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Distortion of sectoral roles in climate change threatens climate goals

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The longstanding method for reporting greenhouse gas emissions—carbon dioxide equivalence (CO₂e)—systematically underestimates methane-dominated economic sectors' contributions to warming in the coming decades. This is because it only calculates the warming impact of a pulse of emissions over a 100-year period. For short-lived climate forcers that mostly influence the climate for a decade or two, like methane, this method masks their near-term potency. Assessing the impacts of future greenhouse gas emissions using a simple climate model reveals that midcentury warming contributions of sectors dominated by methane—agriculture, fossil fuel production and distribution, and waste—are two times higher than estimated using CO₂e. The CO₂e method underemphasizes the importance of reducing emissions from these sectors, and risks misaligning emissions targets with desired temperature outcomes. It is essential to supplement CO₂e-derived insights with approaches that convey climate impacts of ongoing emissions over multiple timescales, and to never rely exclusively on CO₂e.

KEYWORDS

climate change, climate metrics, greenhouse gas emissions, climate modeling, methane, climate goals, climate policy, economic sectors

Introduction

Quantification of sectoral contributions to future warming is critical for guiding climate change mitigation priorities. However, the current method for evaluating the contributions of economic sectors to temperature increases is distorting their relative magnitudes. This distortion is most salient in the coming decades but persists for over a century. Given that sectoral emissions include a variety of greenhouse gases, aggregating their impacts without a climate model requires a metric for intercomparison. Sectoral contributions are almost always quantified using current annual greenhouse gas (GHG) emissions in carbon dioxide equivalence (CO₂e) which employs global warming potentials with a 100-year time horizon (GWP100). A long-term calculation from 1 year's emissions overlooks the near-term potency of short-lived climate forcers such as methane. This is problematic because several sectors are dominated by methane emissions and therefore their impacts (and thus sectoral share) in the near-term would be greater. While the time dependency of the calculation is therefore critical to the statistic, it is continually left out of reporting. The result is a simplified statistic (sectoral share) devoid of its more nuanced meaning (sectoral share over a particular period). In other words, it doesn't mean what people think it means.

Employing a climate model can more accurately convey the relative roles of economic sectors by considering impacts of multiple climate forcers with varying radiative potencies and atmospheric lifetimes over all timescales and accounting for ongoing emissions. In this perspective, we use a reduced-complexity climate model to show that GWP100/CO₂e vastly

undervalues methane-dominated sectors' contributions to mid-century warming for both “no further climate action” and “strong mitigation” scenarios. Further, we discuss the policy implications of the resulting distortion and offer recommendations to improve accuracy.

A more accurate representation of sectoral contributions

As our indicator of “true” temperature impacts from future sectoral greenhouse gas emissions, we use a reduced-complexity climate model (MAGICCv6) (Meinshausen et al., 2011). Though models are not without uncertainties (see [Supplementary material](#) for how uncertainties influence our analysis), they are more accurate than simplified metrics because they consider interacting chemistry and physics along with climate feedbacks and treat changing climate forcer emissions and resulting atmospheric concentrations with more sophistication.

We consider two global GHG emissions scenarios: a “no further climate action” reference pathway and a “strong mitigation” pathway designed to limit global mean temperature increase to 1.5°C (Keramidas et al., 2018) ([Supplementary Figure S1](#)). We use these two scenarios to investigate both the breakdown of global sectors' contributions to absolute warming, as well as their contributions to avoided warming from potential emissions reductions. The reason for this is to determine how standard metrics can influence the perception of sectors in not just contributing to the climate change problem, but in contributing to climate change solutions as well. For example, it is important that we not only understand the full extent in which different sectors cause warming, but also the full extent in which their mitigation can avoid warming. We evaluate the impacts of future emissions from 2021 to 2100 for the three major GHGs: carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O); we do not evaluate changes in hydrofluorocarbons (HFCs) because their current contributions to warming are relatively small and are already covered under a global phaseout agreement ([The Kigali Amendment, 2016](#)). Though sectoral emissions also include other warming and cooling climate forcers, as analyzed in [Unger et al. \(2010\)](#), we limit our focus to the main GHGs included in net-zero targets.

We categorize emissions into nine global economic sectors, three dominated by methane—agriculture; fossil fuel production & distribution (FFPD); and waste—and six dominated by CO₂—power generation; industry; transport; buildings; land-use, land-use change, and forests (LULUCF); and Other CO₂ (e.g., energy losses, transfers, etc.). For all sectors, the dominant gas accounts for more than two-thirds of emissions as weighted by GWP100 and a GWP with a shorter time horizon of 20 years (GWP20) ([Supplementary Figure S3](#)). We evaluate the global mean temperature responses to sectoral emissions through midcentury to convey near-term warming on policy-relevant timescales, as well as through the end of century to convey long-term warming and relevance for temperature targets.

For the “no further climate action” scenario, the climate model suggests that around half (53%) of additional warming in 2050 due to future GHG emissions, and slightly less than half (44%) in

2100, will be attributed to the three methane-dominated sectors ([Figure 1](#)). Methane sectors' contributions are substantial because methane is a potent gas with emissions expected to increase throughout most of the century in the absence of further action ([Ocko et al., 2021](#)). In fact, our analysis suggests that around 60% of warming over the next decade from future GHG emissions will come from methane-dominated sectors. Increases in methane emissions will continue to reinforce its near-term potency, even as the warming share of methane-dominated sectors decreases over time due to the accumulation of CO₂ in the atmosphere from the CO₂-dominated sectors.

The methane-dominated fossil fuel production and distribution (FFPD) and agriculture sectors, along with the CO₂-dominated power generation sector are the three largest contributors—amounting to 59% of warming in 2050 with no further climate action. This broadly aligns with previous findings that the highest contributing sectors in the near-term are energy sectors (including FFPD and power generation) and agriculture ([Lund et al., 2020](#)).

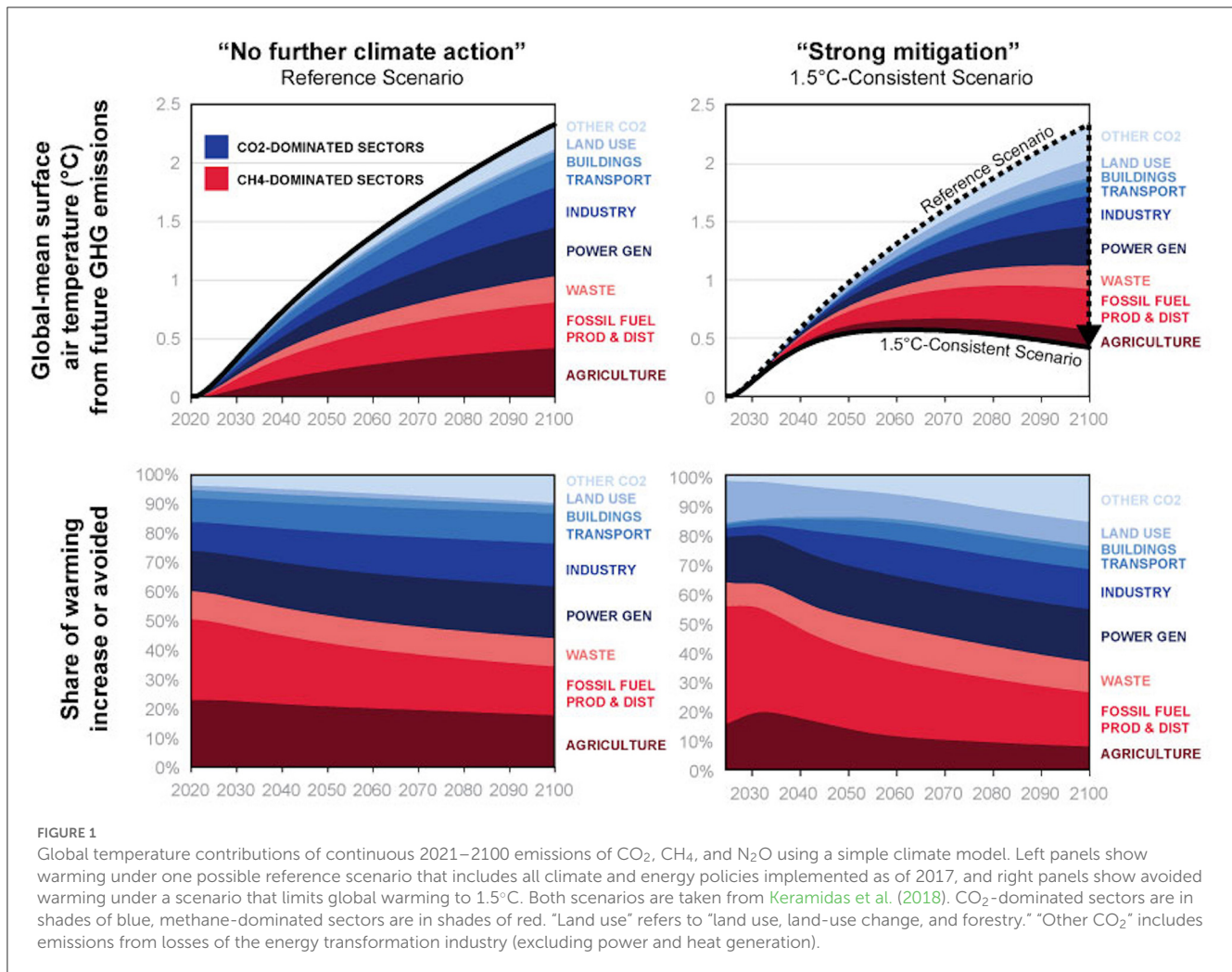
For the “strong mitigation” scenario consistent with a 1.5°C target, emissions reductions from methane-dominated sectors could contribute half (52%) of the total avoided warming by 2050 (avoided warming relative to absolute warming in the “no further climate action” scenario; note that this is different than the absolute warming analyzed under the reference scenario and thus not directly comparable), and at least a third (36%) of avoided warming in 2100 ([Figure 1](#)). While the modeled mitigation scenario in this paper is just one of many potential pathways to achieve 1.5°C, it illustrates the substantial impact that methane mitigation efforts can have on reducing near-term, as well as longer-term, warming.

Misleading metrics and a distorted climate problem

The metric almost always chosen to convert GHGs into their CO₂e is GWP: a measure of the relative potency (in terms of cumulative radiative forcing) of 1 year's (pulse) non-CO₂ emissions as compared to a pulse of CO₂ emissions over a specified time horizon. While the time horizon is an arbitrary choice, 100 years has become the standard. GWP100 is used in Nationally Determined Contributions (NDCs), corporate climate targets (Net Zero), state and company level emissions reporting (Greenhouse Gas Protocol)¹, and widely used emissions inventories such as WRI's Climate Watch platform, EPA's annual greenhouse gas inventory, and the European Commission's annual JRC GECO report.

Decades of literature have illustrated the shortcomings of GWP100 ([Lynch et al., 2021](#)) and a prominent issue is that it does not convey the near-term impacts of short-lived gases ([Balcombe et al., 2018](#)). This is significant because, of the two GHGs responsible for most of current warming—CO₂ and methane—CO₂ can last for centuries in the atmosphere whereas methane is a potent but short-lived gas that on average remains in the atmosphere for around a decade ([IPCC, 2021](#)). When GWP100 is used to convert methane emissions into CO₂e, the result is a skewed perception of methane's impact because the metric relies

¹ <https://ghgprotocol.org/>



on averaging the warming impact of a pulse of methane over multiple decades when the pulse has substantially decayed and is not considerably influencing the atmosphere. A continuing flow of methane will maintain a corresponding elevated atmospheric concentration, and warming impact; but again, this is not well reflected via GWP100.

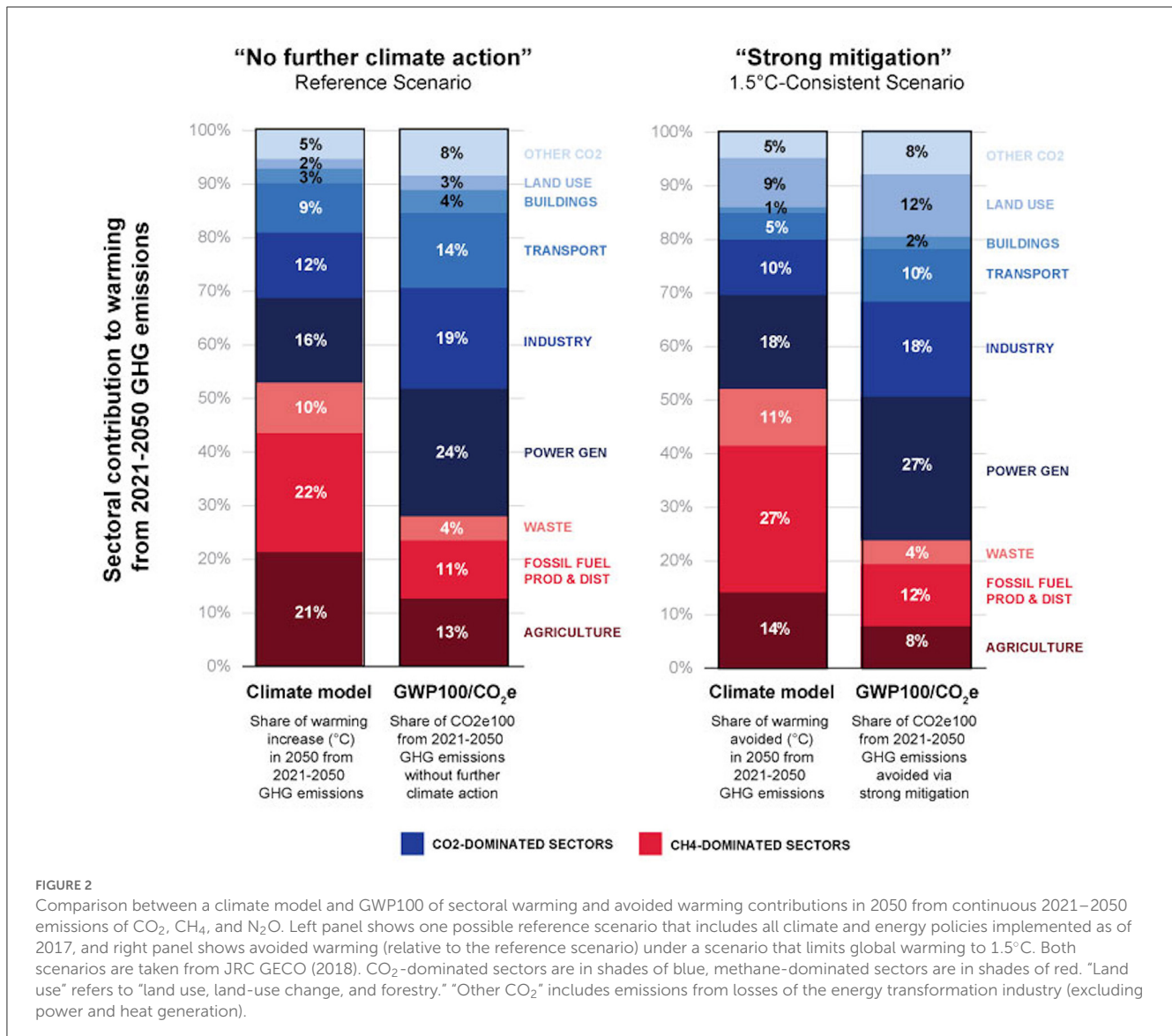
Our analysis illustrates the inadequacy of relying solely on GWP100. While the climate model makes it clear that methane-dominated sectors could account for around half of (1) warming from future GHG emissions in the absence of climate action and (2) avoided warming from a strong mitigation scenario, using the standard GWP100/CO₂e approach leads to vastly different results.

For example, cumulative CO₂e using GWP100 practically halves the role of methane-dominated sectors over the 2021–2050 period relative to the model results (53% model; 28% metric; [Figure 2](#)). While GWP100 performs better in the long-term, as the period from 2021 to 2100 more closely matches a 100-year time horizon, the results in 2100 over this time period are still distorted, with the methane-dominated sectors' role cut by around a third when using the metric relative to the model (44% model; 30% metric).

Similarly, GWP100 obscures the importance of emissions reductions from methane-dominated sectors—cutting their

avoided warming potential almost in half in 2050 (52% model; 24% metric) and by almost a third in 2100 (36% model; 22% metric). This yields a misrepresentation of the relative potentials of economic sectors to mitigate additional warming ([Figure 2](#)).

While alternative metrics for comparing GHGs with different lifetimes have been proposed (e.g., [Ocko et al., 2017](#)), there is no single simplified metric that can capture impacts over all timescales. Nevertheless, we test the accuracy of two other popular climate metrics: GWP20 and GWP* [a metric that evaluates the relative climate impact of a change in the emission rate of a short-lived climate pollutant compared to a pulse of CO₂ ([Cain et al., 2019](#))]. In 2050, both GWP20 and GWP* can provide sectoral shares that are consistent with the climate model ([Supplementary Figure S4](#)). In 2100, neither metric replicates the climate model as closely; GWP20 slightly overvalues the contributions of methane-dominated sectors and GWP* slightly overvalues the contributions of CO₂-dominated sectors ([Supplementary Figure S4](#)). However, both can perform better than GWP100 out to 2100. We also note that the specific distortion of methane's contributions assessed via cumulative GWP is highly dependent on the methane emissions pathway under consideration in addition to the chosen time horizon.



Climate decision making must adopt new standard practices

Given how GWP100-based CO₂e calculations distort the roles of economic sectors in contributing to future warming, relying solely on GWP100 can lead to suboptimal policies and priorities by misleading climate actors from the top levels of government (e.g., U.S. NDC)² to grassroots organizations. This is because the importance of methane emissions in several sectors is systematically underestimated by GWP100.

The prominent role of methane in climate change and its mitigation has been increasingly recognized (UNEP, 2021), culminating in the recent Global Methane Pledge. However, GWP100/CO₂e in isolation continues to be pervasive in climate policy, advocacy, and education. Yet there are examples of acknowledgment of the metric issue by stakeholders (such as

work by the Irish Climate Change Advisory Council to establish multi-gas GHG budgets, as well as the State of New York publishing their emissions inventory using GWP20). Given that prioritizing sectoral mitigation efforts is often necessary under cost and political constraints, the current sectoral share distortion imposed by GWP100/CO₂e risks mis-prioritizing sectors for emissions reductions, undervaluing the benefits of methane-sector mitigation—especially in the near-term—and potentially overlooking important abatement measures. This can have implications for the temperature outcomes of climate policies. For example, if CO₂-dominated sectors are regularly prioritized for mitigation, the realized temperature benefits in the near-term will be lower than anticipated because the remaining warming impact from methane-dominated sectors will be underestimated.

The bottom line is that GWP100 should never be singularly relied upon for emissions assessments. Fortunately, myriad alternative or supplemental metric strategies have been proposed.

² <https://unfccc.int/NDCRE>

These include dual-reporting of emissions using two metrics to capture both the near- and long-term climate impacts, (Ocko et al., 2017) separately indicating contributions of short- and long-lived pollutants to a total CO₂e target, (Allen et al., 2022) or defining metric time horizons according to global temperature goals (Abernethy and Jackson, 2022). While there is no “one-size-fits-all” metric for climate decision making (IPCC, 2021), this should not be a reason to always defer to the status quo. We urge the climate policy community to recognize the necessity for additional metrics or methods that can adequately convey the impacts of GHG emissions in both the near- and long-term. Furthermore, we recommend that:

1. All emissions accounting start by breaking down emissions by gas in units of mass. This is an essential practice for ensuring that the most appropriate evaluating method and time horizon can be used by making the underlying information available. Too often emissions are presented—whether for a company, a sector, or an entire country—only as a combined CO₂e. Without the breakdown by gas, it is impossible to convert the emissions to any other metric or input accurately into a model. The UNFCCC is a prime example of requiring emissions inventories to be broken down by gas, and we strongly recommend this practice be widely adopted.
 - a. We also recommend that this method of emissions accounting by gas be extended to emissions projections and commitments, such as those included in countries’ NDC targets.
2. Data tools, inventories, and reports allow users to see GHG emissions according to different metrics, side by side. This means reconfiguring the way we present sectoral emissions data to better account for varying sectoral contributions to warming over time. This would introduce a user-oriented decision-making process regarding which metric is most appropriate for the application at hand.
3. Emissions totals and percentage contributions that combine multiple greenhouse gases using a specific time-horizon in the aggregation should never be reported without explicitly stating the time-horizon of the climate metric used to calculate them. This would bring the time-dependency of the information to the forefront.

These new standard practices must become embedded across the climate science and policy communities if we want to secure the best chance at reducing emissions and mitigating the worst of climate change over all timescales.

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Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

IBO designed the study. NC-S carried out the experiments with help from TS. NC-S analyzed the results. IBO and NC-S prepared the visuals. All authors wrote the article. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fclim.2023.1163557/full#supplementary-material>

TABLE 1
Data Appendix; emissions data and GWP calculations.

DATA SHEET 1
Model Parameters; used to run MAGICCv6 in this study.

DATA SHEET 2
Supplementary Material; including supplemental figures, experiment descriptions, and tabular data.

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