

Impact of the choice of emission metric on greenhouse gas abatement and costs

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Maarten van den Berg¹, Andries F Hof¹, Jasper van Vliet¹ and Detlef P van Vuuren^{1,2}¹ PBL Netherlands Environmental Assessment Agency, Bilthoven, the Netherlands² Utrecht University, Department of Geosciences, Copernicus Institute of Sustainable Development, Utrecht, the NetherlandsE-mail: maarten.vandenberg@pbl.nl**Keywords:** emission metric, global warming potential (GWP), global temperature potential (GTP), emission pathway, abatement costs, carbon dioxide, methaneSupplementary material for this article is available [online](#)**Abstract**

This paper analyses the effect of different emission metrics and metric values on timing and costs of greenhouse gas mitigation in least-cost emission pathways aimed at a forcing level of 3.5 W m^{-2} in 2100. Such an assessment is currently relevant in view of UNFCCC's decision to replace the values currently used. An emission metric determines the relative weights of non-CO₂ greenhouse gases in obtaining CO₂-equivalent emissions. For the first commitment period of the Kyoto Protocol, the UNFCCC has used 100 year global warming potential (GWP) values as reported in IPCC's Second Assessment Report. For the second commitment period, the UNFCCC has decided to use 100 year GWP values from IPCC's Fourth Assessment Report. We find that such a change has only a minor impact on (the optimal timing of) global emission reductions and costs. However, using 20 year or 500 year GWPs to value non-CO₂ greenhouse gases does result in a significant change in both costs and emission reductions in our model. CO₂ reductions are favored over non-CO₂ gases when the time horizon of the GWPs is increased. Application of GWPs with time horizons longer than 100 year can increase abatement costs substantially, by about 20% for 500 year GWPs. Surprisingly, we find that implementation of a metric based on a time-dependent global temperature potential does not necessarily lead to lower abatement costs. The crucial factor here is how fast non-CO₂ emissions can be reduced; if this is limited, the delay in reducing methane emissions cannot be (fully) compensated for later in the century, which increases total abatement costs.

1. Introduction

While carbon dioxide (CO₂) has clearly the largest contribution to anthropogenic climate change several other gases also play a significant role, including methane (CH₄), nitrous oxide (N₂O) and halocarbons. For several reasons, it is useful to express the contribution of different greenhouse gases in a common metric. First of all, this enables monitoring overall trends in greenhouse gas emissions and comparing the importance of different sources. Secondly, such a metric allows for a determination of possible (economic) trade-offs between reducing different greenhouse gases as part of a multi-gas mitigation strategy. The option to substitute between gases is sometimes referred to as what-flexibility. It has been

shown that strategies that allow such flexibility can reach climate objectives more cost-effectively than single-gas mitigation approaches (van Vuuren *et al* 2006b, Weyant *et al* 2006). This was, in fact, already acknowledged by policy-makers in 1997, as the Kyoto Protocol (UNFCCC 1998) was formulated in terms of a multi-gas approach. In addition to the reduction of CO₂, the Kyoto Protocol covers methane, nitrous oxide and a selection of F-gases.

Expressing the contribution of individual gases in one metric is far from straightforward: there are notable differences in radiative properties and atmospheric lifetime between gases. Moreover, many of these properties change over time, as they depend on the composition of the atmosphere. As a result, various metrics have been proposed that all have their strengths and

weaknesses in representing the contribution of different gases (see for an overview Fuglestedt *et al* 2003). The so-called global warming potential (GWP) is by far the most used metric. However, the GWP is criticized, among others because the value strongly depends on the time span over which the potential is calculated and the inconsistency of the GWP concept with an overall long-term temperature target (Fuglestedt *et al* 2000, Smith and Wigley 2000, Manne and Richels 2001, Shine 2009, UNFCCC 2011). The latter may imply that the use of GWPs does not lead to cost-optimal solutions for achieving certain temperature targets (Manne and Richels 2000, O'Neill 2003). Despite the criticism, GWP forms the basis of most multi-gas policies used today, such as the Kyoto Protocol (UNFCCC 1998). The global temperature potential (GTP) (Shine *et al* 2005) has been proposed as alternative. Proponents of the GTP metric indicate that its link to a temperature target implies that it better relates to the objective of international policies. However, also GTP values depend on particular assumptions in the cause-and-effect chain from emissions to temperature.

Some time ago, the UNFCCC called upon IPCC, and indirectly the research community, to look systematically into the consequences of the use of different metrics and metric values (UNFCCC 2011). The UNFCCC also announced that in the second commitment period of the Kyoto Protocol GWP values of the IPCC AR4 report (IPCC 2007, UNFCCC 2011) will be used, whereas in the first commitment period the GWP values of the IPCC SAR report (IPCC 1995) were used. Several studies have analyzed the impact of different metrics, including GTP and economic based metrics (e.g. Shine *et al* 2005, Johansson 2012, Reisinger *et al* 2013). The paper by Reisinger *et al* (2013), for instance, discusses the impact of using GTP instead of 100 year AR4 GWPs on global mitigation costs. They found that whereas a fixed 100 year GTP metric would increase costs, time-varying GTPs would reduce costs by about 5% compared to 100 year GWPs. Others have studied metric impacts on costs and emission profiles of multi-gas abatement strategies and find in general small impact on global costs. Smith *et al* (2013) found, using the GCAM Integrated Assessment Model, that methane emissions vary by at most 18% globally under a range of methane metric weights (4–70) for a fixed carbon price, while global costs increase by 4–23%. Johansson *et al* (2006) and Aaheim *et al* (2006) concluded that an optimized emission metric can reduce global costs by several percentage points, compared to an abatement strategy using GWPs. Finally, Godal and Fuglestedt (2002) found that on a regional scale, the impact on the abatement profile and costs can be significant.

This paper adds to the existing literature by addressing not only the effect of GTP, but also the immediate policy-relevant question of using 100 year

GWP values from the different IPCC Assessment Reports and GWPs calculated over different time spans. The impact of different metrics and metric values on both the level and timing of emission reductions of CO₂, CH₄ and N₂O and global abatement costs are analyzed using the FAIR-SiMCAp integrated assessment model, by considering (i) 100 year GWPs from the SAR, TAR and AR4 IPCC reports, (ii) 20 and 500 year GWPs, and (iii) time-varying GTPs. In this way we contribute to the request by UNFCCC (2011) to assess the implications of the choice of metric used to calculate the carbon dioxide equivalence of anthropogenic emissions.

2. Methods

2.1. Modeling framework

The FAIR-SiMCAp model (Framework to Assess International Regimes for the differentiation of commitments—Simple Model for Climate Policy Assessment) was used for the analysis (den Elzen *et al* 2007). This model combines a greenhouse gas abatement cost model with the MAGICC 6 climate model (Meinshausen *et al* 2011) to calculate long-term emission pathways. FAIR-SiMCAp calculates emission pathways from 2010 to 2100 that achieve climate targets at lowest cumulative discounted abatement costs, using a 5% discount rate (for a sensitivity analysis see the *Online Material*). The model determines a cost-optimal mix of reduction measures across the emission sources of greenhouse gases covered by the Kyoto Protocol. For this purpose the optimization procedure employs a nonlinear, constrained, optimization algorithm (the MATLAB FMINCON procedure). The optimization procedure optimizes an emission pathway over time, while the substitution metric determines the substitution among gases in any year by multiplying the carbon price with the metric value. The *Online Material* provides more information on the optimization procedure.

Abatement costs are based on time-dependent and regional information on baseline emissions (see section 2.3) and a set of price-response curves, from now on referred to as marginal abatement cost (MAC) curves. For energy- and industry-related CO₂ emissions, these curves are determined using the TIMER energy model (van Vuuren *et al* 2007) by imposing a carbon tax and recording the induced reduction in CO₂ emissions. The behavior of the TIMER model is mainly determined by the substitution processes of various technologies based on long-term prices and fuel preferences. These two factors drive multinomial logit models that describe investments in new energy production and consumption capacity. The demand for new capacity is limited by the assumption that capital goods are only replaced at the end of their technical lifetime. The long-term prices that drive the

model are determined by resource depletion and technological development. Technological development is determined using learning curves or through exogenous assumptions. Emissions from the energy system are calculated by multiplying energy consumption and production flows by emission factors. A carbon tax can be used to induce a dynamic response, such as an increased use of low- or zero-carbon technologies, energy efficiency improvements and end-of-pipe emission reduction technologies. Negative emissions can be achieved by a combination of the use of bioenergy and carbon capture and storage.

FAIR-SiMcaP captures the time- and pathway dependent dynamics of the underlying TIMER model, that are caused by technology learning and inertia related to capital-turnover rates, by scaling the MAC curves based on the reduction effort in the previous years. The model limits the MAC curves to 1500 \$/tC-eq (409 \$/tCO₂-eq), as the underlying TIMER model provides little additional emission reductions above this value.

For non-CO₂, the MAC curves of Lucas *et al* (2007) were used. These are based on MAC curves from the EMF21 project (Weyant *et al* 2006), but made time-dependent to account for technology change and the removal of implementation barriers, while consistency was ensured by using relative reductions rates compared to a business-as-usual emission level. Moreover, the annual reduction in non-CO₂ emissions are assumed to be limited to 2.5%–5% of yearly baseline emissions for most sources, depending on the source (van Vliet *et al* 2012). These limits are implemented to model the inertia in non-CO₂ emission reductions and are based on an estimate of the capital turn-over rate and practices in these sectors. The *Online Material* provides more information on the shape of the MAC curves and implementation of non-CO₂ inertia.

2.2. Metric implementation

The chosen metric in FAIR-SiMcaP impacts the substitution across the different gases in a single year as it changes the value of the gas vis-à-vis other case. In the model, this is implemented by scaling the MAC curve of each individual gas using the different conversion factors from tons of a specific greenhouse gas to C-equivalent emissions. A change of metric also affects the optimization over time and may result in different optimal emission pathways. For instance, an increase in the methane GWP value from 21 to 25, makes it more attractive to reduce methane. In this example, the price for reaching a certain reduction potential of C-equivalent methane emissions changes by a factor of 21/25. As indicated in the introduction, we have compared the 100 year GWP metric to the time-varying GTP metric and other metrical GWP values.

Table 1. GWP values and lifetimes for CH₄ and N₂O used in scenarios, where SAR, TAR and AR4 refer to 100 year GWP values (IPCC 1995, IPCC 2001, IPCC 2007).

	AR4			AR4	AR4	Lifetime (yr)
	AR4	SAR	TAR	20 yr	500 yr	
CO ₂	1	1	1	1	1	—
CH ₄	25	21	23	72	7.6	12
N ₂ O	298	310	296	289	153	114

2.2.1. GWP metric

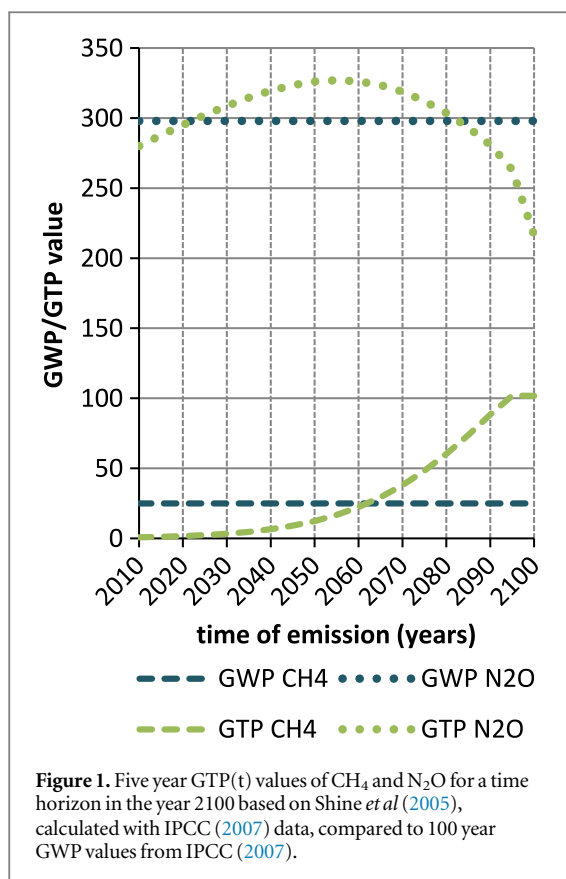
In this paper we use GWP values reported by subsequent IPCC reports. GWPs are based on the integrated radiative forcing over a specific time period of a certain greenhouse gas resulting from a 1 kg pulse emission. IPCC follows a methodology assuming an atmospheric background of constant greenhouse gas concentrations. Alternatively, GWP values can be calculated assuming a dynamic atmospheric background concentration. These have the advantage that more of the relevant dynamics are captured, but at the cost of introducing an arbitrary element regarding the development of future emissions.

For determining GWPs, two important inputs are needed: the specific radiative efficiency of a greenhouse gas and its atmospheric lifetime. GWPs are usually expressed relative to the absolute GWP value of CO₂, so the ratio of these two numbers results in a dimensionless GWP value. As there are large differences in the lifetimes of greenhouse gases, GWPs strongly depend on the time span over which the potential is calculated. To cover this, the IPCC Fourth Assessment Report (AR4) quotes 20, 100 and 500 year time spans. The warming potential of CH₄ relative to CO₂ is a factor 9 higher with a 20 year time span than with a 500 year time span (see table 1), due to the short atmospheric lifetime of CH₄.

Current policies mostly use the 100 year GWP values from the Second Assessment Report (IPCC 1995). To explore the potential impact of a change in metric value, we consider the effects of differences in 100 year GWP values between the three IPCC reports SAR, TAR and AR4, but also look at the impact of AR4 values based on a 20 and 500 years time span (IPCC 1995, IPCC 2001, IPCC 2007).

2.2.2. GTP metric

The GTP is one of the most discussed alternative metrics to the GWP (Fuglestedt *et al* 2003, Shine *et al* 2005). Instead of the integral of the radiative forcing over some fixed time span, the GTP considers the influence of the emission of a greenhouse gas at time t on the global temperature at a certain predefined future year. This effectively makes the GTP time dependent, as the relative impact of different gases varies over time, mostly as result of differences in their atmospheric lifetime. Alternatively, one can also consider a fixed GTP metric of which the associated metric values are very similar to those of a 500 year GWP.



The GTP values used in this paper are based on calculations by Shine *et al* (2005). The dynamic nature of the GTP values can be easily explained using a simple representation of the climate system (equation (1)).

$$C \frac{d\Delta T}{dt} = \Delta F - \lambda \Delta T. \quad (1)$$

In equation (1), the heat capacity of the climate system is indicated as C (in $\text{J m}^{-2} \text{K}^{-1}$), the temperature change as ΔT (in K), the climate sensitivity parameter as λ , which entails climate feedback processes (in $\text{W m}^{-2} \text{K}^{-1}$) and the radiative forcing resulting from each of the greenhouse gases as ΔF (in W m^{-2}). The radiative forcing and temperature change variables are time dependent. Shine *et al* (2005) solved this equation for ΔT , with a description for the radiative forcing following a pulse emission of each relevant greenhouse gas. This way absolute GTPs are obtained, representing the change in temperature at time t due to an emission of 1 kg of a specific greenhouse gas. As with the GWP, we assume a constant atmospheric background and take the ratio between the GTP of each greenhouse gas to that of CO₂ (see figure 1). Taking this ratio shows the relative temperature effect of the non-CO₂ greenhouse gas with respect to CO₂.

In our analysis of the GTP metric, we only substitute the metric values of CH₄ and N₂O with GTP values, as these gases are the most important in terms of warming and therefore are the main focus of our

analysis. For reasons of simplification, we use AR4 100 year GWP values for the other gases HFCs, PFCs and SF₆ (note that the GWP scenarios do use the corresponding metric values for all Kyoto gases).

2.3. Scenarios

As baseline scenario for the analysis, the IMAGE implementation of the OECD Environmental Outlook 2012 is used (OECD 2012). Greenhouse gas emissions in this scenario are driven by factors such as population growth, industrial activity, land-use change and technological development. In the first 30 years, the baseline roughly follows the IEA (2010) baseline scenario; after this period, the baseline follows medium assumptions for population, income and technology development. The scenario results in a rapid increase in greenhouse gas emissions in the next 50 years—followed by a more modest increase later on, reaching a radiative forcing level of 6.7 W m^{-2} in 2100.

The mitigation scenarios are based on a radiative forcing target of 3.5 W m^{-2} in 2100, with a corresponding global temperature change of $2.2 \text{ }^\circ\text{C}$ relative to pre-industrial, where the same temperature is reached for all metric scenarios, under an equilibrium climate sensitivity of $3 \text{ }^\circ\text{C}$. The forcing target covers the contribution of all major greenhouse gases and aerosols as represented in the MAGICC model. This target was chosen as it is a commonly studied policy target, while there is also sufficient flexibility in emission pathways towards this target to assess the importance of different metrics (see also van Vuuren and Riahi 2011). In reaching the long-term target, we allow for an overshoot in the period 2010–2100. To analyze the sensitivity of targets and overshoot on the results, we have performed several sensitivity runs—the results of which are provided in the *Online Material*.

In our analysis, we focus on CO₂, CH₄ and N₂O, but all Kyoto gases are included in the model calculations. In the mitigation analysis, we use the 100 year GWP values from AR4 as reference scenario and compare those to the scenarios with the alternative metrics.

Because in the FAIR model, mitigation costs in a certain year depend in a nonlinear way on the mitigation pathway, the model can yield different emission pathways that achieve the 3.5 W m^{-2} target at nearly the same cumulative costs. For instance, an early action profile profiting from learning may achieve the same target at similar costs as a profile with some delay profiting from discounting. The nonlinearity and pathway dependencies imply that the optimization routine may report local minima. To account for this, the optimization is run 64 times for every scenario using randomized initial conditions. Some of these runs may yield infeasible solutions due to infeasible starting conditions. We report the results of the set of runs that are within 0.5% of total cumulative discounted costs of the cheapest run (see table 2). In this way, flexibility in the choice of early action versus late

Table 2. Number of runs within 0.5% of cumulative discounted costs of the cheapest run for each scenario.

	AR4	SAR	TAR	AR4 20 yr	AR4 500 yr	GTP
#runs	19	18	18	11	22	13

response—with similar costs over the whole period—is accounted for. This results in a range of emissions that accounts for the different possible strategies in emission reduction. The emissions range can therefore be interpreted as an indication of flexibility in the most optimal reduction pathway.

3. Results

3.1. Baseline

As shown in figure 2, both CH₄ and N₂O emissions increase in the baseline scenario, but only modestly as the growth of main drivers of these emissions (agricultural production, production of fossil fuels) slow down (van Vuuren *et al* 2006a). The different metric values of GWPs lead to large differences in total C-eq emissions. The time-dependent GTP value leads to a change of relative importance of CH₄ and N₂O with respect to CO₂ and to each other over time. In order to compare emission reductions of different greenhouse gases over time between scenarios, the rest of the paper describes emissions of CH₄ and N₂O in tons of gas.

3.2. Mitigation scenario

3.2.1. Results for different GWP values (SAR, TAR and AR4—and 20, 100 and 500 years)

Changing between SAR, TAR and AR4 100 year GWP values leads to very small differences in global CO₂, CH₄ and N₂O emissions in the mitigation scenario (see left panels of figure 3). The (small) difference in the emissions of methane can be readily understood: since methane has a higher GWP value in AR4 than in SAR and TAR, methane emissions are lowest for AR4 GWP values. As for the impact on emissions, also the impact on global cumulative costs and carbon price are small (see left panel figure 4).

Using 20 year or 500 year GWP values instead of the 100 year GWP values leads to much larger changes in the global CH₄ reduction strategy (right panel of figure 3(b)). As expected, reducing methane becomes more attractive for the 20 year GWP values. For the 500 year GWP values, the opposite is true. Reductions in N₂O emissions exhibit less variation over the different scenarios than methane emissions (right panel of figure 3(c)), as N₂O has a relatively smaller variation in the GWP value than CH₄. The AR4 500 year GWP value for N₂O forms an exception, as it is merely half of the 100 year GWP value (see table 1), resulting in higher N₂O emissions throughout the larger part of the century.

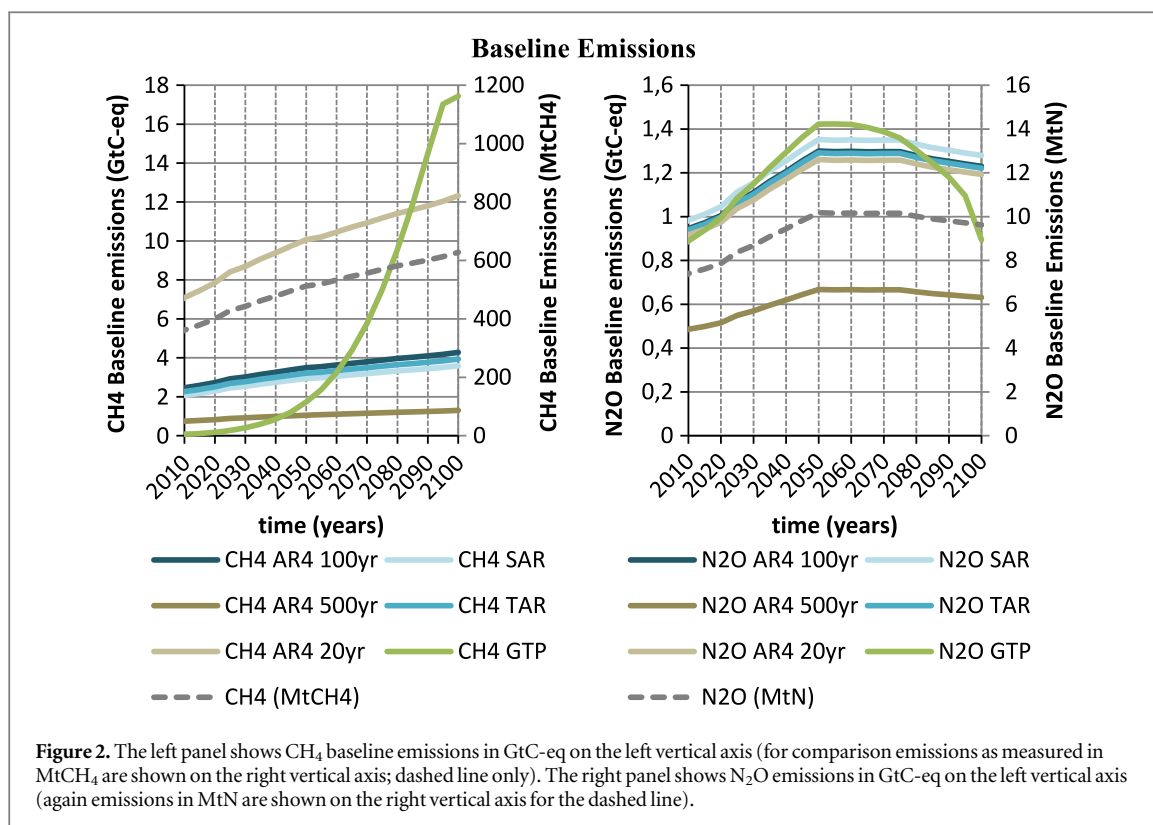
The large difference in impacts on emissions, in particular methane, between 20, 100, and 500 year GWP values not only leads to a different substitution among gases, but also to a change in the overall timing of emission reductions. The early cuts in methane emissions in the 20 year GWP scenario lead to some delay in CO₂ emission reductions of 5–10 years, with emissions about 1 GtC/year higher during the 2035–2060 period. By the end of the century more intensive reductions are required in CO₂ emissions in the 500 year GWP scenario to compensate for the lower reduction of methane. Consequently, CO₂ emissions are clearly lower than in the 100 year GWP scenario.

Since a large part of the non-CO₂ reductions is relatively cheap, the carbon price dynamics in the first part of the century can be readily understood through the achieved CO₂ reductions: delayed reductions are associated with a delayed increase of the carbon price. The differences in global discounted costs between the scenarios are small, except for the AR4 500 year scenario. This scenario has 20% higher costs than all the other scenarios, while the other five scenarios only differ by a maximum of 6% (see figure 4). In the 500 year GWP scenario, the lower non-CO₂ reductions (or equivalently, the higher CO₂ weight) imply extra CO₂ reductions especially in the second half of the century. These additional reductions drive up the carbon price and therefore increase costs substantially. The carbon price path shows a pathway that reflects, among others, the underlying dynamics in the energy system related to inertia and learning dynamics, model comparison shows that the carbon price pathways across models can vary between simple exponentially increasing pathways, more linear pathways to even stabilizing ones.

3.2.2. Results of using GTP values

The GTP scenario values methane reductions in particular by the end of the century. The results seem to be a cross-over scenario between the 20 and 500 year GWP scenarios with small methane emission reductions in the period 2010–2050 and a more rapid emission reduction rate for methane in the second half of the century (figure 3(b), right panel). Despite the rapid reduction rate at the end of the century, the CH₄ emission level in 2100 is still higher than in the reference GWP scenario. This is compensated by lower emission levels of N₂O and CO₂ at the end of the century.

Contrary to the result of Reisinger *et al* and the common assumption that using GTP results in achieving climate targets at lower costs, our GTP scenario results in slightly higher costs than the AR4 100 year GWP scenario. The main reason for this is our assumed restriction on the annual reduction rate of CH₄ emissions by sector. This results in less CH₄ reductions by 2100 with a GTP metric than with the 100 year GWP, even though the CH₄ emissions are valued higher with GTP in equivalent terms at the end



of the century. As CH₄ emission reductions are lower using the GTP metric, additional CO₂ reductions are required in this scenario, which (slightly) increases overall costs. Without the restriction on the annual CH₄ reduction rate (compared to the previous year) and other non-CO₂ reductions, the GTP scenario is slightly cheaper than the 100 year GWP scenario, in line with the Reisinger *et al* result (see *Online Material*). The FAIR simulation model represents current policies, the abatement of CH₄ and CO₂ is coupled via the CO₂-eq price—and in addition governed by inertia dynamics. The model will not invest in CH₄ abatement before it becomes economic to do so. This is different from a full optimization model that could, depending on the set-up, invest in CH₄ abatement early independent from CO₂ abatement to profit from it later in the century.

All scenarios reach a temperature of 2.2 °C by 2100 under a radiative forcing target of 3.5 W m⁻². The transient temperature and forcing levels over the century are very similar, with a maximum difference of 0.1 °C and 0.19 W m⁻² in all years for all different metrics.

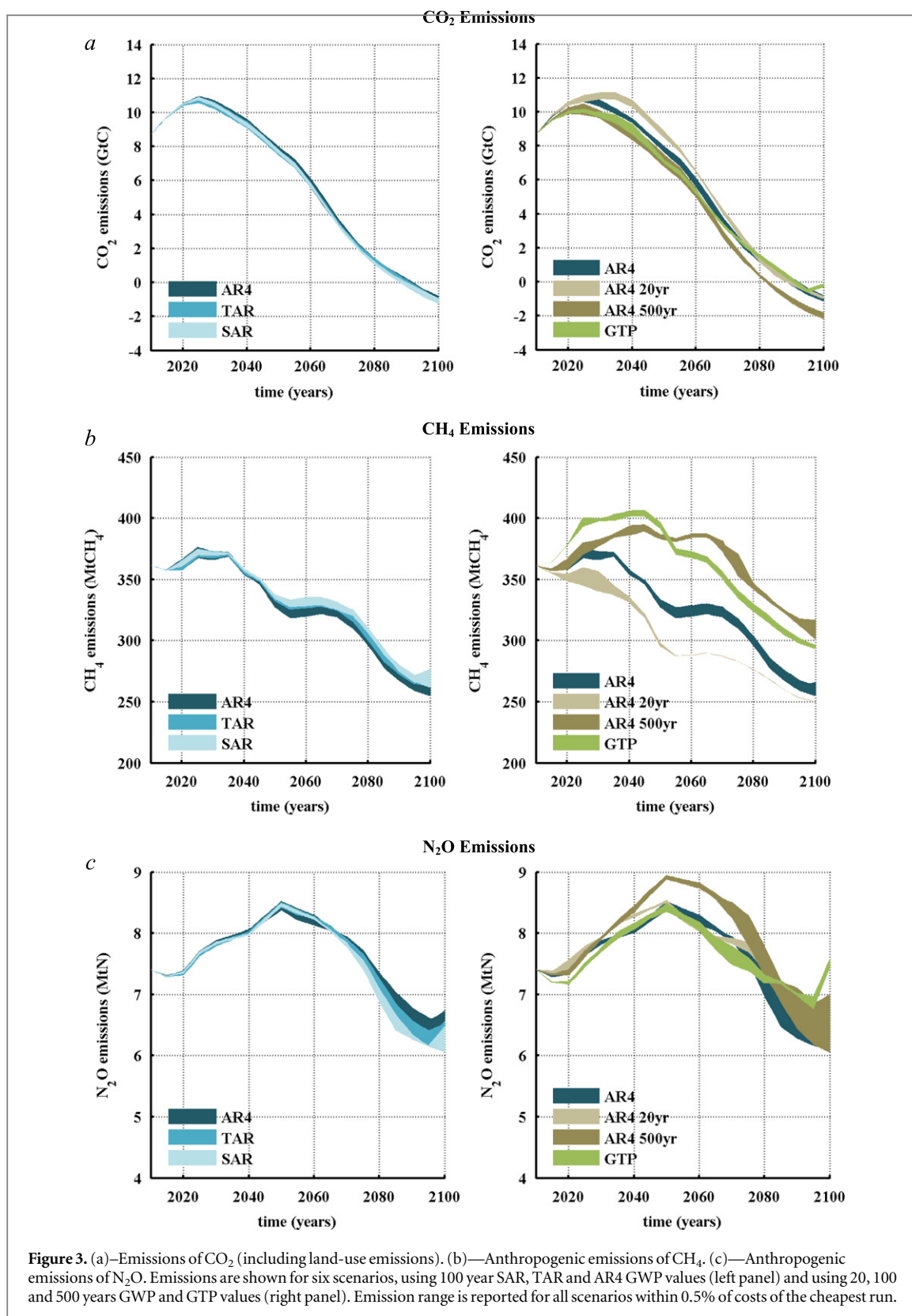
As a sensitivity analysis, we performed the 100 year GWP and GTP scenarios under different climate targets (both forcing and temperature targets), which are presented in more detail in the *Online Material*. The scenario under a temperature target of 2.2 °C with a GTP emission metric leads to very similar costs and emissions as the same scenario under a radiative forcing target of 3.5 W m⁻². The 100 year AR4 GWP and

GTP scenarios exhibit similar behavior for different climate targets. For a forcing target of 2.8 W m⁻², a 3.5 W m⁻² target without the option of an overshoot and a temperature target of 2 °C, the GTP scenario shows higher costs, while the emission dynamics are similar to a 3.5 W m⁻² scenario, albeit with different emission levels. A more ambitious climate target (i.e. a 2 °C and a 2.8 W m⁻² target) leads to smaller differences in CO₂ emissions between the two scenarios compared to a 3.5 W m⁻² target, whereas the inability to overshoot the climate target during the century induces earlier reductions. Also, scenarios under discount rates of 3% and 7% show similar dynamics to the scenario under a discount rate of 5%, although emission and cost differences are smaller between 100 year AR4 GWPs and GTPs for the lower discount rate (see *Online Material*).

4. Conclusions and discussion

4.1. The choice of the metric mostly impacts the time profile of methane reductions

As different GWP values assign a different value to CH₄ emissions, the change of metric also changes the emission reductions of this gas. Obviously, these changes become relevant if the differences between the metric values are substantial enough. In our study, this is the case for the AR4 20, 100 and 500 year GWPs and the GTP scenario. These changes in CH₄ emissions also affect the timing and depth of CO₂ reductions. However, indirect reductions in CH₄ due



to efforts to mitigate CO₂ emissions, for instance a decrease in coal use, are not included in the calculations. This type of interaction can lessen the impact of a change of metric value, as discussed in Smith *et al* (2013).

Nitrous oxide emission reductions show less variation than methane reductions when applying different

GHG weights, as a result of the smaller relative differences among N₂O metric values compared to those for CH₄.

The radiative forcing target as chosen in this study (3.5 W m⁻²) allows for some flexibility in the timing of emission reductions; for more stringent climate targets this flexibility can be less (see *Online Material*).

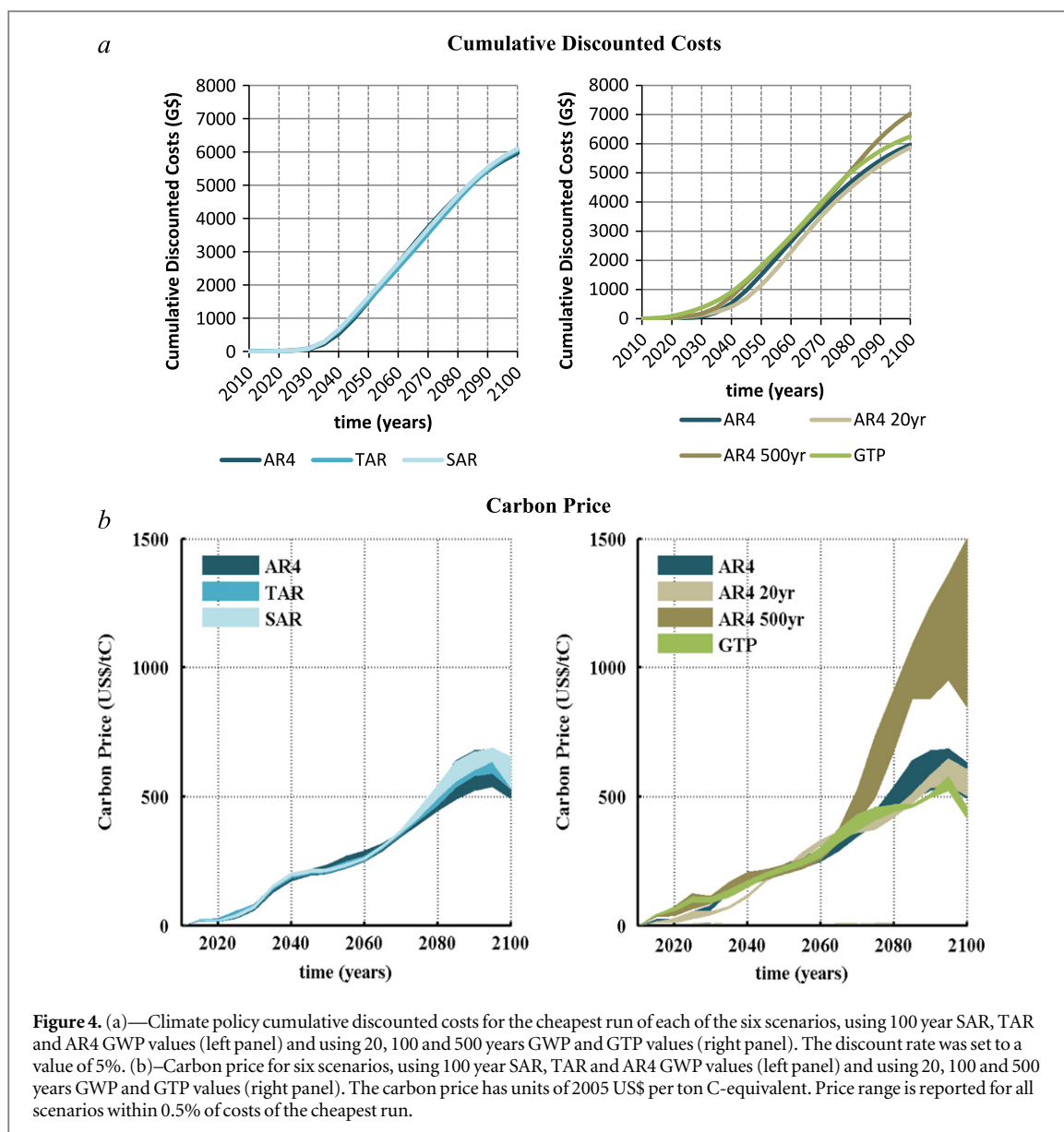


Figure 4. (a)—Climate policy cumulative discounted costs for the cheapest run of each of the six scenarios, using 100 year SAR, TAR and AR4 GWP values (left panel) and using 20, 100 and 500 years GWP and GTP values (right panel). The discount rate was set to a value of 5%. (b)—Carbon price for six scenarios, using 100 year SAR, TAR and AR4 GWP values (left panel) and using 20, 100 and 500 years GWP and GTP values (right panel). The carbon price has units of 2005 US\$ per ton C-equivalent. Price range is reported for all scenarios within 0.5% of costs of the cheapest run.

4.2. The global mitigation profile and associated global costs are found to be not very sensitive to the changes in metric values of CH₄ and N₂O as reported in SAR, TAR and AR4

The most important reason for this is that the differences between the metric values reported in the subsequent IPCC reports are relatively small: the largest difference is about 20% for the GWP of methane. The Fifth Assessment Report states an increase in GWP metric values for CH₄ and a decrease for N₂O (IPCC 2013). This will in principle lead to somewhat higher CH₄ and lower N₂O reductions. The changes in metric values are expected to have a minor impact on emission reductions and costs, although the change in N₂O GWP values is somewhat larger than between previous assessment reports.

Additionally, the CH₄ abatement cost curve as used in our model plays a role: as a considerable amount of the reductions is relatively cheap, differences in CH₄ mitigation only slightly affects total

abatement costs. Moreover, at the high end of the curve a considerable part of the methane emissions cannot be reduced (as a result of lack of abatement potential); here also the abatement decision is independent of the metric choice. The small differences in emissions among these scenarios result in minor global cost differences.

4.3. Using GWP values calculated over different time spans has a moderate impact on global costs

The difference in impact of using 20 and 100 year GWP values on global costs is relatively small (up to 4%). However, the 500 year GWP values lead to significantly higher costs (of 18%), as non-CO₂ GHGs are given such low weights that considerable additional CO₂ reductions are necessary. In other words, the importance of CO₂ for reaching a radiative forcing target at the end of the century is so large that the exploitation of the CH₄ mitigation potential is much lower than in the other GWP scenarios, leading to

higher costs. Reisinger *et al* (2013) also find higher (up to 10%) costs for their fixed GTP scenario, which uses a CH₄ weight comparable to a 500 year GWP weight.

4.4. The impact of different metric values on temperature is very small

All scenarios yield the same temperature change relative to pre-industrial of 2.2 °C in 2100. The differences in temperature change and radiative forcing during the century among the scenarios are small (up to a maximum temperature difference of 0.1 °C).

4.5. Implementing a time-varying GTP metric does not necessarily lead to lower costs, depending on inertia and other nonlinear impacts on the methane reduction rate

Using a GTP metric leads to higher CH₄ emissions at the end of the century compared to the 100 year GWP scenario, due to limitations to the annual reduction of non-CO₂ emissions implemented in the FAIR model, even though in the GTP scenario methane has a higher associated weight at that time. Without these limitations on annual reductions, GTP does lead to lower costs than 100 year GWPs, confirming the results by for instance Reisinger *et al* (2013). Although it is uncertain how large the inertia in reducing non-CO₂ emissions is, the addition of inertia in reducing non-CO₂ emissions leads to higher costs in general, and specifically when using the GTP metric. So the advantage, or disadvantage, of a GTP metric depends on the speed by which methane can be reduced. Future work on the speed by which non-CO₂ emissions can be reduced is therefore warranted.

4.6. In this paper we focus on global results only. Regional impact of different metrics or metric values might diverge from global results, depending on the relative contribution of non-CO₂ GHGs to total emissions and emission trading

Some regions have particular large shares of CH₄ emissions. For these regions, more substantial impacts for regional costs can be expected. The impacts are likely to be strongly dependent on the climate policy regime: different metric values will not only change relative abatement costs, but also the allocation of emission permits and resulting emission trading.

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