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Inconsistencies when applying novel metrics for emissions accounting to the Paris agreement

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Abstract

Addressing emissions of non-CO_2 greenhouse gases (GHGs) is an integral part of efficient climate change mitigation and therefore an essential part of climate policy. Metrics are used to aggregate and compare emissions of short- and long-lived GHGs and need to account for the difference in both magnitude and persistence of their climatic effects. Different metrics describe different approaches and perspectives, and hence yield different numerical estimates for aggregated GHG emissions. When interpreting GHG emission reduction targets, being mindful of the underlying metrical choices thus proves to be essential. Here we present the impact a recently proposed GHG metric related to the concept of CO_2 forcing-equivalent emissions (called GWP*) would have on the internal consistency and environmental integrity of the Paris Agreement. We show that interpreting the Paris Agreement goals in a metric like GWP* that is significantly different from the standard metric used in the IPCC Fifth Assessment Report can lead to profound inconsistencies in the mitigation architecture of the Agreement. It could even undermine the integrity of the Agreement's mitigation target altogether by failing to deliver net-zero CO_2 emissions and therewith failing to ensure warming is halted. Our results indicate that great care needs to be taken when applying new concepts that appear scientifically favourable to a pre-existing climate policy context.

Introduction

To achieve the climate targets expressed in the 2015 Paris Agreement (UNFCCC 2015a), stringent reductions in all greenhouse gas (GHGs) emissions are required (IPCC 2018). Different metrics are used to account for and compare the contributions of different GHGs. They typically provide conversion factors between the emissions of non-CO_2 GHGs and equivalent emissions of CO_2, often over a chosen set time horizon. The most common approaches to account for different GHGs are using forcing centred metrics known as 'global warming potentials' (GWPs). GWPs express the ratio of the time-integrated radiative forcing effect of a pulse emission of a certain GHG relative to the effect of a pulse emission of an equal mass of CO_2 (Myhre *et al* 2013). As an alternative, metrics focussing directly on the temperature effects like 'global temperature potentials' (GTPs) have been proposed (Shine *et al* 2005). There are significant uncertainties related to both GWPs and GTPs, although the relative uncertainties are larger for GTPs (Myhre *et al* 2013).

The GWP with a 100 year time horizon (GWP100) is the common metric to account for and compare GHGs under the United Nations Framework Convention

Table 1. Interpretations and implications of the long term temperature and mitigation goals of the Paris Agreement.

Elements of the Paris agreement	Interpretation
Article 2.1: 'This Agreement, in enhancing the implementation of the Convention, including its objective, aims to strengthen the global response to the threat of climate change, […], including by: (a) Holding the increase in the global average temperature to well below 2 °C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5 °C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change'	– The long-term temperature goal (LTTG) of the Paris Agreement constitutes one goal referencing two temperature levels, while establishing 1.5 °C global mean temperature (GMT) rise above pre-industrial levels as the long-term warming limit (Schleussner *et al* 2016) – The LTTG caters two interpretations: Establishing a 1.5 °C limit that should not be exceeded, or allowing for a temporarily exceedance (overshoot) of the 1.5 °C limit, while warming should always remain 'well below 2 °C' (Mace 2016) – Specifically, the LTTG expresses the need to pursue (continuous) efforts towards 1.5 °C which includes the need to peak and decline GMT and reduce GMT again below 1.5 °C in the case of a temporary overshoot – The LTTG does not reference levels of temperature stabilization, but establishes warming levels that should not be exceeded – The LTTG serves the purpose to 'enhance the implementation' of the objective of the UNFCCC that is to achieve a 'stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system.' The LTTG does not prejudge on where this GHG level would be nor does it imply in any form that stabilizing warming at e.g. 1.5 °C would be sufficient to avoid dangerous interference. It is thereby not in contradiction with assessments that find that present levels of warming of 1 °C may already constitute dangerous interference for the most vulnerable (UNFCCC 2015b) – The LTTG is linked to assessments of the risks and impacts of climate change based on the science available at the time, i.e. as reflected in the IPCC AR5 and metrics used in therein (Pfleiderer *et al* 2018)
Article 4: 'In order to achieve the long-term temperature goal set out in Article 2, Parties aim to reach global peaking of greenhouse gas emissions as soon as possible, […], and to undertake rapid reductions thereafter in accordance with best available science, so as to achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century, on the basis of equity, […]'	– The mitigation goal (MG) is explicitly linked to the LTTG and therefore also needs to cater both the LTTG interpretations outlined above – The MG establishes conditions under which the LTTG can be achieved. Ambiguity with respect to several of its elements exist, but any interpretation that achieves the MG cannot be fundamentally at odds with the LTTG – The language on 'balance of sources and sinks' is equivalent to achieving net zero GHG emissions (Fuglestvedt *et al* 2018) – The reference to 'best available science' constrains potential 'rapid reductions thereafter' to pathways that are achieving the LTTG – The MG constrains pathways up to the achievement of net zero GHG emissions. It does not speak to actions after this benchmark has been achieved – The MG is embedded in the UNFCCC policy context including the concept of equity

(UNFCCC) since the Kyoto Protocol (UNFCCC 1997) under the United Nations Framework Convention on Climate Change (UNFCCC) and also under the Paris Agreement (UNFCCC 2018). The GWP100 metric is also used for emissions accounting in energy-economic emission pathways assessed by the Working Group 3 Contribution (IPCC 2014) to the Intergovernmental Panel on Climate Change's (IPCC) Fifth Assessment Report (AR5), reports by the UNFCCC on the effect of intended national determined contributions (UNFCCC 2015c), and the recent IPCC Special Report on Global Warming of 1.5 °C (Rogelj *et al* 2018b). It is therefore the approach underlying the key scientific inputs that fed into the preparations and design of the Paris Agreement framework.

The focus of GWP100 is to account for the difference in radiative forcing effects of different GHGs over the period of a century, i.e. the long-term warming effect. As a consequence, the near-term effect of non-CO_2 GHGs on global warming is not well represented by this metric (Allen *et al* 2016). In the context of the Paris Agreement's 1.5 °C limit, questions of

Table 2. Overview of stylised emission pathways developed for this study. All pathways are based on the SSP1-RCP1.9 marker scenario with modified emission trajectories for CO_2, CH_4 and N_2O.

Pathway set	Figure	Specifications
Illustrative net-zero pathways	Figure 1(b)	Constant emissions for CO_2, CH_4 and N_2O (CO_2, CH_4) following net-zero total GHG (CO_2) for GWP100 (GWP*). The SSP1-RCP1.9 is extended beyond 2100 by keeping emissions of all GHGs constant at 2100 levels
Illustrative set of CO_2 and CH_4 emissions reduction pathways starting in 2020	Figure 2	Linear reductions for CH_4 (0%–10% relative to 2020 per year) and CO_2 (1.3 to 3.5% relative to 2020 per year). CH_4 emissions are reduced until a floor level equal to the maximum feasible reductions in the SSP1-RCP1.9 reference scenario is reached. CO_2 emissions are reduced until net-zero GHG emissions in GWP100 are reached. After net-zero GHG emissions in GWP100 are reached, CO_2 and CH_4 emissions are kept constant. Pathways that do not achieve net zero GHGs in GWP* before 2100 are removed. Not all pathways achieve net zero in GWP100 until 2100
Illustrative set of CO_2 and CH_4 emissions reduction pathways with limited methane reduction until 2050 and rapid thereafter	Figure 3	Limited reduction in CH_4 up to 2050 (1% of 2020 emissions per year) and rapid reductions thereafter (5% of 2050 levels per year from 2050 onwards). Linear CO_2 emission reductions from 2020 onwards until net zero GHGs are reached in GWP*. Once net zero GHG in GWP* is reached for the first time, CO_2, N_2O and CH_4 emissions are being held constant throughout the 21st century

near-term warming contributions have become more relevant, and in order to better address the warming effect of forcing agents over time, a metric focusing on the forcing-equivalence of non-CO_2 GHGs and other forcers has been proposed, called GWP* (read: GWP-star) (Allen *et al* 2016, 2018). In GWP* a sustained change in the rate of emission of a short-lived GHG is treated as being equivalent to a one-off pulse of emissions of CO_2 over a given time frame. By doing so, GWP* allows to more accurately capture the direct impact of changes of emissions in short-lived GHGs on radiative forcing and temperature.

Interpreting the Paris agreement goals

The Paris Agreement includes a wide-ranging set of goals. Two articles of the Paris Agreement, however, are particularly relevant to the question of global climate change mitigation: Article 2.1 and Article 4. Article 2.1 establishes the long-term temperature goal (LTTG) of the agreement (see table 1 for an interpretation of the goal). The LTTG is ambiguous with regard to its interpretation. Following Mace (2016), the LTTG might be interpreted as either establishing an absolute 1.5 °C limit, or a long-term limit that can be temporarily exceed. In any case, warming should always be held 'well below 2 °C'. The LTTG needs to be interpreted in conjunction with the mitigation goal (MG) expressed in Article 4 (equally analysed in detail in table 1). The MG sets out to achieve a GHG balance that is interpreted as achieving net-zero anthropogenic GHG emissions (Fuglestvedt *et al* 2018). The metric in which GHGs should be accounted for and compared to each other, however, is not directly specified and some scholars have argued for the use of GWP* in the context of the Paris Agreement (Allen *et al* 2016, 2018).

Taken together, Article 2 and 4 provide a comprehensive set of criteria that allow to assess the validity of interpretations of the Paris Agreement with different emissions accounting metrics. In the following, the implications of interpreting Article 4 with GWP* versus GWP100 will be assessed using a stylized set of emission pathways that are informed by the integrated climate scenario literature (Huppmann *et al* 2018, Rogelj *et al* 2018b).

Methods

We create a set of Paris Agreement compatible pathways based on the SSP1-RCP1.9 marker scenario (Rogelj *et al* 2018a). By modifying the SSP1-RCP1.9 CO_2, CH_4 and N_2O emissions trajectories, we generate three sets of stylised emission reduction scenarios that are detailed in table 2.

The global mean temperature (GMT) response is derived using the MAGICC6 model median projections relative to pre-industrial levels (Meinshausen *et al* 2011). Our MAGICC6 setup is reflecting the climate sensitivity range assessed by IPCC AR5 (Rogelj *et al* 2014a) and the C4MIP carbon cycle response range (Friedlingstein *et al* 2014). We use GWP100 estimates based on the IPCC Second Assessment Report. Adopting other GWP100 estimates i.e. from later IPCC reports (Myhre *et al* 2013) would lead to slightly different numbers but not qualitatively change our findings. GWP* is derived as in Allen *et al* (2018) using a 100 year time horizon (like GWP100) and a window of 20 years following an increase in short-lived greenhouse gas emissions.

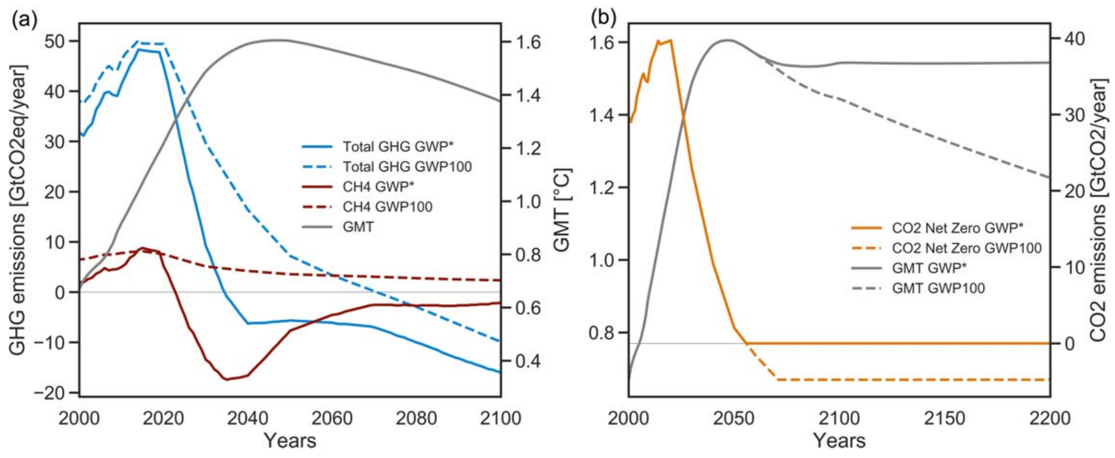

Figure 1. Illustrating key differences between GWP100 and GWP*. (a) Emissions profiles of the SSP1-RCP1.9 scenario for all Kyoto greenhouse gases (blue) and methane (red) accounted in two different global warming potential metrics (GWP*, solid line; GWP100, dashed). For comparison, also the global mean temperature (GMT, grey) increase above pre-industrial levels for the SSP1-RCP1.9 scenario using the MAGICC6 model is shown. (b) Stylized modifications of the CO_2 trajectories (orange) in SSP1-RCP1.9 scenario to reach and sustain long-term zero GHGs in GWP* (solid line) and GWP100 (dashed).

We create a first set of stylized scenarios to illustrate the effect of sustained net-zero GHGs in different metrics (compare figure 1(b)). For GWP100, we keep emissions of CO_2, CH_4, and N_2O constant following the date when net-zero in total GHGs is reached (dashed lines in figure 1(b)). For GWP*, we keep CO_2 and CH_4 emissions constant following the year net-zero CO_2 emissions are reached (full lines in figure 1(b)). Here, N_2O emissions remain unchanged from the SSP1-RCP1.9 marker scenario, but we note that also compensating remaining N_2O emissions with negative emissions of other gases would not substantially alter the results.

In a second set, the trajectories of CO_2 and CH_4 are modified: after 2020, CH_4 and CO_2 emissions are reduced by a constant amount per year expressed in percentage of 2020 emission levels. Global CO_2 emissions are reduced linearly between 3.5% and 1.3% of 2020 emissions per year until net-zero GHG emissions in GWP100 are reached and held constant thereafter. CH_4 emissions are reduced between 10% and 0% per year relative to 2020 levels until a floor level informed by the mitigation potential found in the SSP1-RCP1.9 marker scenario is reached or net-zero GHG in GWP100 is achieved. Pathways achieving net-zero GHGs in GWP* before 2100 are retained. Reduction rates are informed by 1.5 °C compatible emission reduction pathways assessed in the IPCC Special Report on Global Warming of 1.5 °C (Huppmann *et al* 2018, Rogelj *et al* 2018b) and chosen to sample net-zero timings between 2050 and 2100 in GWP100. The range of reduction levels is broadly consistent with the range suggested by pathways in the 1.5 °C scenario database (compare figure S1 available online at stacks.iop.org/ERL/14/124055/mmedia). We note that some combinations, i.e. very limited reductions in CH_4 and but very deep reductions in CO_2 or vice versa, are unlikely to be seen in current scenarios, because they are typically subjected to a common carbon price, but can occur in the real world because they have few common sources (Rogelj *et al* 2014b).

A third set of scenarios is analysed with limited CH_4 reductions until 2050 (1% of 2020 emissions per year) and rapid CH_4 reductions thereafter (5% of 2050 levels per year from 2050 onwards). CO_2 emissions are reduced linearly from 2020 onwards until net zero GHGs are reached in GWP*. Once net zero GHG in GWP* is reached for the first time, CO_2, N_2O and CH_4 emissions are being held constant throughout the 21st century.

These sets of stylized pathways of course do not reflect the full range of possible emission reduction pathways. However, they sample a range of possible CH_4 and CO_2 emission reduction trajectories in pathways that 'peak as soon as possible' (in 2020), 'undertake rapid emission reductions thereafter' (constant reductions after 2020) and achieve net-zero GHGs in various kinds of interpretations.

Results

The use of GWP* instead of GWP100 leads to substantial differences in the accounting of GHG emissions, the timing of net-zero GHG emissions, and the GMT trajectories resulting from achieving Article 4 of the Paris Agreement. This is illustrated in figure 1(a) for the SSP1-RCP1.9 scenario, which assumes strongly decreasing CH_4 emissions (Rogelj *et al* 2018b). The CH_4 GWP* contribution is largely negative over the remainder of the 21st century. This is because under the GWP* metric, decreasing absolute CH_4 emissions are accounted for as 'negative CO_2 equivalent emissions'. This effect contributes to a shift in the timing of net-zero GHGs between GWP* and GWP100. Net zero GHGs are reached about 35 years

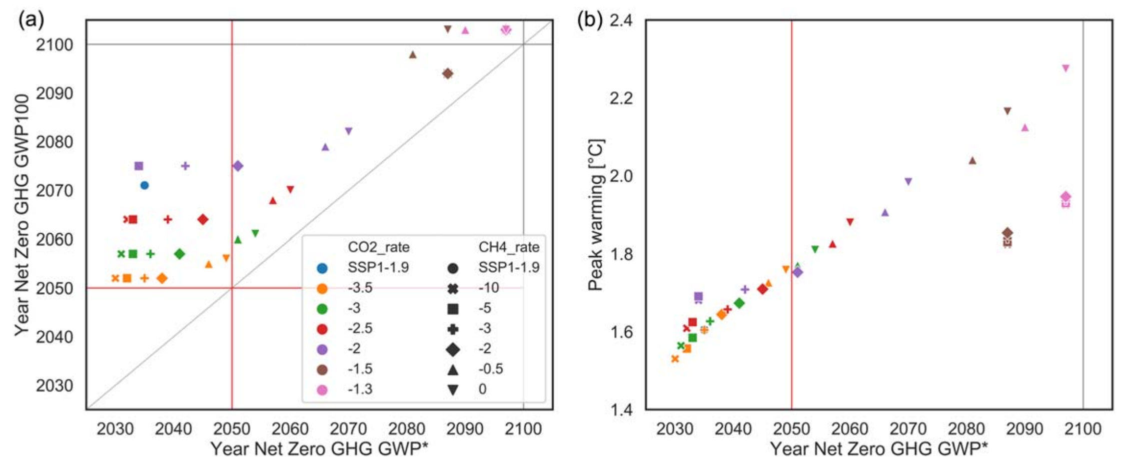

Figure 2. Timing of global net zero GHG emissions for stylized emission reduction scenarios using different emission metrics. Emissions scenarios are created by modifying CO_2 and CH_4 emission reduction trajectories from SSP1-RCP1.9 (see Methods). CO_2 and CH_4 are linearly reduced with a constant reduction rate given in percent from 2020 levels (see legend). Different CO_2 reduction rates are indicated by different colours, whereas different symbols indicate different CH_4 reduction rates. As an example, a red cross symbols a pathways with a CO_2 reduction rate of 2.5% and a CH_4 reduction rate of 3%. Red (grey) lines indicate the year 2050 (2100), marking the range of when net-zero GHG emissions need to be achieved according to Article 4. (a) Timing of net-zero GHG emissions using the GWP100 versus GWP*. Scenarios that do not reach net-zero GHG in GWP100, but in GWP* before 2100 are placed outside the 2100 range. (b) Median peak GMT increase above pre-industrial levels in the 21st century versus net zero GWP* timing.

earlier using GWP* compared to GWP100, for exactly the same evolutions of absolute GHG emissions.

As a result of the different treatment of short-lived GHGs, the long-term warming effects of sustained net-zero GHGs differ between the two metrics. Under GWP100, each ton of remaining non-CO_2 gases needs to be compensated by an equivalent amount of negative CO_2 emissions. The sustained net negative CO_2 emissions lead to declining long-term temperatures (compare figure 1(b) or see Mengel *et al* (2018)). This is an important element of the Paris Agreement long-term goal architecture, linked to the requirement to 'pursue efforts' to limit warming to 1.5 °C even in the case potentially temporary exceeding that temperature earlier (also referred to as an 'overshoot', see table 1). Through the combined goals expressed in Article 2 and 4, 1.5 °C is established as the long-term temperature limit of the Paris Agreement (Schleussner *et al* 2016). Achieving and sustaining net-zero GHGs (including net-zero CO_2) in GWP* at best leads to a long-term temperature stabilization but not reversal (compare figure 1(b)).

GWPs and the Paris agreement mitigation goals

The variation of CO_2 and CH_4 reductions rates shows very different net-zero timings in GWP100 and GWP* (compare figure 2(a)). While by design none of the scenarios achieves net-zero CO_2 before 2050 in GWP100, several scenarios actually do so in GWP*. At the same time, a range of scenarios with very little to no CH_4 reduction achieve net-zero GWP*, but not GWP100 in the 21st century. The implications for peak warming are depicted in figure 2(b). For strong CH_4 reduction scenarios achieving net-zero GWP* already in the 2030s, the peak warming is dominated by the reduction in CO_2. For more moderate reductions rates, peak warming scales almost linearly with the timing of net-zero, as is expected by the design of GWP* (Allen *et al* 2016). Only scenarios at the very lower end limit peak warming to close to 1.5 °C. Such scenarios, however, reach net-zero GWP* much before 2050. Achieving net-zero GWP* around 2050 leads to peak warming of around 1.8 °C (compare figure 2(b)), which would be at the upper end of the 'lower 2 °C' pathway category identified by the IPCC Special Report on Global Warming of 1.5 °C (Rogelj *et al* 2018b). Other scenarios that achieve net-zero GWP* before 2100 even exceed 2 °C peak warming. This contrasts strongly with the results when using the GWP100 metric. Achieving net-zero GWP100 around 2050 limits peak warming to close to 1.5 °C and none of the scenarios that achieve GWP100 before 2100 significantly exceed 2 °C in our analysis.

Reaching net-zero GWP* without further actions leads to stabilizing temperatures at best. As outlined above, a stabilisation above 1.5 °C is inconsistent with the need to 'pursue efforts' to limit to 1.5 °C expressed in Article 2 of the Paris Agreement. The only consistent option that allows for a stabilisation target to be pursued is to achieve stabilization below 1.5 °C without an overshoot. In order to achieve this, however, net zero GWP* would need to be reached much earlier than 2050. Therefore, an interpretation of Article 4 in GWP* is not consistent with achieving the LTTG set out in Article 2. On the contrary, using GWP100 as in the IPCC AR5, both plausible interpretations of Article 2 are consistent with emission pathways achieving Article 4.

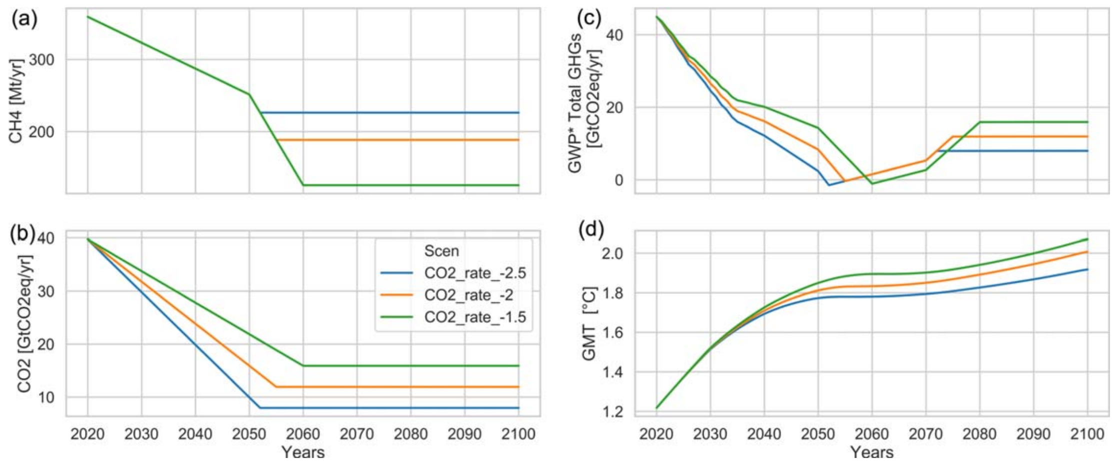

Figure 3. Long-term warming in scenarios that reach early net zero levels when assessed with GWP* of global GHGs after 2050. The scenarios are characterized by limited reduction in methane up to 2050 (1% of 2020 emissions per year) and rapid reductions thereafter (5% of 2050 levels per year from 2050 onwards). CO_2 reduction rates are varied between 1.5% and 2.5% per year after 2020. Once net-zero GHGs are reached in GWP*, CO_2, N_2O and CH_4 emissions are being held constant throughout the remaining century. (a) CH_4 emissions, (b) CO_2 emissions, (c) GWP* evolution, (d) GMT increase above pre-industrial levels.

Achieving net-zero and long-term warming

Using net-zero GWP*, it is possible to temporarily reach net zero GHGs without achieving net-zero CO_2 emissions (i.e. through sudden, stringent CH_4 reductions). Since Article 4 does not explicitly mandates to 'sustain' net-zero GHGs, such a one-time achievement could be presented as fulfilling the targets set out in Article 4, but would fail in setting the world on a path towards achieving the LTTG set out in Article 2. The third set of stylised pathways (with limited CH_4 reductions until 2050 and rapid reduction thereafter) illustrate this problem. They comprise a set of pathways that achieve net-zero GWP* after 2050, but with considerable residual CO_2 emissions (see figure 3). This is achieved by a negative CO_2-eq pulse arising from efforts to strongly reduce methane emissions in a relatively short period of a couple of decades. The residual CO_2 emissions lead to continued long-term warming when no further action is assumed. Such scenarios would undermine the environmental integrity of the Paris Agreement but are excluded when GWP100 is used, because the achievement of net-zero CO_2 is a prerequisite of achieving net-zero GHGs in the GWP100 metric.

At the same time, even achieving net-zero GHG under GWP* with net-zero CO_2 may not guarantee temperature stabilization (Cain *et al* 2019). While this can be corrected for, the correction factors are scenario dependent and subject to substantial uncertainties. The complexity of GWP* hinders the meaningful application of the GWP* concept in climate policy.

Discussion

In our analysis, we have detailed the implications of different GHG accounting metrics for the internal consistency of the Paris Agreement. The Agreement was based on science available at the time as assessed and reported by the IPCC AR5. Article 4 of the Paris Agreement also explicitly references it being in line with this 'best available science'. GWP100 is the standard emission metric used in the IPCC AR5 as well as under the UNFCCC (IPCC 2014). We have shown that using GWP100 to interpret Article 4 is fully consistent with the various possible interpretations of the LTTG set out in Article 2. Therefore, an interpretation of Article 4 using GWP100 appears to be the scientifically sound approach that accounts for the full context of the Paris Agreement.

This finding does not preclude the application of other GHG accounting concepts for stringent mitigation efforts in line with the Paris Agreement. However, our findings indicate that switching to other GHG accounting concepts like GWP* requires a re-formulation of the emission reduction targets in Article 4 to continue to capture core elements of the Paris Agreement mitigation goal. Elements that would need to be covered by such a re-formulation are summarized in table 3.

We have identified a range of inconsistencies that would be introduced if the Paris Agreement's Article 4 is interpreted using GWP* as the GHG metric. Specifically, the absence of long-term declining temperatures following net-zero GHGs under GWP* conflicts with the Article 2 interpretation of pathways that hold warming 'well below 2 °C' (see table 1) but temporarily exceed 1.5 °C while 'pursuing' to limit warming to 1.5 °C thereafter. If the MG interpreted in GWP* does not yield declining temperatures, this only leaves one possible interpretation of Article 2 which is that 1.5 °C has to be seen as a not-to-exceed limit. In our analysis, however, scenarios that achieve net zero calculated with a GWP* metric after 2050 fail to limit peak warming to below 1.5 °C. If interpreted verbatim in GWP*, achieving Article 4 without additional action thus

Table 3. A summary of core elements that consistent interpretations of the Paris Agreement mitigation goal need to fulfil. Any re-interpretation of Article 4, e.g. in a novel emissions metric, needs to ensure it captures these elements.

Elements of the Paris agreement mitigation goal	Reasoning
Consistency with emissions pathways that limit warming to 1.5 °C without an overshoot	– Achieving Article 4 needs to be sufficient to achieve the long-term temperature goal of the Paris Agreement and be fully consistent with all its interpretations including a 'no-overshoot' 1.5 °C limit
Achieve and sustain negative CO_2 emissions with at least stabilization of all other greenhouse gases in the second half of the 21st century	– A 1.5 °C overshoot pathway pursuing efforts to achieve the 1.5 °C limit is a valid interpretation of the LTTG in Article 2. A stabilization of global mean temperature increase above the 1.5 °C limit, however, would not be consistent. Therefore, long-term declining temperatures are required under overshoot pathways as a result of achieving Article 4. Sustained declining temperatures can only be achieved by negative CO_2 emissions
Achieving Article 4 must be sufficient for achieving Article 2	– Article 4 sets out the requirements for pathways up to the achievement of net-zero GHGs, but does not specify additional actions beyond that – While such actions might be taken (or needed as in the case of negative CO_2 emissions beyond net-zero GHGs in many 1.5 °C emissions pathways), they cannot be assumed in an interpretation of Article 4

becomes inconsistent with the achievement of the 1.5 °C limit established in Article 2. We have further shown that pathways exist that achieve net zero in GWP* before 2100 while leading to a peak warming of more than 2 °C adding to the inconsistencies created between Article 4 and 2 when using GWP*.

Achieving (but not maintaining) net-zero GWP* after 2050 cannot guarantee temperature stabilization for scenarios that do not also achieve net-zero CO_2 emissions. If no further actions are assumed (i.e. emissions are being held constant after net-zero GWP* is reached for the first time), the remaining CO_2 emissions in such scenarios would lead to long-term warming.

Ultimately, the core issue of applying GWP* to Article 4 of the Paris Agreement can be brought back to a question of horses for courses. GWP* has shown to be excellent at linking cumulative CO_2-equivalent emissions to GMT, but performs poorly to link annual emission benchmarks to long-term temperature outcomes (a feature we clearly illustrate in figures 2 and 3). This feature therewith undercuts the adequacy of GWP* for application to the Paris Agreement. Article 4 of the Paris Agreement is expressed in terms of an evolution of annual emissions over time (peak as soon as possible in a given year, a rapid decline in annual emissions, and a net zero GHG in a given year), not in terms of cumulative CO_2-equivalent emissions for which GWP* would be superior. Taken together, we have shown that applying GWP* directly to the Paris Agreement would introduce major conflicts in the Agreement's architecture, undermine its overall internal consistency and deteriorate the environmental integrity of the targets that are set out in the Agreement's Articles 2 and 4. As a result of its dependency on historic emissions, applying GWP* to any other than the global level further raises fundamental questions of fairness and equity (Rogelj and Schleussner 2019). With the explicit reference to equity in Article 4 and given the national determined nature of the Paris Agreement, this further limits the scope of the applicability of the metric in climate policy.

Our analysis of GWP* in the context of the Paris Agreement can serve as an illustration of how introducing novel concepts to the policy context of the UNFCCC can create inconsistencies or loopholes in a carefully crafted policy landscape or even unwillingly lead to a shift in goalposts (Rogelj *et al* 2017). Avoiding such undesirable outcomes is of paramount importance for successful science policy advice.

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Data availability statement

The data that support the findings of this study are available from the corresponding author upon request.

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