all metric applications (e.g. emissions trading, greenhouse gas inventories, life-cycle assessments), however, explicit or implicit assumptions about the marginal utility of emission abatement of different forcing agents are made, and thus metric design also has high relevance for the field of economics.

In the past, policymakers agreed on using a purely physical metric, the Global Warming Potential to set up the Kyoto Protocol (henceforth GWP(*H*)). The IPCC introduced this metric approach but also stressed that there is no unambiguous methodology for combining all relevant factors into a single metric approach (IPCC, 1990; Shine, 2009). The GWP(*H*) has been subject to criticism from both natural scientists and economists (O'Neill, 2000; Fuglestvedt et al., 2003, 2010; Shine, 2009; Dorbian et al., 2011).

Most of the scientific climate metric literature assesses the rationale, the performance and limitation of certain metric types, such as physico-economic cost-benefit approaches (Eckhaus, 1992; Reilly and Richards, 1993; Schmalensee, 1993; Hammitt et al., 1996; Tol, 1999), cost-effectiveness approaches (Manne and Richels, 2001; van Vuuren et al., 2006; Reilly and Richards, 1993) or physical metrics (Lashof and Ahuja, 1990; IPCC, 1990; Gillett and Matthews, 2010; Shine et al., 2005, 2007; Tanaka et al., 2009; Peters et al., 2011). However, only few scholarly papers exist which consider metrics from a meta-perspective, including atmospheric and economic sciences. Fuglestvedt et al. (2003 and 2010) provide a detailed overview of climate metric design issues. Forster et al. (2007) present a general formulation of an emission metric, based on Kandlikar (1996). Finally, Tol et al. (2012) and Johansson (2011) highlight interrelations between metric approaches. A clearly structured discussion of climate metrics along the general formulation of an emission metric is lacking.

The design of climate metrics involves explicit and implicit assumptions on the functional relationship between climate impacts and physical climate change, and the aggregation of impacts occurring at different points in time. The objective of this article is to provide a physico-economic framework which classifies the Global Damage Potential (GDP), the Global Cost Potential (GCP) and currently discussed physical metrics in a straight-forward manner. The framework, based on impact and temporal weighting functions, provides a transparent classification scheme, thus revealing underlying implicit assumptions and value judgments. Our economic interpretation of physical metrics aims to foster trans-disciplinary exchange on this highly policy-relevant issue and to support decision-makers in identifying an appropriate metric, given normative judgments about the trade-off between policy targets.

Section 2 presents the general formulation of an emission metric. By linking it to the economic derivation of a climate metric, we develop a conceptual framework which classifies the variety of climate metrics from literature on the basis of economic rationales. The framework is established step by step in Section 3. Finally, Section 4 discusses implications of alternative metrics regarding different types of uncertainties and draws some conclusions.

## 2. General formulation of an emission metric

The starting point of the conceptual framework is a generalized formulation of an emission metric as previously introduced by Kandlikar (1996) and Forster et al. (2007). It can be written as the integral over time of the incremental weighted impact incurred by a pulse emission of gas *i*.

$$AM_i = \int_0^{\infty} \frac{I(C_{(\text{ref}+\Delta E_i)}(t)) - I(C_{\text{ref}}(t))}{\Delta E_i} \cdot W(t)\, dt \qquad (1)$$

where the impact function *I* describes the climate impact as a function of physical climate change *C* along a reference concentration pathway ref. *W* specifies the temporal weighting function. The corresponding metric value $M_i$ ($M_i = AM_i/AM_{CO_2}$) refers to the impact of 1 kg of emission *i* ($\Delta E_i$) normalized to the one of 1 kg reference gas, usually $CO_2$ ($\Delta E_{CO_2}$). *I* and *W* are crucial determinants of the metric value $M_i$, and can be used to characterize alternative metrics.

### 2.1. Impact function

The impact function *I* relates the metric to a climate impact proxy in the chain of impacts, such as global mean radiative forcing (*RF*), the change in global mean temperature ($\Delta T$) or economic damage (Hammitt, 1999; Fuglestvedt et al., 2003; van Vuuren et al., 2006; Plattner et al., 2009). In some cases, the rate of change of a climate impact parameter is also used as proxy. An ideal metric would consider the entire causal chain of impacts. Since, however, the last step, quantifying damages as a function of physical impact parameters, is subject to large scientific and value-based uncertainties (e.g. Forster et al., 2007; Wuebbles et al., 2010; Stern, 2007; Hanemann, 2010), it is common to make simplifying implicit assumptions about the interrelation between economic damage and physical impact and apply physical climate parameters as an impact proxy. Further, the assumed future concentration pathway is an important aspect of the impact function.

The impact function *I* in the generalized formulation of an emission metric (Eq. (1)) refers to a pulse emission. Some approaches, however, calculate metric values based on sustained emissions or an emission scenario over an extended period of time (e.g. Shine et al., 2005; Deuber et al., 2013). Sustained emission metrics can be derived from pulse emission metrics through convolution, see e.g. Boucher (2012). For the sake of conceptual clarity, we focus our analysis on pulse emissions.

### 2.2. Weighting function

The weighting function *W* aggregates impacts occurring at different points in time. The following three variants are

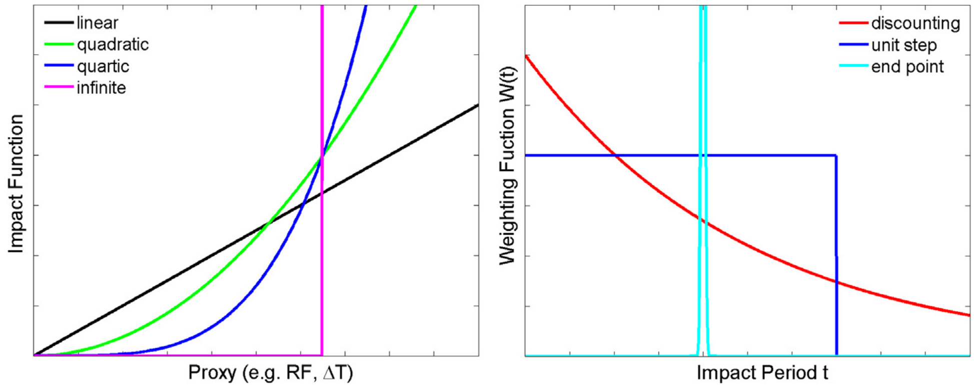


**Fig. 1 – Schematic representation of commonly used (a) impact functions and (b) temporal weighting functions. All physical metrics assessed in this study use linear impact functions, while impact functions considered for the GDP typically include non-linear convex functions. The GCP implicitly considers zero impacts below the climate threshold and infinite impacts above. Physico-economic metrics typically use exponential discounting for the temporal weighting function, while unit-step and end-point weighting is more commonly used in physical metrics.**

commonly used in climate metric design (Section 3.3, Fig. 1b) [1]:

(a) the exponential weighing function $W(t) = r \cdot e^{-rt}$, corresponding to the discount function commonly used in economics for aggregating monetary values over time with a discount rate $r$, given in % per year;

(b) the unit step function ($\theta$-function, e.g. Boas, 2006)

$$W(t) = \frac{1}{H}\,\theta(H-t) = \begin{cases} 1/H & \text{for } t \le H \\ 0 & \text{for } t > H \end{cases} \quad (2)$$

which assigns equal weight to all impacts occurring over a finite time horizon $H$; and

(c) the Dirac Delta function ($\delta$-function, e.g. Boas, 2006)

$$W(t) = \delta(t_x - t) = 0 \quad \text{for} \quad t \neq t_x \quad \text{with} \quad \int_{-\infty}^{\infty} F(t)\,\delta(t_x - t)\,dt = F(t_x) \quad (3)$$

which only evaluates the impacts at one discrete point in time $t_x$ (end point weighting).

For each of these weighting functions, free parameters exist that determine the time scale of evaluation: the discount rate $r$ (discounting), the time horizon $H$ ($\theta$-function) and the end point $t_x$ ($\delta$-function). Again, the choice of these time frame parameters involves normative decisions. In most metric approaches they are taken as constant. Some physical metrics exist, however, in which the time frame parameter is replaced by the distance between the point in time of emission release and a specific target year (e.g. Berntsen et al., 2010; Shine et al., 2007; Tanaka et al., 2009).

## 3. Characterizing climate metrics

In the following, we establish a conceptual framework by characterizing alternative metric choices based on the applied impact and weighting function. In Section 3.1 we demonstrate how the Global Damage Potential is derived from first economic principles. Other metrics can be interpreted as variants of this benchmark approach (Section 3.2). The synthesis provided in Section 3.3 reveals the implicit assumptions underlying the alternative approaches and highlights interrelations across the metric types.

### 3.1. *The first-best approach: Global Damage Potential*

The concept of marginal impacts from emission pulses, which serves as a basis for the definition of the absolute metric (Section 2), is grounded in the cost-benefit analysis, building on marginal climate change impacts and marginal costs of emission reductions. An economically optimal abatement strategy implies that the sum of mitigation and damage costs assumes a minimum. In our case of greenhouse gases with varying atmospheric lifetimes, this means that the discounted present value of marginal abatement costs (*MAC*) of an emission of agent *i* has to be equal to the marginal discounted present value of damage costs (*MDC*) of the same emission;

$$MAC_i = MDC_i \quad (4)$$

In the case of $CO_2$, these *MDC*s are often referred to as the social costs of carbon and correspond to the optimal (Pigouvian) tax level (Pigou, 1932; Baumol, 1972; Nordhaus, 1991; Fankhauser, 1995).

In view of uncertainty about the *MAC*s, it is not possible for policymakers to define *ex ante* optimal abatement levels for each individual greenhouse gas. Instead, emissions can be regulated by introducing a cap for the total emissions and assigning an emission metric to each individual gas, thus letting the market decide how best to achieve the total emission constraint (“what flexibility”). An optimal climate metric is one that relates the marginal costs of emission control to the future stream of damages of climate change avoided by that emission reduction. In this case, the metric $M_i$ of a pulse emission *i* equals its potential climate impact (also referred to as absolute metric $AM_i$) normalized to the impact incurred by a reference gas

[1] We normalized the weighting functions such that $\int_0^\infty W(t)dt = 1$.

(usually carbon dioxide ($CO_2$, $AM_{CO2}$), see for a detailed mathematical framework Tol et al. (2012):

$$M_i^D = \frac{AM_i}{AM_{CO_2}} = \frac{MDC_i}{MDC_{CO_2}} \stackrel{!}{=} \frac{MAC_i}{MAC_{CO_2}} \tag{5}$$

By establishing a ratio of *MDC*s, the scaling factor from physical impact to economic costs including the related uncertainties cancels out; solely the functional form of the economic damage function remains relevant. The requirement in Eq. (5) that the metric be equal to the ratio of *MAC*s arises directly from the efficiency condition (Eq.(4)).

The corresponding first-best metric approach from a socio-economic point of view is the Global Damage Potential (GDP, Eckhaus, 1992; Kandlikar, 1996; Tol, 1999). The GDP, also named Economic Damage Index (EDI) (Hammitt et al., 1996), is based on the evaluation of the future stream of discounted economic damages:

$$\text{GDP} : M_i^D = \frac{\int_0^\infty (\partial D/\partial E_i)\cdot \Delta E_i \cdot e^{-rt}dt}{\int_0^\infty (\partial D/\partial E_{CO_2})\cdot \Delta E_{CO_2} \cdot e^{-rt}dt} \tag{6}$$

Typically, exogenous scenario assumptions on future atmospheric background greenhouse gas concentrations are taken. Beyond predicting changes in physical parameters, the fundamental challenge in GDP calculation consists of determining the functional form of the damage function, which relates economic damages to changes in physical impact parameters. In economic analysis of climate change it is most common to assume damage to be a convex function of $\Delta T$ (e.g. $D = \alpha \cdot \Delta T^n$, Nordhaus, 1991; Kandlikar, 1995; Tol, 1999; Nordhaus and Boyer, 2000; Stern, 2007) while some approaches (e.g. Hammitt et al., 1996; Tol, 2003) additionally consider potential discontinuities.

Even though in economic literature there is a rough conception of the functional interrelation between economic damage and physical climate impact parameter, it is very challenging to quantify damages. It is characterized by a high degree of scientific uncertainty since it requires a full representation of the relevant complex causal relationships, including a down-scaling of global changes to the regional and local level (Hanemann, 2010). On the other hand, valuing climate impacts is closely related to questions of irreversibility and inter- and intragenerational equity and requires value judgements, in particular with regards to the aggregation of impacts across regions and over time, as well as the treatment of non-market impacts (Tol, 2005). The economic evaluation of non-market goods such as ecosystem loss, climate amenity, health and higher mortality risks is strongly controversial (e.g. Stern, 2007).

In climate metric design, handling uncertainty with respect to the functional form of the economic damage function is the key motivation to refrain from the theoretically optimal cost-benefit approach. Specific assumptions are taken to simplify the case (“second best approaches”) (Tietenberg, 1992).

### 3.2. *Classification of other metric approaches*

There are two fundamentally different second-best approaches to avoid the uncertainty associated with the functional form of the economic damage: physical metrics use impact functions that are based on physical climate variables, whereas cost-effectiveness approaches calculate economically optimal exchange rates between greenhouse gases given a prescribed climate target. Both approaches are discussed in the following.

#### 3.2.1. *Physical metrics*

Physical climate metrics avoid the perils of economic evaluation by choosing a physical impact proxy that is located further upstream in the chain of impacts ($\Delta T$ or *RF*), implicitly assuming linearity between economic damage and physical impact proxy. The uncertainty affecting metric calculation is thus reduced to uncertainties related to the physical processes of the climate system, e.g. the carbon cycle, atmospheric chemistry interactions and radiative effects (*RF* as proxy), as well as the climate sensitivity and the time scale of the climate response ($\Delta T$ as proxy) (Fuglestvedt et al., 2003, 2010; Forster et al., 2007). Simplifications are achieved by assuming a specific background concentration pathway $C_{ref}$.

A multitude of temperature-based metrics are proposed in literature: They differ in their choice of *W*, time frame parameter and $C_{ref}$. The Global Temperature Change Potential applies the $\delta$-function, referring either to a pulse or a sustained emission with a constant end point $t_x$ ($t_x$ = const) ($GTP_p$, $GTP_s$) (Shine et al., 2005), or to a pulse emission with a time-dependent end point representing the distance between the time of emissions release $t_0$ and the time $t_{tar}$ at which a specific climate target is expected to be reached ($t_x = t_x(t_0, t_{tar})$) ($GTP_p(t)$, Shine et al., 2007). The Mean Global Temperature Potential MGTP(*H*) (Gillett and Matthews, 2010), in contrast, applies the $\theta$-function for weighting. The MGTP(*H*), $GTP_p$ and $GTP_p(t)$ in their original versions assume constant atmospheric conditions ($C_{ref} = C_{ref}(t_0)$). However, the $GTP_p(t)$ refers indirectly to an exogenously determined emission scenario via the shortening of the time horizon over time ($t_x = t_x(t_0, t_{tar})$). It suggests itself that the exogenously determined scenario can also be used as $C_{ref}$ (e.g. Deuber et al., 2013).

*RF*-based metrics, such as the GWP(*H*), relate generally to a defined constant atmospheric state. The GWP(*H*) applies the $\theta$-function and assumes constant atmospheric condition of the emission year ($C_{ref} = C_{ref}(t_0)$) (IPCC, 1990). Its physical and economic performance is well analyzed (e.g. Forster et al., 2007; Johansson et al., 2006; O'Neill, 2003), including its physical uncertainties related to atmospheric sinks (Reisinger et al., 2010; Manning and Reisinger, 2011). The original version of the GWP (henceforth: GWP(*r*)) (Lashof and Ahuja, 1990), in contrast, discounts the impacts and considers an average forcing value over possible future ranges in concentration ($C_{ref} = C_{ref}(\varnothing$ future)) to account for the non-linearities in the concentration-forcing relation. The economic global warming potential (EGWP) (Wallis and Lucas, 1994), a formally extended form of the GWP, additionally covers the rate of change of atmospheric forcing. In its two variants, it uses either the $\theta$-function or discounting for inter-temporal aggregation. The Temperature Proxy Index TEMP (Tanaka et al., 2009; Shine, 2009) offers a slightly different perspective: it describes the optimal gas-dependent time horizon *H* for the GWP(*H*) as a result of a tuning process with respect to historical *RF* and temperature development. The Forcing Equivalent Index (FEI)

**Table 1 – Classification of climate metrics. $I$ specifies the selected climate impact proxy including the underlying damage function and $\vec{C}_{ref}$ (scenario (scen), constant (const), specifications see text). $W$ is characterized by the type of weighting function and the relevant time frame parameter $r$, $H$ or $t_x$, respectively (specification see text).**

| Impact function I | | | Weighting function W | | |
|---|---|---|---|---|---|
| Impact proxy | Implicit Damage function | Atmospheric background ($C_{ref}$, specification) | Discounting discount rate $r$ | Constant ($\theta$-function) time horizon $H$ | End point ($\delta$-function) end point $t_x$ |
| D | $D = f(\Delta T)$ | Scen, exogenous | GDP | | |
| $\Delta T$ | $D = \theta_\infty(\Delta T - \Delta T_{thres})$ | Scen, endogenous | GCP(T) | | |
| $\Delta T$ | $D \propto \Delta T$ | Const, ref($t_0$) | | MGTP | |
| $\Delta T$ | $D \propto \Delta T$ | Const, ref($t_0$) | | | GTP |
| $\Delta T$ | $D \propto \Delta T$ | Scen, historical | | TEMP | |
| RF | $D = \theta_\infty(RF - RF_{thres})$ | Scen, endogenous | GCP(RF) | | |
| RF | $D \propto RF$ | Scen, ref(Øfuture) | GWP(r) | | |
| RF | $D \propto RF$ | Const, ref($t_0$) | | GWP(H) | |
| RF, $\partial RF/\partial T$ | $D = \gamma \cdot RF + \omega \cdot \partial RF/\partial T$ | Const, ref($t_0$) | EGWP | | |
| RF | $D \propto RF$ | Scen, historical | | FEI | |

(Manning and Reisinger, 2011; Wigley, 1998), a similar approach, was also designed to reproduce a historical pathway of $RF$.

### 3.2.2. Global Cost Potential

The GDP is grounded in the cost-benefit analysis, building on marginal climate change impacts and marginal costs of emission reductions. In view of the large uncertainty associated with economic evaluation of climate impacts, and the possible existence of discontinuous changes in the earth's climate system (or "Tipping Points", cf. Lenton et al., 2008), the cost-effectiveness framework is proposed as an alternative to the cost-benefit approach (Markandya et al., 2001): "guardrails" or "tolerable windows" for one or several climate variables such as $\Delta T$ or the rate of temperature change are adopted as boundary conditions for climate mitigation strategies (Petschel-Held et al., 1999; Bruckner et al., 1999). A prominent example of the cost-effectiveness approach is the objective to avoid dangerous anthropogenic interference with the climate system by keeping global warming below 2 °C, a target which is widely accepted in the international climate policy community (Copenhagen Accord) (e.g. Meinshausen et al., 2009). Also, the vast majority of climate change mitigation scenarios are based on a cost-effectiveness approach (Fisher et al., 2007).

Analytically, cost-effectiveness approaches can be treated as special cases of the cost-benefit analysis in which the damage cost curve ($D$) is implicitly assumed to be zero within the "tolerable window" and to diverge to infinity at a physical impact threshold $PI_{thres}$ ($\theta_\infty$-function):

$$D(PI) = \theta_\infty(PI - PI_{thres}) = \begin{matrix} 0 & \text{for } PI < PI_{thres} \\ \infty & \text{for } PI \geq PI_{thres} \end{matrix} \qquad (7)$$

In the hypothetical case of $CO_2$ as the only greenhouse gas, the optimal carbon price would emerge as $MAC$ at the predefined climate threshold.

While cost-effectiveness approaches are primarily designed for the derivation of global emission targets, they have peculiar implications for the derivation of metrics, which are an inherently marginal concept. In cost-effectiveness approaches, marginal damages are implicitly assumed to be zero below the climate target and infinitely large at the threshold. While Eq. (4) (Section 3.1) cannot be evaluated in this case, one can take advantage of the condition that for cost-optimal climate policy, the metric also has to be equal to the ratio of MACs. This gives rise to the Global Cost Potential (GCP) (Kandlikar, 1996; Tol et al., 2012; Johansson, 2011), also referred to as "price ratios" (Manne and Richels, 2001):

$$M_i^{CE} = \frac{MAC_i^{PI_{thres}}}{MAC_{CO_2}^{PI_{thres}}} \qquad (8)$$

The GCP is given by the ratio of two gases' $MAC$s least cost emission trajectory maintaining a prescribed climate target. Typically, the physical impact threshold $PI_{thres}$ is either expressed in terms of $\Delta T$ (e.g. Manne and Richels, 2001) or $RF$ (e.g. van Vuuren et al., 2006).

## 3.3. Synthesis

Using our conceptual framework, the prevalent metrics can be categorized unambiguously according to their choice of impact and weighting function (Table 1). The impact proxy is the most pivotal element of a metric and therefore serves as a primary classification criterion. The GDP considers economic damage as impact proxy which is in general a nonlinear function of the physical state of the climate and subject to substantial uncertainty (Fig. 1a). As elaborated in Section 3.2.1 and illustrated in Fig. 1a, purely physical climate metrics take a simplifying approach by (using physical climate parameters as an impact proxy, thus) implicitly assuming a linear relationship between economic damage and physical impact proxy $\Delta T$ ($GTP_p$, MGTP, TEMP), $RF$ (GWP($r$), GWP($H$), FEI), or $RF$ and the change of $RF$ (EGWP). An alternative group of metrics is based on cost-effectiveness approaches, thus implicitly assuming damages to be zero below a certain temperature (GCP($\Delta T$)) or forcing threshold (GCP($RF$)), cf. Section 3.2.2 and Fig. 1a.

The second important dimension in metric design is the choice of temporal weighting function (Fig. 1b). All physico-economic metrics and some physical metrics use exponential discounting for aggregating impacts over time. Alternative approaches are unit step functions (GWP($H$), MGTP, TEMP, FEI) or end-point weighting ($GTP_p$, $GTP_p(t)$).

As in the GCP metrics, the $GTP_p$ is based on the cost-effectiveness rationale. In fact, the $GTP_p(t)$ was designed to

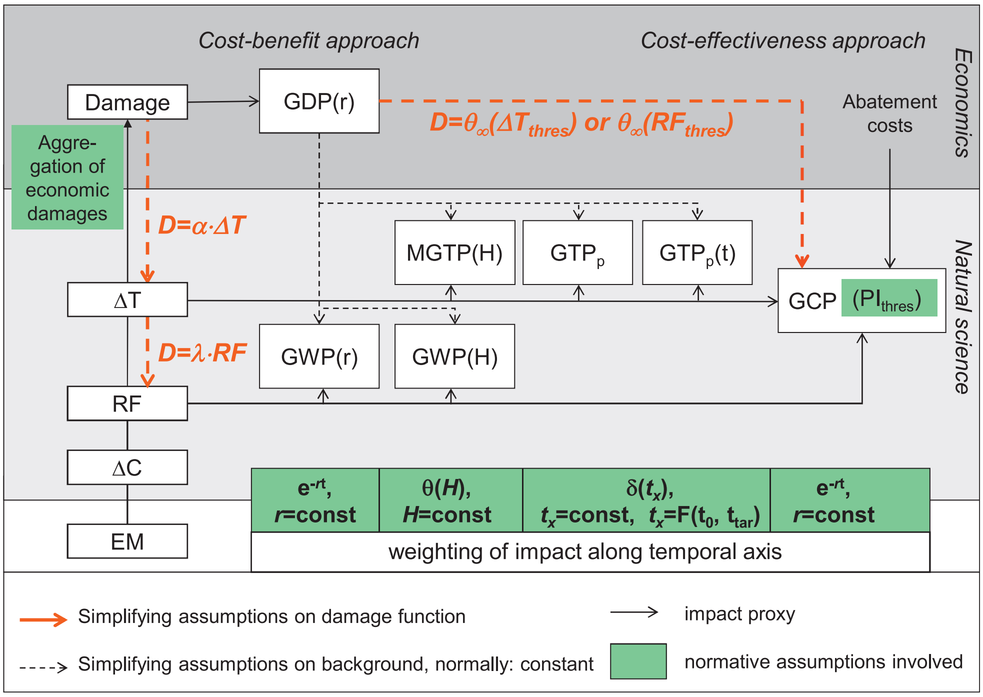


**Figure 2 – Interrelation between the GDP and selected physical and physico-economic metric approaches (GWP, MGTP, $GTP_p$, $GTP_p(t)$ and GCP) highlighting the underlying policy objective, impact proxy, weighting function and respective scientific discipline.**

provide an easy-to-calculate alternative to the GCP and indeed yields similar metric values (Shine et al., 2007). This can be understood from the fact that both approaches only consider the long-term effect of emissions, either by explicitly assuming a temporal weighting function that excludes the short and medium time-scales (as in the case of the $GTP_p$), or by assuming an impact function that is non-zero only in the distant future (as in the case of the GCP). In more formal terms, it can be shown that the GTP is a special case of the GCP if abatement costs in different periods can be assumed to be independent (Tol et al., 2012). The cost-effective temperature potential (CETP), which by construction of its temporal weighting function only considers climate impacts that occur after the climate target has been reached, is a physical metric that can almost exactly reproduce the behavior of the GCP (Johansson, 2011).

The conceptual framework illustrates the interrelations between different metrics (Fig. 2). It shows that alternative metrics can be constructed as variants of the GDP. For all metrics, normative judgements are involved in the choice of the time frame parameter, be it the discount rate $r$ in the context of exponential discounting, the time horizon $H$ in unit step aggregation or the end-point $t_x$. In the case of the physico-economic metrics, further normative assumptions are relevant in the derivation of the damage function or the choice of the climate target $PI_{thres}$.

## 4. Discussion and conclusion

Our conceptual framework illustrates that metric approaches can be classified unambiguously according to their implicit assumptions about the impact and temporal weighting function. For a metric to be optimal from an economic point of view, it must be based on the evaluation of marginal economic costs incurred by emissions. The GDP follows this basic rationale, and thus would ensure–absent uncertainty–multi-gas abatement strategies to be cost-optimal for a given set of normative assumptions.

As shown in Section 3.3, the vast majority of metrics used in the literature can be constructed as variants of the GDP. Also the guardrail approach used in a cost-effectiveness framework can be seen as special case of the GDP in which damages are assumed to grow to infinity at a particular climate threshold. Given (a) its property of economic efficiency, and (b) its flexible formulation of the damage function, which allows establishing all other metrics as variants of it, the GDP is uniquely positioned and can be used as a reference point for the evaluation of metrics.

The paramount challenge in the design of metrics is to deal with uncertainty. Following Dorbian et al. (2011), and with partly different definitions than in Plattner et al. (2009), we distinguish between the following types of uncertainties:

- *value-based uncertainty*, the degree to which normative judgements are involved,
- *scientific uncertainty*, uncertainty in the knowledge about the underlying processes in the causal chain between emissions and impact function,
- *scenario uncertainty*, the degree to which the metric depends on the future states of the world, e.g. atmospheric background conditions, and

**Table 2 – Commonly used metric approaches: Indicative and qualitative assessment of different kinds of uncertainties (uncertainty increases with number of bullet points). Exemplary $CO_2$ equivalences for methane illustrate the range of possible values.**

| Metric | Explicit uncertainties | | | Implicit uncertainties | $CO_2$ eq. for $CH_4$ (examples)[a] | |
|---|---|---|---|---|---|---|
| | Scientific | Value-based | Scenario | Structural | Median[b] | Uncertainty range[c] (standard deviation) |
| GWP | • | •• | • | •••••• | 27.2 | 22.5–32.5 (2.8) |
| GTP | •• | •• | •• | •••• | 6.2 | 4.5–9.0 (1.8) |
| GCP (*RF*) | •• | ••• | •• | ••• | | |
| GCP (*T*) | ••• | ••• | •• | •• | | |
| GDP | ••• | •••• | •• | • | 26.3 | 15.0–40.0 (6.7) |
| | Increasing operationalizability with decreasing uncertainty | | | Increasing policy relevance with decreasing uncertainty | | |
| | Implications for policy applications | | | | | |

[a] Boucher (2012).
[b] 100-year GWP, 100-year $GTP_p$ and GDP, include the conversion of $CH_4$ into $CO_2$.
[c] 90% confidence interval.

- *structural uncertainty*, the degree to which the metric represents the policy-relevant real world trade-offs.

While the first three types of uncertainties are of explicit nature with a direct link to operational feasibility, the latter takes effect implicitly. The choice of metric is largely characterized by trade-offs between different kinds of uncertainties. This can be illustrated by comparing the GWP and GDP metrics. The key advantage of the GWP(*H*) lies in the fact that (a) the value-based uncertainty is reduced to the choice of time horizon, (b) the scientific uncertainty is kept to a manageable level by only considering the causal chain between emissions and forcing, and (c) the scenario uncertainty is eliminated by assuming constant background conditions. On the other hand, the GWP is characterized by rather high implicit structural uncertainty and low policy relevance, since there is no direct link between *RF* and climate damages, and likewise, future atmospheric background conditions will not remain constant.

In this respect, the GDP is distinctly different from the physical metrics. As elaborated above, it ensures economic efficiency, thus it accurately represents real-world trade-offs and features low implicit structural uncertainty. This comes, however, at the expense of more explicit uncertainty: (a) high value-based uncertainty as, in addition to the choice of discount rate, normative judgements are involved in the valuation and aggregation of damages, (b) higher scientific uncertainty as the entire causal chain from emissions to damages is represented, and (c) scenario uncertainty as we are unsure about the future state of the world.

Table 2 provides an indicative overview of how metrics perform in terms of different uncertainty categories. It further demonstrates numerically some explicit uncertainties, using the example of $CO_2$ equivalences for methane. Generally speaking, physico-economic metrics are characterized by lower structural uncertainty which in principle makes them most policy relevant and more flexible to adjust to our knowledge of climate change and its impacts. This feature comes at the expense of higher scientific, value-based and scenario uncertainties (wider range of possible metric values). Physical metrics, in contrast, have high structural but lower value-based, scientific and scenario uncertainties (smaller range of possible metric values).

While economic efficiency and environmental effectiveness are the most crucial evaluation criteria, it is important to note that for any practical policy application, simplicity and transparency are also important (Fuglestvedt et al., 2003, 2010; Wuebbles et al., 2010). So far, the GWP, simple and transparent and thus easy to operationalize, has been the metric of choice for policy applications. In this metric, many of the relevant uncertainties are concealed by simplifying structural assumptions. While physico-economic metrics such as the GDP are much more difficult to operationalize, it can be seen as their advantage that they make the relevant uncertainties explicit. As an alternative approach to the use of simplifying physical metrics, policymakers could consider a GDP-based approach, in which the relevant value judgements and assumptions are considered in a direct and transparent manner, see e.g. Hammitt et al. (1996), Dorbian et al. (2011) and Boucher (2012).

Particularly with regard to the interdisciplinary retrial of climate metrics stipulated in the scientific literature (e.g. Shine, 2009) and on the level of the IPCC (Plattner et al., 2009), the conceptual framework provides a valuable basis for discussions, since it allows scientists and policymakers to disentangle and compare relevant implicit and explicit assumptions in a transparent way. As the framework elucidates the relationship between physical metrics and more comprehensive metrics that include the economy, it may help to enhance the scientific discourse between researchers from different climate research communities.

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