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# Unintentional unfairness when applying new greenhouse gas emissions metrics at country level

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## Abstract

The 2015 Paris Agreement sets out that rapid reductions in greenhouse gas (GHG) emissions are needed to keep global warming to safe levels. A new approach (known as *GWP**) has been suggested to compare contributions of long- and short-lived GHGs, providing a close link between cumulative $CO_2$-equivalent emissions and total warming. However, comparison factors for non-$CO_2$ GHGs under the *GWP** metric depend on past emissions, and hence raise questions of equity and fairness when applied at any but the global level. The use of *GWP** would put most developing countries at a disadvantage compared to developed countries, because when using *GWP** countries with high historical emissions of short-lived GHGs are exempted from accounting for avoidable future warming that is caused by sustaining these emissions. We show that when various established equity or fairness criteria are applied to *GWP** (defined here as *eGWP**), perceived national non-$CO_2$ emissions vary by more than an order of magnitude, particularly in countries with high methane emissions like New Zealand. We show that national emission estimates that use *GWP** are very sensitive to arbitrary choices made by countries and therewith facilitate the creation of loopholes when $CO_2$-equivalent emissions based on the *GWP** concept are traded between countries that use different approaches. In light of such equity-dependent accounting differences, GHG metrics like *GWP** should only be used at the global level. A common, transparent and equity-neutral accounting metric is vital for the Paris Agreement's effectiveness and its environmental integrity.

## Main text

With the adoption of the 2015 Paris Agreement, governments have set stringent global goals that aim to limit the impacts of climate change to safe levels (UNFCCC 2015). This includes a long-term temperature goal in Article 2 of the Paris Agreement (to '*[hold] the increase in the global average temperature to well below* 2 °C *above pre-industrial levels and pursu[e] efforts to limit the temperature increase to* 1.5 °C *above pre-industrial levels*') as well as an emissions reduction target defined in its 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 (GHG) emissions as soon as possible, recognizing that peaking will take longer for developing country Parties, 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 GHGs in the second half of this century, on the basis of equity, and in the context of sustainable development and efforts to eradicate poverty.'

The mitigation target defined here refers to emissions reductions at the global as well as at the national scale, and further paragraphs of Article 4 mandate that countries' mid-century, long-term low GHG emission development strategies should be in line with this overall global emissions reduction goal and reflect countries' highest possible ambition (UNFCCC 2015). The reductions should be implemented 'on the basis of equity', which means that they should consider different concepts of how the global mitigation effort can be distributed to the country level (Rajamani and Werksman 2018). Concepts of equity, burden sharing or fair shares, can be informed by science, but are in essence reflecting value and ethical judgements (Stavins *et al* 2014, Robiou du Pont *et al* 2016, Klinsky and Winkler 2018). It is thus essential to transparently reflect upon such concepts when considering new scientific approaches towards achieving the agreement's goals.

Achieving a 'balance between anthropogenic emissions by sources and removals by sinks of GHGs in the second half of this century' is equivalent to achieving net-zero GHG emissions (Fuglestvedt *et al* 2018). The GHG metric which determines how different GHGs are accounted for in pathways (and hence how the achievement of net-zero GHG emissions is measured) is not explicitly specified, but it can be inferred based on information and reports that fed into the development of the Paris Agreement. The Paris Agreement was informed by the IPCC's fifth assessment report (AR5) that used Global Warming Potentials (GWPs) of different GHGs over a time frame of 100 years (*GWP*-100) as the standard emission metric to aggregate GHG emissions for its assessment and presentation of emissions pathways (IPCC 2014). Similarly, also the United Nations Framework Convention on Climate Change (UNFCCC) uses *GWP*-100 as the common GHG accounting metric (UNFCCC 2016). For context, it is thus important to realize that all the key scientific and analytical inputs on emissions pathways that were available during the preparations and adoption of the Paris Agreement used the *GWP*-100 metric.

A range of alternative emission metric concepts and time frames have been discussed for some time (Myhre *et al* 2013, Fuglestvedt *et al* 2018). Recently, a metric has been proposed (named $GWP^*$) to assess the almost direct temperature effect of non-$CO_2$ GHGs, rather than their integrated long-term forcing effect (Allen *et al* 2016). $GWP^*$ has scientific merits when assessing global emissions and warming trajectories: cumulated global GHG emissions expressed in the $GWP^*$ metric are broadly proportional to global mean temperature increase (Allen *et al* 2018). A recent advancement of the methodological approach achieves even better outcomes of linking GHG emissions to global mean temperature increase by introducing scenario specific correction factors for carbon cycle and other feedbacks (Cain *et al* 2019). However, applying novel metrics to a pre-defined policy context is problematic if no appropriate measures are taken to ensure internal consistency with the earlier use of other metrics in that same policy context. In absence of such appropriate measures, policy targets can be re-interpreted without clear scientific or moral reasoning (Pfleiderer *et al* 2018). Being aware of value judgements that are embedded in physically argued methods and approaches is hence of the essence when operating at the science-policy interface (Rogelj *et al* 2017).

$GWP^*$ assesses the warming effect of short-lived climate forcers (SLCFs) such as methane ($CH_4$) by relating the level of present-day emissions to emissions in the (recent) past. Such an approach is unproblematic at the global scale, but when applied at a country scale, this introduces a preferential treatment of countries or other emitters that have large historical methane emissions—an unintended feature which we illustrate further in the body of this paper. An assessment of the use of the new $GWP^*$ metric in the context of fairness and equity is hence useful (Klinsky *et al* 2017).

Several equity or fairness principles are important for climate policy discussions and the fair distribution of mitigation action across countries (Stavins *et al* 2014). These include both burden sharing and resource-sharing principles (Rao 2011), that is, principles that emphasize the need for efforts to reduce global emissions (i.e. the 'burden') to be shared, and those that start from equal rights to access to the global commons of our planetary atmosphere, respectively. Emissions of short- or long-lived climate forcers are interpreted differently in this context.

Any amount of long-lived climate forcer emissions, and $CO_2$ in particular, will continue to contribute to warming over timescales well beyond centuries (Solomon *et al* 2010). Net-zero $CO_2$ emissions hence have to be reached to halt global warming and total cumulative emissions have to be kept to within a certain budget in order to achieve warming targets that aim to cap global warming at a given level (Knutti and Rogelj 2015). Resource-sharing principles applied to $CO_2$ and other long-lived climate forcers intend to inform the question of how a remaining carbon budget should be distributed while taking into account historical emissions or responsibility. Burden-sharing principles applied to this context intend to inform the question of how emissions reductions of $CO_2$ should be distributed globally taking into account the cost and potential of emissions reductions in each country.

For SLCFs like methane, however, warming is not irreversible and declining SLCF emissions would allow to reduce the warming impact of these species (Solomon *et al* 2010). This is sometimes misunderstood or misrepresented by suggesting that reducing methane emissions would result in global cooling (Cain 2019). However, when correctly considering historical emissions, lower future methane emissions simply result in

less warming, not in cooling. Only when historical warming is ignored, reducing SLCFs are perceived to lead to cooling. In a world in which a precautionary principle is applied and warming is to be limited to very low levels (United Nations Framework Convention on Climate Change 1992, UNFCCC 2015), this physical characteristic of SLCFs implies that SLCF emissions arguably have to be reduced to as low a level as possible in order to minimize their contribution to global warming—a logical consequence supported by scenario modeling (Rogelj *et al* 2018b). When looked at from a burden-sharing perspective as defined above (Rao 2011, Stavins *et al* 2014), SLCF reductions and their resulting global emission levels should be the result of the highest ambition of SLCF mitigation within and between countries. Reflecting upon this from a resource-sharing equity perspective suggests that access to this lowest level has to be distributed equally (or at least equitably) across countries. In no case seems a mere stabilization of national and global SLCF emissions (and hence also their warming) at current levels consistent with the equity and other climate policy principles agreed upon internationally (United Nations Framework Convention on Climate Change 1992), in particular as mitigation options for SLCFs are readily available (Gernaat *et al* 2015).

In the following, we assess some of the equity implications that occur when applying the *GWP** metric to the national level, and propose alternative approaches that account for historical emissions as well as future emission levels in line with the 1.5 °C limit. We refer to these approaches as *eGWP**. Finally, we will outline the implications for the applicability of *GWP**-based approaches in the context of national climate policy and global climate targets.

## Methods

We contrast the use of *GWP*-100 and *GWP** in terms of the perceived GHG emissions of various countries. We use GWPs for different GHGs as reported in AR5 (Myhre *et al* 2013) and use the PRIMAP-hist database (Version 2.0) (Gütschow *et al* 2016) for historical emissions, noting that more recent updates of *GWP*-100 values (Gasser *et al* 2017) would not affect the qualitative insights of this analysis that focus on the relative difference between the *GWP*-100 and *GWP** metrics.

Using the standard *GWP*-100 metric, $CO_2$-equivalent ($CO_2e$) emissions of SLCFs in any given year are derived directly from annual SLCF emissions (with GWP specified over a time horizon, here $H = 100$ years):

$$E_{CO_2e}(t) = E_{SLCF}(t)\mathrm{GWP}_H, \qquad (1)$$

where $E_{SLCF}$ is the annual emission of a certain SLCF in metric tons of the specific SLCF and $\mathrm{GWP}_H$ the standard GWP over time horizon $H$.

In contrast to this 'flow' based approach, *GWP** translates short-lived flow pollutants to a 'stock' of a certain SLCF-caused $CO_2$-equivalent warming in the atmosphere. Following Allen *et al* (2018), the $CO_2$-equivalent emissions of non-$CO_2$ short-lived GHGs using *GWP** is defined as

$$E_{CO_2e*}(t) = \frac{\Delta E_{SLCF}(t)}{\Delta T}\mathrm{GWP}_H H, \qquad (2)$$

where $\Delta E_{SLCF}$ is the change in emissions of an SLCF over a preceding time interval $\Delta T$. Unless changes in emissions are highly nonlinear, the choice of the interval length is of little influence. As in Allen *et al* (2018), we set $\Delta T = 20$. Following an emissions pulse, the abundance of SLCFs in the atmosphere decays rapidly over time. Concentrations of SLCFs hence track annual emissions quite closely. A change in SLCF emissions and the resulting change in atmospheric concentrations matter for the SLCF radiative forcing and its temperature change contribution. This is reflected in *GWP**-weighted emissions being computed relative to historical emissions.

However, when applying equation (2) at the level of a specific country this is equivalent to implementing a 'grandfathering' principle because *GWP** takes a country's historic emissions level as its starting point. The grandfathering principle is often regarded as being inequitable and strongly criticized (Caney 2009, Peters *et al* 2015, Kartha *et al* 2018), because it reflects the view that a continuation of present-day emissions shares across countries is a fair distribution key for emissions in the future. Under this *GWP** approach the highest historically polluting countries are thus rewarded for their past GHG pollution by receiving the right to continue to emit similar shares in the future.

Alternative equity concepts exist to distribute emissions, and are moreover more widely accepted as adequate representations of fairness (Stavins *et al* 2014, Robiou du Pont *et al* 2016). For example, future emissions can be assigned on a per-capita basis. We here introduce several equity approaches and highlight how their application quite radically changes the perception of *GWP**-weighted SLCF emissions at the national level. $CO_2$-equivalent emissions are derived for various countries over the historical period using *GWP** and also using *GWP** adjusted with different equity concepts for distributing emissions. It is important to note that not all equity concepts are considered equally fair, or fair at all (Kartha *et al* 2018). They can simply describe different approaches that can be followed either implicitly or explicitly when distributing future emissions contributions amongst countries. These adjusted *GWP**-based $CO_2$-equivalent emissions are referred to as *eGWP** and listed in table 1.

We derive an illustrative fair share of the global SLCF emissions for a country $C$ by

$$E^{PC}_{\mathrm{SCLF}}(C,\,t) = \frac{E_{\mathrm{Ref,SLCF}}(t)}{P_{\mathrm{Global}}(t)} P(C,\,t). \quad (3)$$

With $E_{\mathrm{Ref,SLCF}}(t)$ the level of global SLCF emissions that is consistent with a specific policy objective, and $P_{\mathrm{Global}}(t)$ and $P(C,\,t)$ the global and country population, respectively, as provided by the World Bank at https://data.worldbank.org/indicator/sp.pop.totl.

Using this per capita reference approach to derive annual emissions, equation (2) and the newly defined *eGWP**-weighted emissions hence become

$$E^{PC}_{\mathrm{CO_2e}*}(t) = \frac{E_{\mathrm{SLCF}}(t) - E^{PC}_{\mathrm{SLCF}}(t-\Delta T)}{\Delta T}\mathrm{GWP}_H H. \quad (4)$$

We look at three different levels of global emissions as illustrative policy reference levels $E_{\mathrm{Ref,SLCF}}(t)$ to distribute per capita emissions: constant emissions (*eGWP**-*CE*), emissions resulting in a constant warming contribution (*eGWP**-*CW*), and an emission level resulting in a minimal warming contribution (*eGWP**-*MW*, see table 1). These approaches hence differ in their global reference level $E_{\mathrm{Ref,SLCF}}(t)$ only. For ease of implementation, $E_{\mathrm{Ref,SLCF}}(t)$ is explored by linearly scaling present global emission with different factors:

$$E_{\mathrm{Ref,SLCF}}(t) = \alpha\, E_{\mathrm{Global,SLCF}}(t'). \quad (5)$$

For the constant emissions case $\alpha$ simply equals 1 and the reference period is constant with $t' = 2015$. For the constant warming contribution, we set $\alpha = 0.9$, an empirically determined value for the $\Delta T = 20$ year time frame and a $t' = t$ moving reference period. If $CH_4$ emissions declined by about 10% over 20 years, they would lead to close to no change in the $CH_4$ warming contribution in our MAGICC6 (Meinshausen *et al* 2011) configuration. For the minimal future warming case, we determine $\alpha = 0.5$ (for $t' = 2015$) as a rough median from a range of 1.5 °C compatible emissions reduction pathways assuming that options for mitigating $CH_4$ emissions have been fully implemented (Huppmann *et al* 2018a, Huppmann *et al* 2018b, Rogelj *et al* 2018a, Rogelj *et al* 2018b). Future advances in mitigation measures for $CH_4$ might further reduce this value (Gernaat *et al* 2015). This approach is also based on a time-invariant reference period.

Finally, although continued emissions of SLCF do not result in strong additional future warming, they are responsible for a significant share of past warming. To account for this when using the *GWP** metric at a national level, we also take 'zero' as one of the reference levels explored here (*eGWP**-*ZR* with $\alpha = 0$). This is diametrical opposite to the grandfathering approach of the original *GWP** metric which takes present-day SLCF emissions as the baseline and thereby ignores the warming already caused by historical emissions. In the 'zero reference' approach that is applied in *eGWP**-*ZR*, this historical warming is explicitly accounted for. It implies that before any distribution of 'fair shares' of emissions can take place, the warming that current SLCF emissions are causing needs to be accounted for, at least once. Therefore, the 'zero reference' approach *eGWP**-*ZR* becomes equivalent to estimating $CO_2e$ emissions with

$$E^{ZR}_{\mathrm{CO_2e}*}(t) = \frac{E_{\mathrm{SLCF}}(t)}{\Delta T}\mathrm{GWP}_H H. \quad (6)$$

## Results

$CH_4$ emissions per capita vary widely between countries and are particularly high for economies with either substantial agricultural or fossil fuel related $CH_4$ emissions (see figure 1, panel (a)). In absolute terms, the developing countries in our illustrative set rank high in absolute $CH_4$ emissions due to their main economic sectors and the size of their economies, while they rank low through the lens of per capita emissions. When applying the original grandfathering *GWP** metric (see figure 1, panel (b)) the picture looks entirely different. As many developed countries have not expanded or even reduced their emissions from $CH_4$ in the past couple of decades, their $CO_2e$ *GWP** emissions are generally lower than when accounted for with *GWP*-100, despite continued high levels of actual per capita $CH_4$ emissions. For several countries, including some with $CH_4$ per capita emissions well above the global average such as the USA, Ireland and Australia, expressing current $CH_4$ emissions through the default grandfathering $CO_2e$ *GWP** metric even results in a perceived negative contribution, which in principle could be accounted against (i.e. used to offset) other GHG emissions including long-lived gases such as $CO_2$.

As illustrated in figure 1, panel (c), and summarized in table 2, the choice of metric (either the traditional *GWP*-100 or grandfathering *GWP**) fundamentally alters the ranking of countries in terms of their accounted (perceived) per capita $CH_4$ emissions. Major developing country emitters such as China and Brazil that have comparably lower historic per capita emissions have seen increases over the recent decades. Applying grandfathering *GWP** leads here to an increase in these countries' perceived $CO_2e$ per capita emissions so that they are now ranked third and second, respectively, in our list of illustrative country emitters. Quite the contrary is true for Australia, which is the third highest per capita emitter of the countries considered here in terms of its actual per capita $CH_4$ emissions or *GWP*-100-weighted $CO_2e$ per capita emissions. Due to emission reductions over recent years, the grandfathering *GWP** accounting metric would suggest Australia to have the lowest (and negative) $CO_2e$ per capita emissions across our set of illustrative countries, together with the EU28, although the latter has only about 20% of Australia's

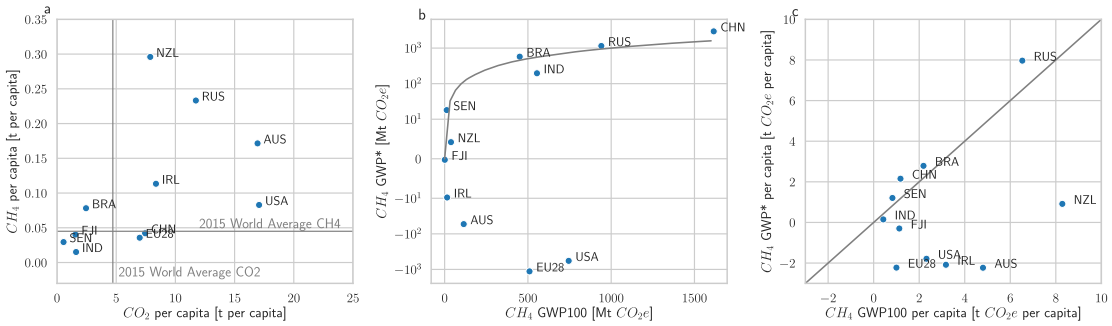


**Figure 1.** Implications of different $CH_4$ accounting methods for selected countries. (a) Country level $CH_4$ and $CO_2$ per capita emissions for the year 2015. The world average is indicated by the gray line. (b) Absolute country level $CO_2$e emissions in 2015 derived using grandfathering GWP* versus GWP-100. Countries above (below) the symmetry line (in gray, note the symlog-scaling of the *y*-axis) have higher (lower) 2015 $CO_2$e emissions from $CH_4$ when using grandfathering GWP* compared to GWP-100. (c) Same as (b), but for per capita emissions. Country labels are defined in table 2.

**Table 1.** Overview of GWP* and eGWP* GHG metrics for methane ($CH_4$), the underlying equity principle, respective properties, and implicit logic of the concept.

| Metric | Equity concept (policy objective) | Properties | Implicit logic of concept |
|---|---|---|---|
| *GWP** | 'Grandfathering' | Derive *GWP** relative to countries' historical emissions using equation (2) | Countries with high current SLCF emissions are rewarded for their past GHG pollution by receiving the right to continue to emit similar shares in the future, and the opposite is true for countries with current low SLCF emissions |
| *eGWP*-CE* | 'Constant emissions' per capita | Keep global $CH_4$ emissions constant at their 2015 levels, and distribute emissions using a per capita 'fair share' as the reference point | Each country receives an equal-per-capita share of current global $CH_4$ emissions for the future and actual emissions in a country are compared to this reference level |
| *eGWP*-CW* | 'Constant warming' per capita | Keep global $CH_4$ warming contribution constant by reducing global emissions $CH_4$ emissions by 10% over a 20 year time frame distributed per capita | Each country receives an equal-per-capita share of the global $CH_4$ emissions that would not result in further warming and actual emissions in a country are compared to this reference level |
| *eGWP*-MW* | 'Minimal methane induced warming' per capita | Achieve minimal future warming contribution from $CH_4$ emissions based on most stringent mitigation scenarios (50% below 2015 levels) distributed per capita | Each country receives an equal-per-capita share of the global $CH_4$ emissions that correspond to the most stringent emissions reductions identified in integrated emissions pathways and actual emissions in a country are compared to this reference level |
| *eGWP*-ZR* | 'Zero reference' per capita | Zero $CH_4$ emissions as the reference point. Countries account for their full historical $CH_4$ warming contribution up to 2015 | Each country's $CH_4$ emissions are compared to a zero emissions case |

per capita $CH_4$ emissions when expressed in annual $CH_4$ emissions per capita.

With the grandfathering *GWP** approach, countries with high historic SLCF emissions are thus rewarded for these high historical emissions and the climate change they caused, because reducing emissions from these high historical levels would allow them to reach 'negative' $CO_2$-equivalent emissions or $CO_2$-equivalent emissions credits for other GHGs. When grandfathering is perversely presented as an appropriate fairness principle, this feature can be used to argue emissions reductions result in global cooling (Cain 2019). In contrast, countries with very low historic SLCF emissions—typically developing countries—will receive penalties from increasing their emissions, even if these are the result of responding to basic development needs.

The application of the grandfathering *GWP** metric at a national level is hence raising concerns about equity and fairness. These concerns are explored further below, using the different equity approaches to derive alternative *eGWP** metrics.

The implications of applying either *GWP** or a per-capita based *eGWP*-CE* approach (equivalent to the Grandfathering and per capita distributed constant emissions approaches, see table 1) are illustrated in figure 2 for a developed country with high historical

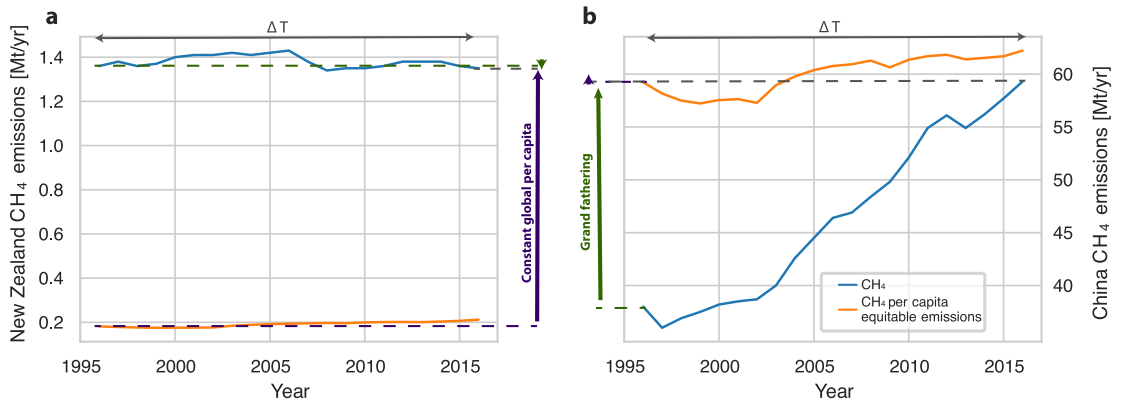


**Figure 2.** Illustration of the implications of different equity (or inequitable) approaches on New Zealand's (panel (a)), and China's (panel (b)) $CH_4$ emissions accounting. The countries' current $CH_4$ emissions are interpreted in terms of grandfather $GWP^*$ relative to the country's historical emissions over the last 20 years (Grandfathering) and relative to constant global equal per capita $CH_4$ emissions ($eGWP^*$-CE, marked with Constant global per capita). For $GWP^*$ calculations for the year 2016 this illustration uses $\Delta T = 20$. Purple and green arrows mark the accounted $CH_4$ emissions difference including sign for the Grandfathering and Constant global per capita approach, respectively.

**Table 2.** Ranking of countries according to the per capita $CH_4$ emissions accounted for using GWP-100 (left) and $GWP^*$ (right). Developed countries are marked in bold and with a gray shading, Russia as a major oil and gas producer in italics and major developing economies in normal font.

| *GWP*-100 2015 per cap $CH_4$ emissions ranking | Tonne $CO_2$e per cap | *GWP** 2015 per cap $CH_4$ emissions ranking | Tonne $CO_2e^*$ per cap |
|---|---|---|---|
| **New Zealand (NZL)** | 8.3 | *RUS* | 8.0 |
| *Russian Federation (RUS)* | 6.5 | BRA | 2.8 |
| **Australia (AUS)** | 4.8 | CHN | 2.2 |
| **Republic of Ireland (IRL)** | 3.2 | SEN | 1.2 |
| **United States of America (USA)** | 2.3 | **NZL** | 0.9 |
| Brazil (BRA) | 2.2 | IND | 0.1 |
| China (CHN) | 1.2 | FJI | −0.3 |
| Fiji (FJI) | 1.1 | **USA** | −1.8 |
| **European Union (EU28)** | 1.0 | **IRL** | −2.1 |
| Senegal (SEN) | 0.8 | **EU28** | −2.2 |
| India (IND) | 0.4 | **AUS** | −2.2 |

emissions (New Zealand, panel (a)), and a developing country with rapidly increasing methane emissions over recent decades (China, panel (b)). Although New Zealand's $CH_4$ emissions are far above the global per-capita fair share, the small emissions reductions between 1996 and 2016 would lead to a perceived negative $CO_2$e contribution under the grandfathering *GWP** approach. To the contrary, China's rising $CH_4$ emissions over the same period would lead to substantial additional $CO_2$e grandfathering *GWP** emissions. When looked at through the lens of a constant emission per-capita approach, China's 2016 $CO_2$e *eGWP*-CE* emissions are close to the global equitable per capita share for constant global $CH_4$ emissions. New Zealand, on the contrary, sees an increase of its accountable $CH_4$ emissions in 2016 by a factor of about 6. The outcomes of the emission accounting using metrics such as grandfathering *GWP** or *eGWP** variations are thus not scientifically neutral, but the result of value judgements and considerations of equity and fairness that need to be made explicit.

This is further illustrated in figure 3, which displays the differences in per capita accounting of *GWP** versus different *eGWP** approaches. When using *eGWP** approaches (figure 3, panels (a)–(c)), $CO_2$e emissions for developed countries are changing sign and are generally much higher than when estimated with the default application of the grandfathering *GWP** metric. While the choice of the accounting metric leads to differences in absolute terms, the general patterns are similar between all alternative *eGWP** metrics that we apply here.

For individual developed countries such as Ireland and Australia, the $CO_2$e per capita emissions of $CH_4$ accounted using alternative equity-based *eGWP** metrics are consistently higher than their per capita $CO_2$ emissions (compare all panels of figure 3 with figure 1, panel (a)). For New Zealand, the country with the highest per capita $CH_4$ emissions in our analysis, annual per capita $CO_2$e values using *eGWP** can reach up to and exceed 40 tons of $CO_2$-equivalent emissions per capita, five times the per capita $CO_2$ emissions of the country.

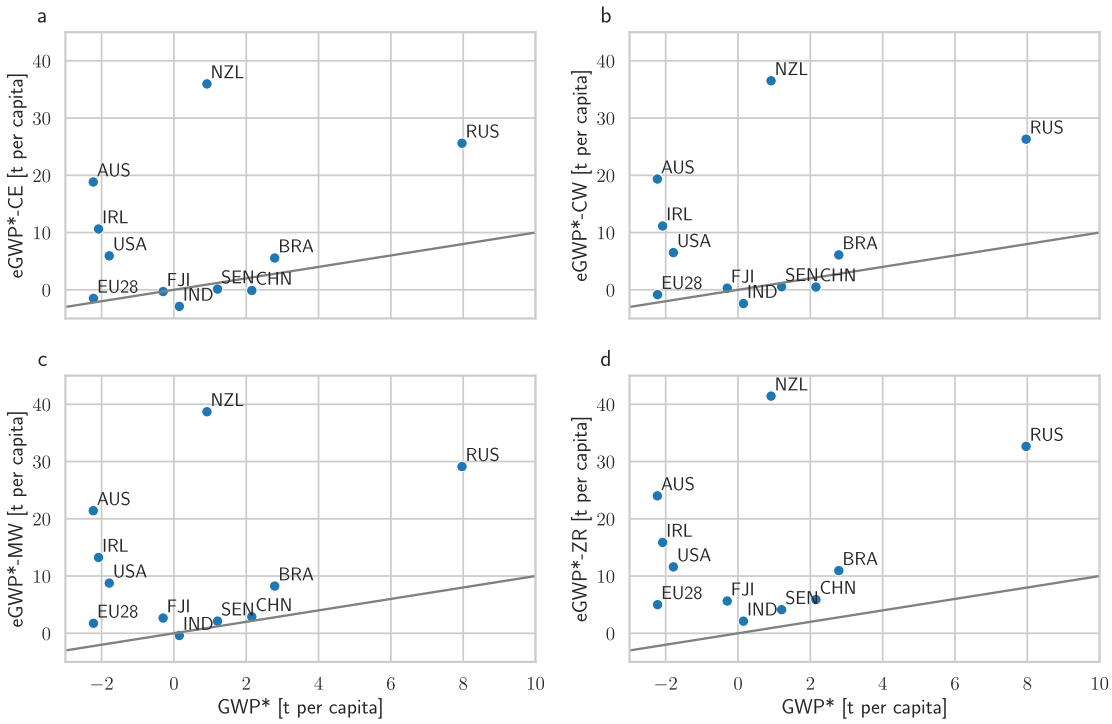


**Figure 3.** Implications of different equity approaches to distribute $CH_4$ emissions reflected in eGWP*s (see table 1) and the corresponding GWP* $CO_2$e emissions based on the standard grandfathering GWP* approach. (a) 2015 constant $CH_4$ emissions per capita eGWP*-CE; (b) 2015 constant warming eGWP*-CW; (c) minimal future $CH_4$ induced warming eGWP*-MW; (d) zero reference (historical warming) eGWP*-ZR. The gray lines indicate whether emissions in alternative equity adjusted eGWP* metrics are higher or lower than the standard grandfathering GWP* approach. Country labels are defined in table 2.

## Discussion

The existing literature on *GWP** approaches is relative young. The *GWP** concept was introduced in 2016 with a study highlighting the important differences in the temperature effect of a pulse of short versus long-lived climate forcers (Allen *et al* 2016), which in turn was building on more broader work on emissions metrics of a decade earlier (Shine *et al* 2005). The grandfathering *GWP** approach was then formally presented in the literature in a follow-up study (Allen *et al* 2018) and several derivative concepts have been published since, for example, using the *GWP** concept to derive $CO_2$ forcing-equivalent (Jenkins *et al* 2018) or $CO_2$ warming-equivalent (Cain *et al* 2019) emissions. Each of these approaches suffers from the same limitation as the original. Applied at the global level they provide clear scientific merit with a more direct link between the representation of $CO_2$-equivalent emissions and their warming impact. However, when applied at a national level they all suffer from the same implicit grandfathering bias, and hence disadvantage developing countries who might want to expand certain economic activities for their development but which at present come with a given amount of unmitigatable short-lived GHG emissions, for example, methane emissions from the agricultural sector. Here, our study provides a critique as well as new insights.

We have shown in our analysis that a grandfathering *GWP**-based approach developed for global applications for a well-mixed atmosphere cannot be simply applied to a context of national emissions because the proposed *GWP** metric only reflects the *additional* warming effect of emissions relative to today (or the recent past), not the historical responsibilities for warming already caused due to past emissions. Doing so is hence not a neutral scientific exercise but comes with strong assumptions about equity and countries' 'rights' to emit. If not accounted for, a direct *GWP** application (Allen *et al* 2016, Allen *et al* 2018) equals a 'grandfathering' approach that favors countries with high historical emissions and which is commonly rejected as being morally unacceptable (Caney 2009, Peters *et al* 2015, Robiou du Pont *et al* 2016, Kartha *et al* 2018).

We have shown that the application of *eGWP** methods that more directly reflect on the equity dimension of emissions metrics, like approaches that start from a per capita equity baseline instead of historical national emissions, lead to a strongly altered picture, with changes in sign of the perceived $CO_2$e emissions for most developed countries. In the case of New Zealand, methane $CO_2$e emissions per capita are even up to 40 times larger when taking into account an equity and fairness-based reference compared to the $CO_2$e emissions estimated with the grandfathering *GWP** approach (Allen *et al* 2016, Allen *et al* 2018).

Applications of per capita approaches also raise methodological questions in relation to *GWP** or *eGWP** approaches. When using the grandfathering *GWP** approach, the choice of $\Delta T$ might only lead to minor modifications in the level of accounted emissions, but for the per capita and zero reference approaches this choice will strongly alter results. For the sake of intercomparability, we have used $\Delta T = 20$ in our analysis. However, there is no reason why other values, e.g. even $\Delta T = 1$, should be ruled out. Such a choice would then simply lead to 20 times higher $CO_2$e emissions in the zero reference case and substantially increased values for the other fairness-based per capita approaches. The arbitrariness of this choice is a profound disadvantage for a broad application of *eGWP** metrics in the light of equity.

In addition to the issues related to equity and grandfathering, the potential for 'negative $CO_2$e emissions' for declining emissions of $CH_4$ is also a troubling implication that can be the result of an imprudent application of the *GWP** concept. In order to achieve the long-term temperature goal of the Paris Agreement, urgent emission reductions are required for all GHGs—$CH_4$ as well as $CO_2$ (IPCC 2018, Rogelj *et al* 2018b). As illustrated in figure 3, applying either *GWP** or *eGWP** could lead to negative emissions. In the case of the EU28, this would amount to about 2 Gt $CO_2$e per capita using the grandfathering *GWP**, which is about 25% of EU28 per capita $CO_2$ emissions. This means that individual countries would create additional $CO_2$ allowances either for themselves or to a market mechanism by reducing $CH_4$.

Such 'negative $CO_2$e emissions' created through the application of *GWP** or *eGWP** could have inequitable spill-over effects into national $CO_2$ emission budgets. For example, if New Zealand decreases its $CH_4$ emissions by 50% in 2035 relative to 2015, this would equate to a perceived 'additional' $CO_2$ budget of about 2.5 times New Zealand's annual $CO_2$ emissions in the year 2015. The application of grandfathering *GWP** at the country level would thereby be prone to opening accounting loopholes that critically undermine the need for stringent mitigation of all GHGs.

In our analysis, we have focused on $CH_4$ as the most common non-$CO_2$ SLCF. The implications for other SLCFs would be qualitatively similar, although smaller in magnitude. Any non-$CO_2$ GHGs with an atmospheric lifetime larger than 20 years is modeled precisely the same by *GWP** as by *GWP*-100. For long-lived non-$CO_2$ GHGs like nitrous oxide, hence no unintended issues exist.

In summary, we have illustrated that the application of the grandfathering *GWP** metric proposed in the literature (Allen *et al* 2016, Allen *et al* 2018), irrespective of its scientific merits for applications at the global scale, introduces substantive bias and concerns related to the equitable and fair share of emissions at the national scale. Applying the grandfathering *GWP** metric in national accounting would lead to substantial and inequitable biases in favor of countries with historically high emissions. Introducing various equity concepts as part of a *GWP** logic, i.e. applying the *eGWP**-like metrics presented in this paper, illustrates how numeric values obtained by this class of metrics depend on chosen reference levels that reflect implicit or explicit moral/ethical value judgments. If more equitable per-capita-based accounting approaches are applied, annual $CO_2$-equivalent methane emissions of many developed countries would be of similar magnitude to, or even exceed, their annual $CO_2$ emissions.

The choice of which equity approach is applied in a national context is at the discretion of individual national governments. Because concepts of equity vary strongly across countries, introducing a *GWP** logic into national accounting would inevitably lead to different *GWP** or *eGWP** approaches being applied by different countries. This, in turn, results in the potential creation of substantial perceived 'allowances' of $CO_2$e emissions if *GWP**-based emissions of SLCFs turn negative, because *GWP** fails to account for historical warming contributions. If such allowances would enter a global market mechanism under the Paris Agreement for which the target was set in *GWP*-100, they would undermine both the scientific integrity of the Paris Agreement and the global efforts to reduce GHG emissions. In order to achieve the required stringent emission reductions of all GHGs, transparent and robust national accounting is key. As a fundamental principle to achieve this, each tonne of GHGs of any kind in any country needs to be accounted for in the same way—or alternatively, a full scientifically robust translation between country approaches should be readily available and agreed upon as part of the market mechanism. As *GWP**-based approaches at present cannot guarantee to fulfill that criterion, they are not suited for application in the efforts to achieve transparent and effective GHG emission reductions under the Paris Agreement.

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## Data availability statement

Data sharing is not applicable to this article as no new data were created or analysed in this study. Emissions data that was analysed is available under DOI: https://doi.org/10.5880/PIK.2019.001.

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