Yale Carbon Containment Lab

Do Emission Metrics Measure Up? Global Warming Potential and Other Emission Metrics, Explained

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Author: Caroline Benedetti

Reviewers: Charlie Mayhew, Tilden Chao, Anastasia O'Rourke

Introduction

Carbon dioxide dominates climate change mitigation conversations. Other greenhouse gases, hiding in our fridges, fertilizers, and farms, are often underdiscussed and underprioritized. These super climate pollutants—such as methane (CH_4), nitrous oxide (N_2O), and fluorinated greenhouse gases ("F-gases")—must also be reduced to curb warming.

Because each of these climate pollutants has a unique molecular structure, they all warm the planet at different rates over different timelines. As a result, simply comparing the amount of each gas emitted will not accurately account for a gas's behavior in the atmosphere. To craft policies that address the proportional contribution of each pollutant to climate change, we need a method to compare their impacts.

Enter emission metrics. You may have seen these tools used within the climate sphere before, implicit in statements like "a molecule of methane warms the Earth 28 times more than carbon dioxide." Emission metrics convert various climate and greenhouse gas parameters to a common scale in order to compare the effects of different greenhouse gases. Often, emission metrics use carbon dioxide as a reference gas and quantify other gases in terms of their carbon dioxide equivalent (CO_2e).

Choice of an emission metric influences how we weigh the impacts of each greenhouse gas. Different metrics lead to different prioritizations for mitigation. In light of these important implications, we must interrogate why we use the metrics we do. This explainer will explore what goes into selecting an emission metric, how they fall short, and how they can change our understanding of the climate crisis.

Global Warming Potential: The Dominant Metric

In its 1990 First Assessment Report, the International Panel on Climate Change (IPCC) proposed an emission metric based on how different greenhouse gases change the Earth's energy balance (also called radiative forcing). The new metric, termed **Global Warming Potential** (GWP), compared the energy absorbed by one metric ton of a gas in the atmosphere relative to that absorbed by one metric ton of carbon dioxide over a chosen time period. If a gas has a GWP of 15 over a 100-year time horizon, that gas will cause 15 times the radiative forcing of carbon dioxide over a 100-year period. Though the IPCC called the metric "simple" and "preliminary," they emphasized that it was "necessary to have a simple means of describing the relative abilities of emissions" to assess all policy options (Shine et al., 1990, p. 58).

Initially, the IPCC calculated GWPs for 20 different gases over 20 years, 100 years, and 500 years. While these three time horizons had no particular scientific importance, the IPCC reasoned that different time horizons could be helpful to understand both long- and short-term climate outcomes. In fact, the IPCC specified that the time horizons were "presented as candidates for discussion and should not be considered as having any special significance" (Shine et al., 1990, p. 59).

Despite the IPCC's caveats, the Kyoto Protocol—the first international treaty to create legally binding emissions reductions targets—codified GWP over a 100-year time horizon (GWP-100) as the emission metric of international policy. The Protocol did not justify this choice within the directive (Kyoto Protocol, 1997). Nevertheless, this decision established a precedent of using GWP-100 as the standard metric for comparing emissions. Countries now use GWP-100 when setting their Nationally Determined Contributions under the Paris Climate Agreement (UNFCCC Secretariat, 2022). Corporations like Amazon and Apple rely on GWP-100 when disclosing their carbon footprint and setting emissions reductions targets (Amazon.com, Inc., 2022; Apple Inc., 2022). Non-governmental organizations release climate reports and interactive tools, like Climate Watch, that base their conclusions on GWP-100 (World Resources Institute, 2022). The metric pervades climate discourse and underlies nearly all decision-making.

It has been over *thirty years* since the IPCC first proposed using GWP as a potential emission metric. In that time, our understanding of the climate systems has developed. Our knowledge of greenhouse gas behavior has improved. Our goals for the climate have evolved. We must now ask: is GWP-100 the best metric for the world to use?

Considerations for an Emission Metric

In an ideal world, we would be able to quantify the exact damages generated by each greenhouse gas to nature, human health, and the economy. The perfect metric would have both a high relevance to our policy goals and little uncertainty. If the metric has too low relevance, it would be at best uninformative and at worst misleading. If the metric has too high uncertainty, the actual observed effect of the greenhouse gas could vastly differ from predictions.

Unfortunately, when it comes to climate change calculations, our world is far from ideal. To estimate damages, many assumptions about climate systems must be made. Differing scientific or economic opinions can cause approximations to vary and increase uncertainty. Herein lies the fundamental challenge of selecting an emission metric: how do we balance uncertainty and policy relevance?

As we work through the questions one should ask when selecting a metric, consider how uncertainty and policy relevance fluctuate.

Which climate effects should we use to compare emissions?

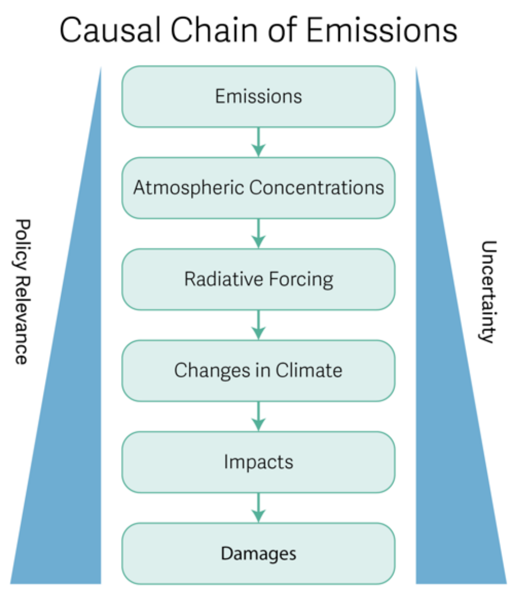

Figure 1 *is adapted from the Meeting Report of the 2009 IPCC Expert Meeting on the Science of Alternative Metrics (Boucher, 2009).*

The causal chain shown in Figure 1 depicts how greenhouse gas emissions link to their ultimate effects on humans and the environment. Emissions increase atmospheric concentrations, which cause changes in the Earth's energy balance. This radiative forcing induces changes in the climate, leading to several different impacts on human society and ecosystems which cause economic damages. In general, the further down this chain the effect is, the more relevant it becomes to policymakers (Boucher, 2009). Policymakers typically care more about concrete impacts and damages—for example, agricultural loss or sea level rise—than rises in atmospheric concentrations or increased radiative forcing.

Since its introduction, some have argued that GWP, as a measure of radiative forcing, does not fulfill policy needs. The majority of international climate goals are temperature targets, but GWP is not necessarily representative of temperature change. Radiative forcing and temperature are not synonymous; while increased radiative forcing leads to temperature increases, other environmental factors influence temperature change as well. For example, a strong short-lived greenhouse gas and weak long-lived greenhouse gas with the same GWP can cause different changes in temperature after the same period of time (Shine et al., 2005). Arguably, we should use an emission metric based on the more politically relevant quantity: average global surface temperature.

In 2005, scientists proposed a new metric, **Global Temperature change Potential** (GTP), to do exactly this. Rather than being a measure of radiative forcing, GTP quantifies the surface temperature change from the emission of one metric ton of a gas relative to carbon dioxide (Shine et al., 2005). Because GTP approximates temperature change, it closely aligns with most climate policy, including the 1.5°C and 2°C temperature goals set by the Paris Climate Agreement. Since the Fourth Assessment Report, the IPCC has included GTP as an alternative to GWP (Forster et al., 2007).

The policy relevance sought by GTP does not come without a cost. As we move farther along the cause-and-effect chain, more variables are introduced, making predictions more uncertain. A metric for radiative forcing, like GWP, requires knowledge of a gas's radiative efficiency and atmospheric lifetime, as well as modeled changes in the background atmosphere. A metric that describes changes in climate, like GTP, requires this knowledge *and* information about climate sensitivity, transient climate change, ocean heat uptake, and more (Boucher, 2009). As a result, more uncertainty exists in GTP approximations. Over time, climate scientists have drastically improved our understanding of these characteristics and continue to work to minimize unknowns. Regardless, uncertainties in climate models persist.

How far into the future should we make predictions?

In addition to choosing a climate parameter, we also need to select a point in the future (a "time horizon") at which to measure our parameter. Each greenhouse gas breaks down in the atmosphere over a different timescale. After a pulse emission (a single emission at one moment in time), gases cause additional radiative forcing, leading to temperature changes and other impacts. These physical effects will peak at some point in the future, then decrease as the gas leaves the atmosphere through chemical decomposition (Forster et al., 2021). For long-lived gases, like carbon dioxide, this process occurs over hundreds of years. For many super climate pollutants, it occurs over decades.

Two metrics that use the same climate parameter, but different time horizons, can have very different values. Why the metric value alters, however, depends on how a metric is calculated. There are two main ways metrics are calculated: GWP compares the **cumulative** radiative forcing that a gas causes over the time horizon, weighing years equally—it is an *integrated* metric; GTP compares the **absolute** difference in temperature during the emission year and temperature during the time horizon, ignoring any temperature fluctuations between—it is an *endpoint* metric.

To understand how time horizons affect integrated metrics, like GWP, let us consider a simplified model of a short-lived highly potent greenhouse gas, with a long-lived less potent greenhouse gas as a reference. In Year 1, we emit one metric ton of each gas. Assume that the short-lived gas is a stronger greenhouse gas than the reference (carbon dioxide is weaker than many short-lived gases) and has an atmospheric half-life of one year (i.e., half the gas leaves the atmosphere after one year). For simplicity, also assume that the gas in the atmosphere becomes negligible ten years after emission. Because the reference gas leaves the atmosphere slowly, we will also approximate that cumulative radiative forcing will increase linearly.

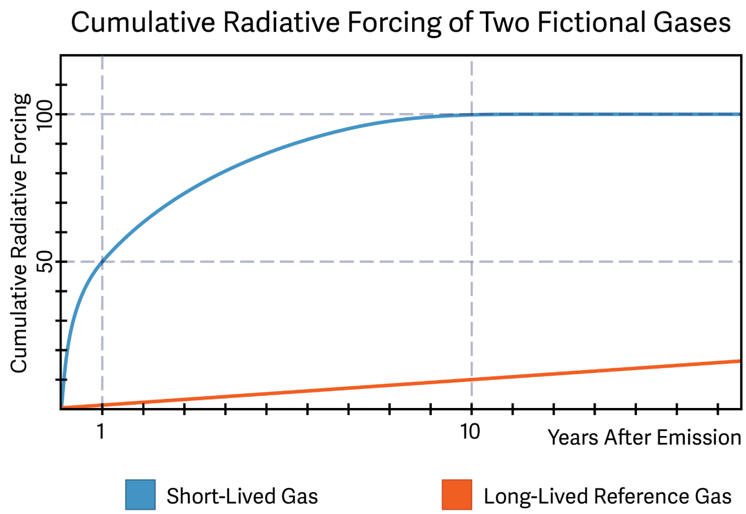

***Figure 2** shows the theoretical cumulative radiative forcing and GWP of the fictional gases in our simplified model. Because the long-lived reference gas leaves the atmosphere at a very slow rate, we can approximate a roughly linear increase in radiative forcing.*

Recall that to calculate each GWP, the cumulative radiative forcing of the short-lived gas is divided by the cumulative radiative forcing of the reference gas:

$$GWP_H = \frac{\text{cumulative radiative forcing of short-lived gas from Year 0 to Year } H}{\text{cumulative radiative forcing of reference gas from Year 0 to Year } H}$$

***Equation 1**: The Global Warming Potential of our fictional short-lived gas over time horizon H. Mathematically, cumulative radiative forcing is expressed by integrating radiative forcing with respect to time from Year 0 to time horizon H.*

In the first year, we will assume that the short-lived gas generates 50 units of radiative forcing. Because the long-lived gas is weaker, we assume it will only cause 1 unit of radiative forcing. In this first year, the short-lived gas traps 50 times the energy of the reference gas.

$$GWP_1 = \frac{50}{1} = 50$$

***Equation 2:** The Global Warming Potential of our fictional short-lived gas over one year.*

After the first year, the short-lived gas begins to leave the atmosphere. The less short-lived gas in the atmosphere, the less radiative forcing that will occur. As a result, in between Year 1 and Year 10, the short-lived gas causes an additional 50 units of radiative forcing. On the other hand, the reference gas will cause an additional 9 units of forcing. Thus, as shown in Equation 3, GWP-10 is equal to 10.

$$GWP_{10} = \frac{100}{10} = 10$$

Equation 3: *The Global Warming Potential of our fictional short-lived gas over ten years.*

During this time period, the cumulative radiative forcing of the short-lived gas doubles, but the cumulative radiative forcing of the long-lived gas increases by a factor of ten. Because the long-lived gas generates radiative forcing at a faster rate proportional to its first year than the short-lived gas, GWP-10 is lower than GWP-1.

After Year 10, the short-lived gas causes no further forcing, but the reference gas retains the same rate of forcing. At Year 50, the cumulative radiative forcing of the short-lived gas and the reference gas will equal 100 and 50, respectively.

$$GWP_{50} = \frac{100}{50} = 2$$

Equation 4: *The Global Warming Potential of our fictional short-lived gas over fifty years.*

Because only the cumulative radiative forcing of the reference gas grows, the radiative forcing of the short-lived gas gradually becomes a smaller multiple of the reference gas. Thus, GWP-50 is smaller than GWP-10. While this model is much simpler than real climate dynamics, it demonstrates how drastically time horizons can affect integrated metrics like GWP.

Global Warming Potentials of Fictional Gases

	Atmospheric Half-Life (Years)	Cumulative Radiative Forcing (Year 1)	Cumulative Radiative Forcing (Year 10)	Cumulative Radiative Forcing (Year 50)	GWP-1	GWP-10	GWP-50
Long-Lived Reference Gas	∞	1	10	50	1	1	1
Short-Lived Gas	1	50	100	100	50	10	2

Figure 3 *shows the theoretical radiative forcing and GWP of the fictional gases in our simplified model. Radiative forcing has units of Power/Distance^2 and GWP is unitless.*

Endpoint metrics like GTP are not immune to the effects of changing time horizons. For example, using GTP-100 to compare temperatures may underestimate the overall impact of a short-lived climate pollutant. As shown in Figure 4, a temperature increase from a single pulse of a short-lived gas could peak, then fade, before 100 years pass. Because GTP-100 only measures temperature change at 100 years, it would not capture this peak and associated global warming effect.

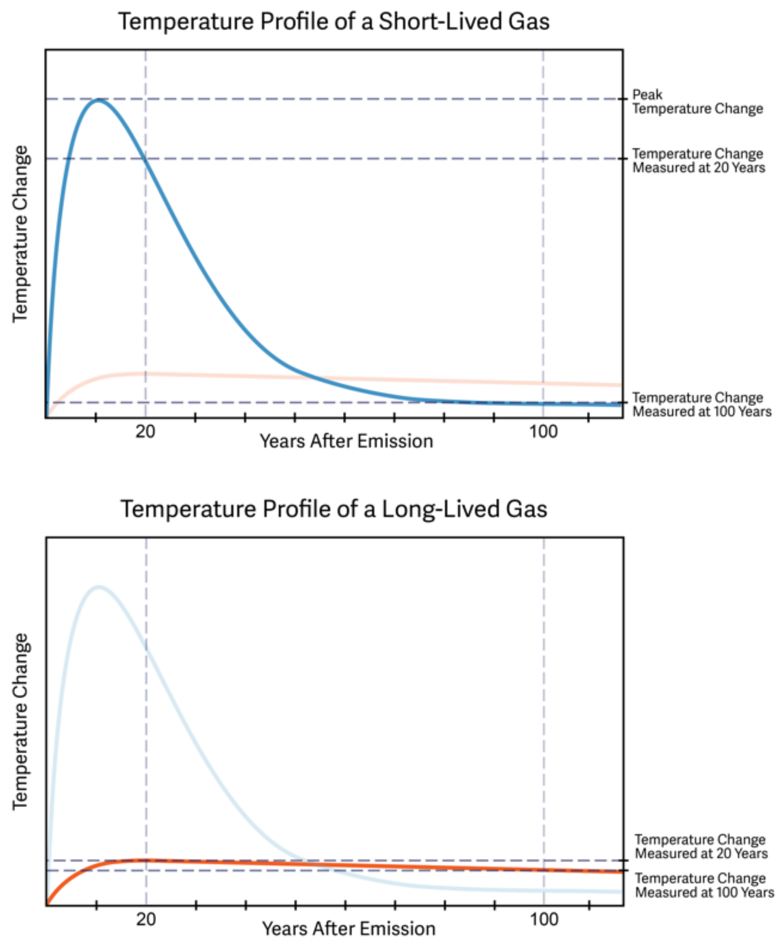

Figure 4 *is adapted from the IPCC's Fifth Assessment Report (Myhre et al., 2013, p. 711). These graphs show how gases with different lifetimes generate different temperature changes. Note, in particular, the differences in peak temperature change, temperature change measured at 20 years, and temperature change measured at 100 years.*

While metrics can be calculated for any time horizon, the most commonly employed are 20 or 100 years. Defenders of the 20-year time horizon often argue that we do not have 100 years to meet our climate goals and that a shorter time horizon emphasizes the need for more immediate action (Stausholm, 2021). Proponents of the 100-year horizon, however, argue that a 20-year metric does not accurately represent the long-term effects of emissions, overemphasizing short-lived gases and downplaying the need to address carbon dioxide emissions (Climate Analytics, 2017).

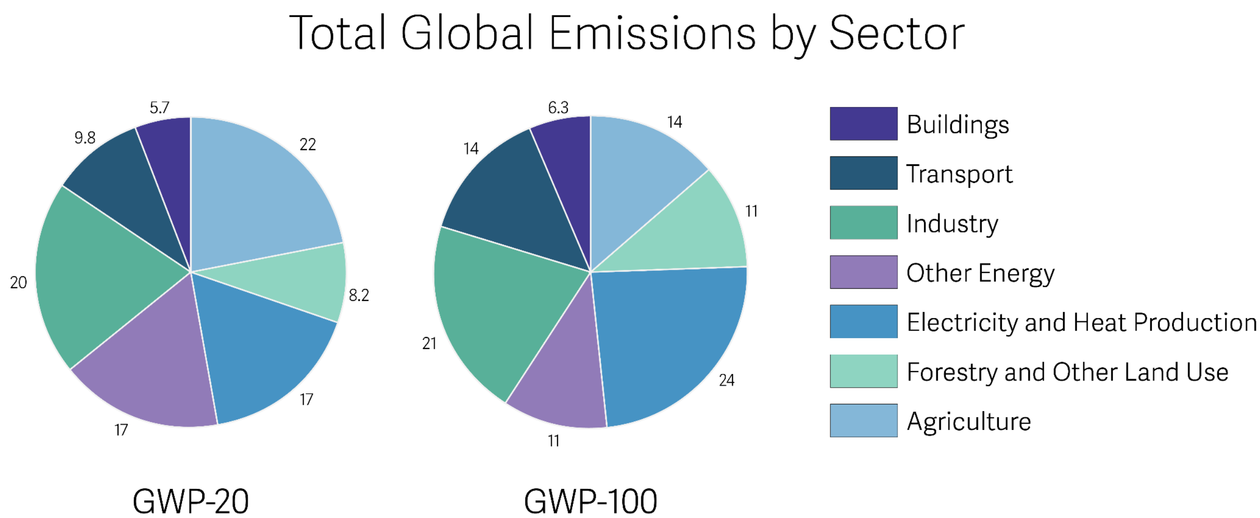

Figure 5 *adapted from the IPCC's Fifth Assessment Report, shows the contributions of different sectors to total global GHG emissions using GWP-20 and GWP-100 (IPCC, 2014, p.18).*

Notably, swapping between time horizons can make a country's CO_2e emissions differ drastically. In Figure 5, the variance of section size across the graphs highlights how the choice in time horizon can affect how we weigh the environmental impact of a sector. One notable difference is the agriculture sector, which has high methane emissions. Because methane is a short-lived gas, its GWP-20 is much higher than its GWP-100. Thus, when using GWP-20, agriculture becomes a much more prominent proportion of global emissions.

Choice of time horizon also affects the uncertainty of an emission metric. Parameters used to calculate climate outcomes, like atmospheric composition of gases and climate feedbacks, become increasingly uncertain as time goes on. It is, for example, much easier to approximate the atmospheric concentration of carbon dioxide one month from now compared to 100 years from now. As a result, metrics with longer time horizons are often more uncertain.

How Previous Metrics Fall Short

Despite their widespread use, some climate scientists argue that neither GWP nor GTP accurately represent relative effects of emissions (Allen et al., 2018; Collins et al., 2020). The two metrics are based on pulse emissions, which are a release of a gas at one moment in time. However, pulses of short-lived gases, like methane, and long-lived gases, like carbon dioxide, spend different amounts of time in the atmosphere, making it difficult to compare their behavior

To understand how pulse-based metrics fall short, let us consider another simplified model of a short-lived fictional gas that remains in the atmosphere for one year. In the first year, we start emitting one metric ton of gas per year for three years, then stop.

If we use a pulse-based metric, like GWP, to calculate CO_2e emissions, the metric will predict that gas will accumulate in the atmosphere as the years progress. As atmospheric concentrations increase, warming will occur. By the third year, three metric tons will have entered the atmosphere, and even after we stop emitting the gas, the metric tons will remain. To reduce the warming effect of those three metric tons, we would have to remove them from the atmosphere.

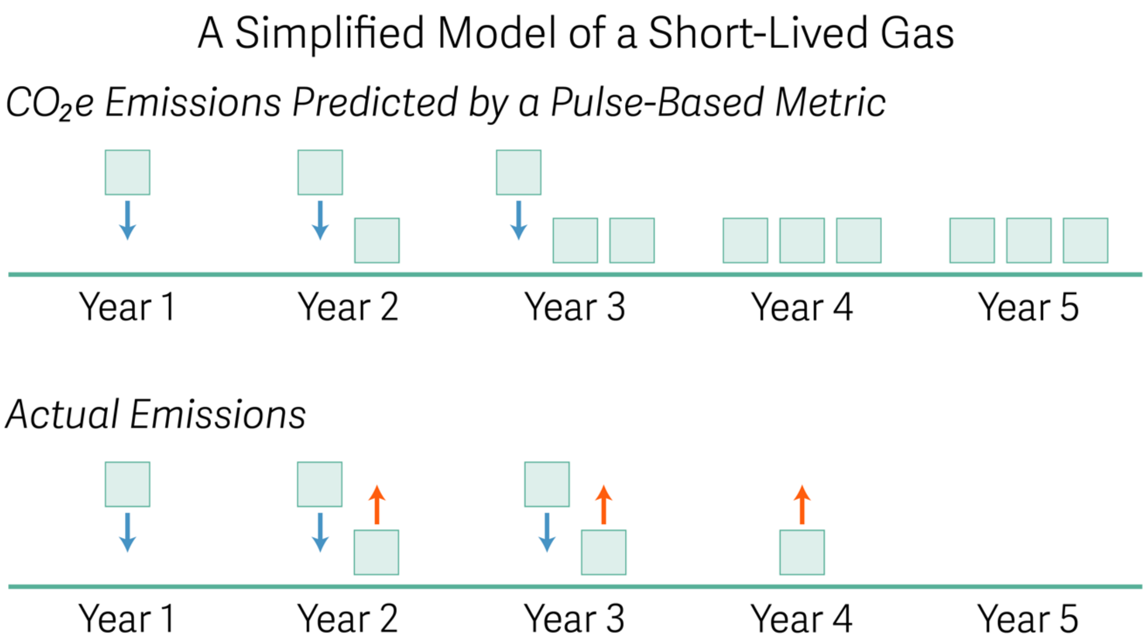

Figure 6 *shows how pulse-based metrics misrepresent how short-lived emissions actually behave in the atmosphere. In the model, we imagine a short-lived gas that remains in the atmosphere for one year. In the first year, we start emitting one metric ton of gas per year but after year three, we stop emitting the gas. Each box represents one metric ton of gas.*

For a long-lived gas, using a pulse-based metric makes sense—newly emitted carbon dioxide remains in the atmosphere for centuries so continued emissions do effectively accumulate in the atmosphere. But our fictional short-lived gas behaves much differently. As illustrated in Figure 4, in the first year, one metric ton will enter the atmosphere. This metric ton increases the concentration of the gas in the atmosphere, causing warming. In the second year, an additional metric ton enters the atmosphere, but the metric ton from the first year breaks down. As a result, there is still only one metric ton in the atmosphere and the concentration of the gas remains constant. Thus, no additional warming will occur. By the fourth year, no gas enters the atmosphere, and the metric ton from the third year breaks down. The atmosphere now has zero metric tons of the fictional gas. This reduction in atmospheric concentration returns radiative forcing to its value before year one.

Importantly, the predictions made by a pulse-based metric and the actual behavior of emissions will lead us to two different approaches to limit warming. For CO_2e emissions calculated using a pulse-based metric, we must stop emitting the gas to prevent further warming. In addition, we would need to remove carbon dioxide from the atmosphere to generate a cooling effect. Conversely, for our fictional short-lived gas, we merely need to keep the rate of emissions constant to prevent further warming. In fact, a decrease in emissions rate may induce cooling (Forster et al., 2021).

While the actual climate dynamics are much more complex, this simplified model highlights how pulse emissions of short- and long-lived gases inherently behave differently. Any emission metric, like GTP or GWP, that compares pulse emissions of short- and long-lived gases fails to represent these differing dynamics and is particularly susceptible to changing time horizons (Collins et al., 2020).

Looking Forward: Emerging Options for Metrics

In the last five years, scientists have attempted to address the shortcomings of pulse-based metrics. A step-change emission (i.e., a permanent change in the emission rate) of a short-lived gas closely resembles a pulse emission of carbon dioxide.

A new metric, **GWP***, measures radiative forcing—like GWP—but takes advantage of this resemblance. To calculate step-change emissions of short-lived gases, the metric uses pre-existing GWP values. GWP describes the effect of releasing one metric ton of a gas; by multiplying a GWP by its time horizon, the authors approximate a sustained increase of one metric ton per year. GWP* compares this value to a single pulse emission of carbon dioxide. Using GWPs to calculate the metric was a deliberate decision to make the new metric continuous with and applicable to current policy. However, GWP*'s dependency on GWP means that the metric is only an approximation. Regardless, because GWP* uses the step/pulse equivalence, it depends less on choice of time horizon (Allen et al., 2020).

Combined Global Temperature Change Potential (CGTP) relates an emissions step-change in a short-lived gas to a pulse of carbon dioxide without relying on GWP in its methodology. Instead, the metric directly compares the temperature change of a short-lived gas step-change emission to the temperature change of a carbon dioxide pulse. As a result, it is a more accurate measure of relative climate effects. However, the metric is in a unit of time because it compares a rate change to an absolute change. Like GWP*, CGTP relies less on choice of time horizon. As a result, it is useful for analyzing the impact of short-lived climate pollutants on long-term temperature outcomes (Collins et al., 2022).

To calculate the CO_2 pulse equivalent of a permanent reduction in a gas's emission rate, multiply the CGTP by that reduction. For example, HFC-134a has a CGTP-100 of 181,408 years (Collins et al., 2022). A permanent reduction of HFC-134a emissions by 1,000 metric tons per year would be equivalent to a one-time reduction of 181,408,000 metric tons of CO_2e.

Step-pulse metrics, like GWP* and CGTP, are not universally applicable. The metrics are geared towards short-lived gases; if a gas has a longer lifetime, a different metric is needed. In addition, if rate reductions of a gas are not permanent, step-pulse metrics overestimate their positive impact.

Even as new metrics are developed, their values still have significant uncertainty, and their methods have significant shortcomings. This variability may seem concerning: how are we supposed to know which gases to address and which actions to take if our methods of comparing them are not accurate or neutral? In climate projections, however, uncertainty is a certainty—in truth, the creation of any usable metrics to compare gases is a scientific achievement.

Selecting the Best Metric

At the beginning of this explainer, we asked if GWP-100 was the best emission metric for the world to use. Unfortunately, there is no "best" metric that is universally applicable. In the Sixth Assessment Report, the IPCC discusses the intricacies of several metrics but refrains from recommending any single one (Forster et al., 2021).

Summary of Emission Metrics

Metric	Definition	Pros	Cons
GWP-20	The amount of energy one ton of a gas absorbs in the atmosphere relative to carbon dioxide over a specific time period.	• Emphasizes the effect of short-lived gases • Less uncertainty than temperature metrics and GWP-100	• Less policy relevance than metrics that measure temperature • Does not estimate any effects after 20 years
GWP-100		• Accounts for long-term effects • Less uncertainty than temperature metrics	• Less policy relevance than metrics that measure temperature • Deemphasizes the effect of short-lived gases
GTP-100	The surface temperature change from one ton of a gas relative to carbon dioxide at the end of a specific time period.	• Greater policy relevance than measures of radiative forcing	• Only measures temperature change at one moment in time so can miss temperature peaks • More uncertainty than radiative forcing metrics
GWP*	The amount of energy a step-change emission of a gas absorbs in the atmosphere relative to a pulse emission of carbon dioxide over a specific time period.	• A more accurate representation of the environment because it compares a pulse of CO_2 to a step change of a short-lived gas • Designed to be easily implementable into current policy	• Relies on GWP values to calculate the effect of step emissions, making the metric less accurate than CGTP • Applicable only for short-lived gases - other metrics are needed for long-lived gases.
CGTP	The surface temperature change from a step-change emission of one gas relative to a pulse emission carbon dioxide at the end of a specific time period.	• A more accurate representation of the environment because it compares a pulse of CO_2 to a step change of a short-lived gas • Uses a formal definition to quantify the effect of a step change emission, improving on GWP* approximations • Compares temperature effects, making it useful for many climate goals	• Applicable only for short-lived gases - other metrics are needed for long-lived gases. • Only measures temperature change at one moment in time so can miss temperature peaks

***Figure** 7 summarizes the emission metrics discussed throughout this explainer.*

Selecting a emission metric from the many options explored in this explainer can feel daunting. To help guide your choice, you can use the following recommendations:

- **Choose the metric that best aligns with your research question or policy goal**. For example, if you are concerned about short term temperature change, you could choose to use GTP-20. On the other hand, if you want to investigate temperature effects in 2100, you may choose to use CGTP-75. One must be careful, however, to not select metrics to justify pre-established conclusions. Consider, for example, that you want to emphasize the relative effect of methane on the environment. It would be misleading to select GWP-20 to talk about the relative effect of methane over 500 years.

- **Be transparent** about which metrics you use and why you chose that metric. When sharing emissions data, try to use multiple metrics to calculate CO_2e emissions, rather than defaulting to GWP-100.
- In general, **be mindful of the strengths and deficiencies** of each metric. Choosing different metrics alters how we weigh the impacts of each greenhouse gas, influencing which mitigation strategies we select.

The reality is, we need emission metrics to confront the climate crisis. We need to be able to compare the relative impacts of gases to know where to direct resources. The most common metric will likely remain GWP-100, as the metric is entrenched in current policy. However, given the tradeoffs of different metrics, it is vital to maintain an open dialogue about the relative strengths and weaknesses of each metric and to be transparent about how metrics affect analyses. By understanding each metric, we can effectively use these tools to guide how we confront the climate crisis.

Species	Lifetime (Years)	Radiative Efficiency ($W\ m^{-2}\ ppb^{-1}$)	GWP-20	GWP-100	GWP-500	GTP-50	GTP-100	CGTP-50 (years)	CGTP-100 (years)
CO_2	Multiple	$1.33 \pm 0.16 \times 10^{-5}$	1.	1.000	1.000	1.000	1.000		
CH_4-fossil	11.8 ± 1.8	$5.7 \pm 1.4 \times 10^{-4}$	82.5 ± 25.8	29.8 ± 11	10.0 ± 3.8	13.2 ± 6.1	7.5 ± 2.9	2823 ± 1060	3531 ± 1385
CH_4-non fossil	11.8 ± 1.8	$5.7 \pm 1.4 \times 10^{-4}$	79.7 ± 25.8	27.0 ± 11	7.2 ± 3.8	10.4 ± 6.1	4.7 ± 2.9	2675 ± 1057	3228 ± 1364
N_2O	109 ± 10	$2.8 \pm 1.1 \times 10^{-3}$	273 ± 118	273 ± 130	130 ± 64	290 ± 140	233 ± 110		
HFC-32	5.4 ± 1.1	$1.1 \pm 0.2 \times 10^{-1}$	2693 ± 842	771 ± 292	220 ± 87	181 ± 83	142 ± 51	$78{,}175 \pm 29{,}402$	$92{,}888 \pm 36{,}534$
HFC-134a	14.0 ± 2.8	$1.67 \pm 0.32 \times 10^{-1}$	4144 ± 1160	1526 ± 577	436 ± 173	733 ± 410	306 ± 119	$146{,}670 \pm 53{,}318$	$181{,}408 \pm 71{,}365$
CFC-11	52.0 ± 10.4	$2.91 \pm 0.65 \times 10^{-1}$	8321 ± 2419	6226 ± 2297	2093 ± 865	6351 ± 2342	3536 ± 1511		
PFC-14	50,000	$9.89 \pm 0.19 \times 10^{-2}$	5301 ± 1395	7380 ± 2430	$10{,}587 \pm 3692$	7660 ± 2464	9055 ± 3128		

Figure 8 *is taken from the IPCC's Sixth Assessment Report (Forster et al., 2021). It shows several emission metrics for several greenhouse gases.*

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