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Abstract

Hydrofluorocarbons are a potent greenhouse gas, yet there remains a lack of quantitative estimates of their social and economic costs. The present study addresses this gap by directly calculating the social cost of hydrofluorocarbons (SC-HFCs) using perturbations of exogenous inputs to integrated assessment models. We first develop set of direct estimates of the SC-HFCs using methods currently adopted by the United States Government, and then derive updated estimates that incorporate recent advances in climate science and economics. We compare our estimates with commonly used approximations based on global warming potentials to show that using the latter is a poor proxy for direct calculation of hydrofluorocarbon emissions impacts using IAMs. Applying our SC-HFCs to current international agreements, we estimate they provide \$37 trillion (2020USD) in climate benefits over the lifetime of the agreement. Expediting the phasedown of hydrofluorocarbons could increase the estimated climate benefits to \$41 trillion (2020USD).

Keywords: Social Cost of Greenhouse Gases, Climate Policy, Hydrofluorocarbons

JEL Codes: Q51, Q54, Q58

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Main text

The most recent observations suggest that global average surface temperatures are already 1.1°C higher than pre-industrial levels (IPCC, 2021). Important adaptation strategies for humans include the widespread adoption of air conditioning and improved building insulation in residential and commercial buildings. These defensive mechanisms offer an indoor reprieve as high temperatures become more common and can help reduce the health consequences of global warming (Carleton et al., 2022; Cromar et al., 2022). Additionally, many mitigation strategies include reduced reliance on energy from fossil fuel sources. This includes the electrification of heating systems such as the widespread adoption of heat pumps to replace natural gas furnaces (Pistochini, 2022; Rosenow et al., 2022). However, each of these proposed strategies, air conditioning, insulating foams, and heat pump units, historically use hydrofluorocarbons (HFCs) in many of their applications.

HFCs are a class of industrial chemicals used primarily for refrigeration, air cooling and heating, insulating foams, and aerosol propellants. They were developed as replacements for the ozone-depleting substances (ODS) being phased out under the Montreal Protocol on Substances that Deplete the Ozone Layer. While HFCs are not ODS and do not contain ozone-depleting chlorine or bromine, they are nevertheless a potent greenhouse gas whose release into the atmosphere contributes to climate change (Montzka, S. A. et al., 2018; EPA, 2021). For example, HFC-134a, the most abundant HFC in the atmosphere, has an estimated global warming potential 1,530 times that of carbon dioxide over a 100-year period (IPCC, 2021). The rapid adoption of these highly potent greenhouse gases, accelerated in part due to the phase out of ODS in conjunction with the widespread adoption of air conditioning and improved building insulation, has the potential to substantially contribute to global warming (Velders et al, 2009). Experts forecast that global warming itself will exacerbate and accelerate this demand for cooling products around the globe, creating a dangerous feedback loop (Biardeau et al., 2020). The Scientific Assessment of Ozone Depletion (2018) reported that HFC emissions increased by 23 percent from 2012 to 2016 alone, and without policy intervention escalated growth is projected to continue, especially in developing countries (Velders et al, 2009).

In recognition of their potency as a greenhouse gas, the 1997 Kyoto Protocol under the 1992 United Nations Framework Convention on Climate Change (UNFCCC) included HFCs as a regulated substance. The Kyoto Protocol, however, only enforces limits on total greenhouse gas emissions—HFC emissions were not explicitly controlled until the adoption of the Kigali Amendment to the Montreal Protocol in 2016. It

provides specific targets for the phasedown of HFCs and is expected to avoid an increase in atmospheric temperature of 0.2-0.4 °C by 2100 (Purohit et al., 2022).

Having a means of quantifying the expected economic impact of regulatory efforts such as the Kigali Amendment is important for assessing the tradeoffs involved with their implementation. The U.S. Government (USG) publishes official estimates of the social cost of CO₂ (SC-CO₂), CH₄, (SC-CH₄), and N₂O (SC-N₂O), collectively known as the social cost of greenhouse gases (SC-GHGs), that are used to value changes in emissions of greenhouse gases in a benefit-cost framework (USG, 2021). The USG approach and associated SC-GHG estimates have been used by many other countries such as Germany, Canada, and Mexico to evaluate emission reduction policies.

Absent directly derived estimates from integrated assessment models, damages associated with the emissions of other gases often rely on approximations using the global warming potential (GWP) of the gas anchored to the SC-CO₂ (Sarofim and Giordano, 2018; Mallapragada and Mignone, 2020). This GWP-based methodology enjoys widespread use but has several limitations that can be addressed with direct estimation methodologies (Marten and Newbold, 2012). Despite the limitations of using GWPs, they remain a popular heuristic. Thus, it is important to understand how close these GWP-based methodologies come to replicating the values of SC-HFCs as calculated through direct estimation technologies.

The directly estimated social costs of hydrofluorocarbons (SC-HFCs) presented in this paper fill a major gap in the understanding of the economic harms caused by HFC emissions and an updated quantification of the benefits from their phasedown as dictated by international climate agreements. We develop a direct estimation methodology to calculate SC-HFCs for the suite of three models currently being used by the USG, as well as for a new open-source model, the Greenhouse Gas Impact Value Estimator (GIVE), and provide a comparison of each to simpler GWP-based methodologies. We then apply our SC-HFC estimates to the Kigali Amendment, calculating the expected climate benefits of an HFC phasedown under the currently proposed timeline, and under a more aggressive phasedown schedule. By supplementing these popular open-source models with the ability to calculate the social costs of a suite of HFCs, we enable a more concrete and more thorough exploration of the potential benefits and costs of climate strategies that include HFCs as part of the technology underlying their implementation.

Results

We calculate the SC-HFC for eleven HFCs in a probabilistic modeling setting, using a Monte Carlo approach with 10,000 simulations for each of the three IAMs underlying the USG methodology (DICE, PAGE, and FUND, jointly named MimiIWG) and the updated GIVE model (MimiGIVE) (Extended Data Table 1). Each simulation of the model draws from the set of random parameters underlying each model and performs a baseline estimation of damages and then, using those same sets of random parameters, repeats the estimation with the additional tonne of HFC in each emissions year. Undiscounted streams of marginal damages are discounted back to the year of emissions at the specified discount rate.

The estimated SC-HFCs for an emissions pulse in 2023 from the USG model range between 24-64% lower than the updated estimates under the GIVE model (Fig. 1, Extended Data Table 1). For example, HFC-134a which is the most prevalent HFC in the atmosphere, is estimated at \$128,000 per tonne (2020 USD) under MimiGIVE and just \$87,000 per tonne (2020 USD) under MimiIWG, a 47% increase with a model that incorporates more recent scientific advances. GIVE also provides a much smoother and more realistic SF-HFC path due to its annual timestep. In contrast, the USG models used HFC gas cycle models that used timesteps ranging from one to one-hundred years. Long timesteps can pose issues for accurate calculation of climate benefits in non-timestep years due to interpolation assumptions needed to obtain annual social cost estimates, which may be particularly inaccurate for short-lived gases such as HFCs. MimiGIVE's upward shift in the SC-HFC estimates as compared to the MimiIWG three-model average (Fig. 1) stems from advances in the climate system representation, more accurate characterizations of damage pathways, probabilistic socioeconomic projections, and improvements in the discounting module and its adoption of growth-consistent Ramsey parameters. Each of these factors contributes to the differences between the two sets of SC-HFCs.

For example, the resulting global mean surface temperature anomaly is noticeably different under MimiIWG and the MimiGIVE methodologies (Fig. 2). By comparison, the radiative forcing responses hardly differ (Extended Data Fig. 1). This indicates a model difference in how radiative forcing perturbations translate to temperature anomalies. The impulse responses under MimiGIVE occur much faster, peak at higher levels, and decay more quickly than they do under MimiIWG (Fig. 2). Recent literature on CO₂ emissions impulse responses emphasizes the importance of accurately modeling the amount of time it takes for temperature pulse responses to peak (Ricke and Caldeira, 2014). We expect this importance to similarly hold for short-lived, high potency GHGs such as HFCs. The climate models underlying MimiIWG (native to DICE, PAGE, and FUND) fail to capture the sudden near-term response and expedited decay from HFC emissions relative to the simple climate model underlying MimiGIVE. This behavior is consistent

with findings by Dietz et al. (2020), who show that climate science models respond much more quickly to a CO₂ emissions impulse than those underlying IAM climate models, with temperature anomalies peaking around 10 years after the emissions impulse in climate science models compared to after 55 years in DICE2013, 67 years in PAGE, and 128 years in FUND.

When using IAMs to calculate the social costs of GHGs it is imperative that the warming response to a change in radiative forcing is consistent with current scientific understanding as reflected in newer climate models such as that in MimiGIVE (NASEM, 2017). Since the stream of damages resulting from an extra tonne of emissions and their discounting are time-dependent, accurate representations of temperature dynamics greatly improves estimates of the SC-HFCs. Indeed, failing to capture short-term temperature responses could have a significant impact on the evaluation of welfare effects from emissions reductions, underestimating the near-term benefits of abatement.

A comparison to global warming potential damage approximations.

Past attempts to quantify the impact of HFC and other non-CO₂ gas emissions most frequently involved the consideration of GWPs (Mallapragada and Mignone, 2020). The GWP is a measure of how much energy the emissions of one tonne of a gas will absorb over a given period, relative to the emissions of one tonne of CO₂ (US EPA, 2023). GWP-based damage approximations simply multiply the GWP of a greenhouse gas by the SC-CO₂ for a chosen discount rate and year. Research shows that GWP values calculated using a time period of 100 years (GWP100s) are most consistent with a discount rate of 3 percent, while those derived from a time period of 20 years (GWP20s) align best with a discount rate of 7 percent (Sarofim et al., 2017). While simple to apply, the GWP has been subject to a variety of criticisms such as their applicability in benefits-cost analyses (Marten and Newbold, 2012), their sensitivity to the time horizon and discount rate (Mallapragada and Mignone, 2020), and the imperfect relationship between forcing and damages (Schmalensee, 1993; Shine et al., 2005). Due to their simplicity, GWPs remain a popular way to approximate SC-HFCs for use in policy analysis. Their prevalence in policy discussions makes it important to understand the differences between these GWP-based values of SC-HFCs and those calculated through the direct estimation method.

We calculate the GWP-based damage approximations for each of the eleven gases by multiplying each one's GWP100, a time-invariant scalar, with the SC-CO₂ from each model. We then compare these estimates with those directly derived in the IAMs estimates by calculating the ratio of GWP-based estimates to the direct SC-HFC estimate. A ratio greater than 1 indicates GWP-based estimates

overestimate the social costs relative to the direct estimates, while ratios less than 1 indicate that GWP-based estimates *underestimate* the social costs relative to the direct estimates (Extended Data Fig. 2).

While the ratios between these quantities vary by HFC species and emissions year, the patterns generally suggest that GWP-based estimates using the MimiIWG methodology underestimate the social costs of HFCs when compared to the direct-estimation method (ie. ratios are less than 1), while estimates with the MimiGIVE methodology overestimate the social costs. (ie. ratios are greater than 1). For example, comparing the 2030 SC-HFCs we find that MimiIWG underestimates by 10-38% while MimiGIVE overestimates by 17-101%. The two direct-estimation methodologies differ in underlying carbon cycles, exogenous emissions scenarios, discounting approaches, and damage representations, all of which have an impact on the relationship between the directly calculated relationship between SC-CO₂ and the SC-HFCs (Marten and Newbold, 2012; Mallapragada and Mignone, 2020). Our findings highlight the importance of carefully pairing the time-dependent nature of radiative forcings, resulting temperature anomalies, damages, and discounting to capture the social costs of greenhouse gas emissions more accurately.

The total climate benefits from phasedown of hydrofluorocarbons.

Whilst a full phase-out of HFCs may be difficult to realize in the short-term, the existence of HFC substitutes (such as HFOs) and low-GWP refrigerants (such as ammonia and CO₂) may enable a more aggressive and accelerated phasedown schedule than that outlined under Kigali (Extended Data Fig. 3). To assess the additional gains from following a more ambitious timeline, we estimate climate benefits under a maximum technologically feasible reduction (MTFR) schedule (Purohit et al. 2020), which would entail a full phaseout of HFCs by 2035 (Extended Data Fig. 4).

We estimate the total climate benefits under the Kigali phasedown schedule and expedited Maximum Technologically Feasible Reduction (MTFR) phasedown schedule using results from both our modified MimiIWG and MimiGIVE models (Fig. 3). Climate benefits from the as-published Kigali Amendment range from \$16.15 trillion (2020USD) using the SC-HFCs from the MimiIWG framework, to \$37.12 trillion (2020USD) using the MimiGIVE SC-HFC estimates. This is an increase of approximately 130% when using GIVE relative to the USG modelling framework (Fig. 3, Panel A). Under MFTR phasedown schedule, total climate benefits range from \$18.09 trillion (2020USD) using the SC-HFCs from the MimiIWG framework, to \$41.17 trillion (2020USD) using the MimiGIVE SC-HFC estimates (Fig. 3, Panel B). Under both modeling

frameworks, we estimate an additional 10% in climate benefits from adopting a more aggressive global phasedown schedule.

Discussion

The methods we develop in this study continue to advance our understanding of the tradeoffs that confront policy makers in the face of a rapidly changing climate. As temperatures continue to increase, air conditioning and insulation offer important adaptation pathways to temperature-related morbidity and mortality. However, employing adaptation technologies that are also powered by fossil fuels risks coupling this adaptation pathway with an increase in fossil fuel emissions—potentially exacerbating of climate change. The efficiency of heat pumps relative to other heating sources, and the prospect of running them with electricity from a decarbonized grid, provides a strong rationale for their deployment in the transition to a net-zero economy. As such, heat pumps are often central to ongoing discussions around mitigation pathways and decarbonization and electrification of indoor home and commercial space heating and cooling. Unfortunately, these adaptation and mitigation mechanisms themselves remain reliant on potent greenhouse gases, hydrofluorocarbons, as inputs to their production.

In this paper, we develop new estimates of the social costs of these greenhouse gases to better inform benefit-cost analyses that address their use. Our integration of these gases into four widely used and fully open-source IAMs (DICE, FUND, PAGE, and GIVE) provides a more comprehensive and transparent approach to evaluate their relationship with climate change and resulting external economic costs. Using our direct estimates of the SC-HFCs, we show that the climate benefits of existing global agreements are large and expediting the transition to less potent more climate-aware alternatives could provide trillions of dollars in additional climate benefits.

Main Display Elements

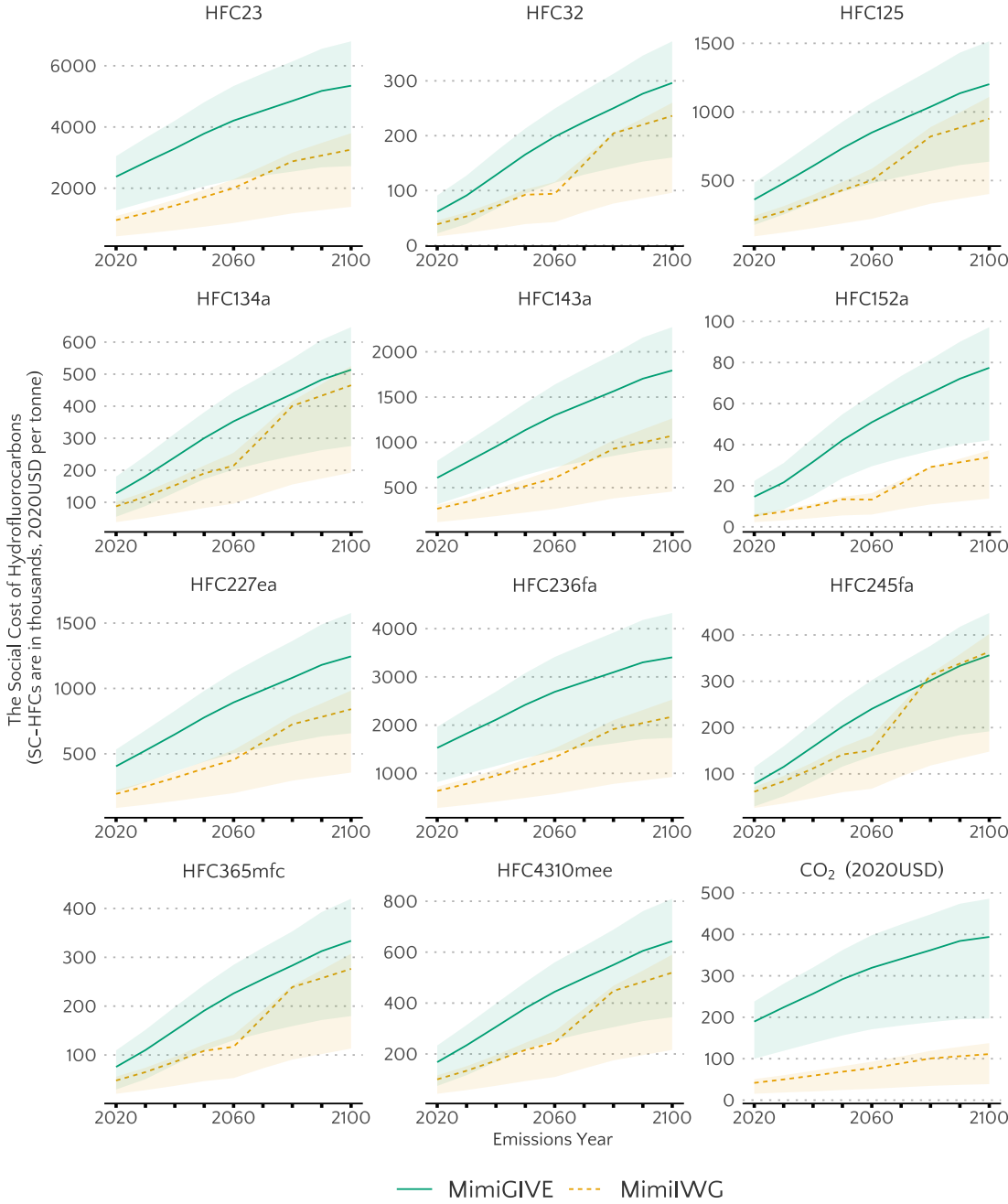


Fig. 1 | The Social Cost of Hydrofluorocarbons. The direct estimates developed in this study are noticeably different under the USG approach (MimiIWG) compared to the updated GIVE model (MimiGIVE). The mean SC-HFCs (lines) along with their 5th to 95th percentile ranges are shown, representing the distribution of estimated SC-HFC values over the 10,000 Monte Carlo simulations. The SC-HFCs from MimiIWG adopt a 3 percent constant discount rate, the USG’s central value, while MimiGIVE adopts a calibrated Ramsey-like framework with a near-term target discount rate of 2 percent, the central value in Rennert et al. (2022b). While it is true that much of the difference stems from advances in the discounting module and adoption of growth-consistent Ramsey parameters, advances in the climate system representation, transparent damage pathways, and socioeconomic projections are equally important updates (Rennert et al. 2022a,b).

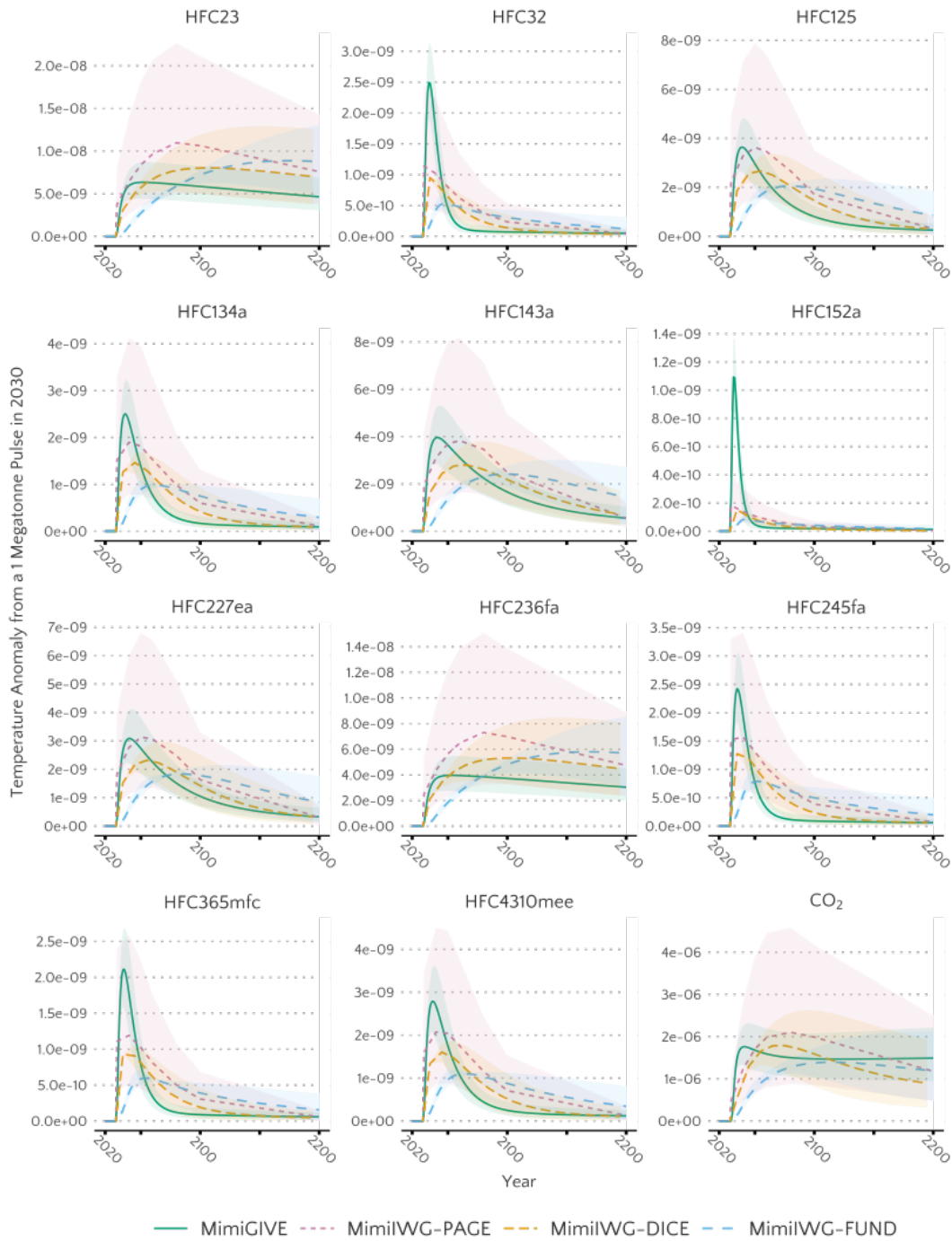


Fig. 2 | Global surface temperature anomaly from one tonne of hydrofluorocarbon gas. The climate representations underlying DICE, PAGE, and FUND fail to capture the sudden near-term response and expedited decay from HFC emissions relative to the simple climate model underlying MimiGIVE (FaIR1.6.2). The mean (lines) and 5th to 95th percentile ranges are shown representing the distribution of estimated temperature anomaly values over the 10,000 Monte Carlo simulations.

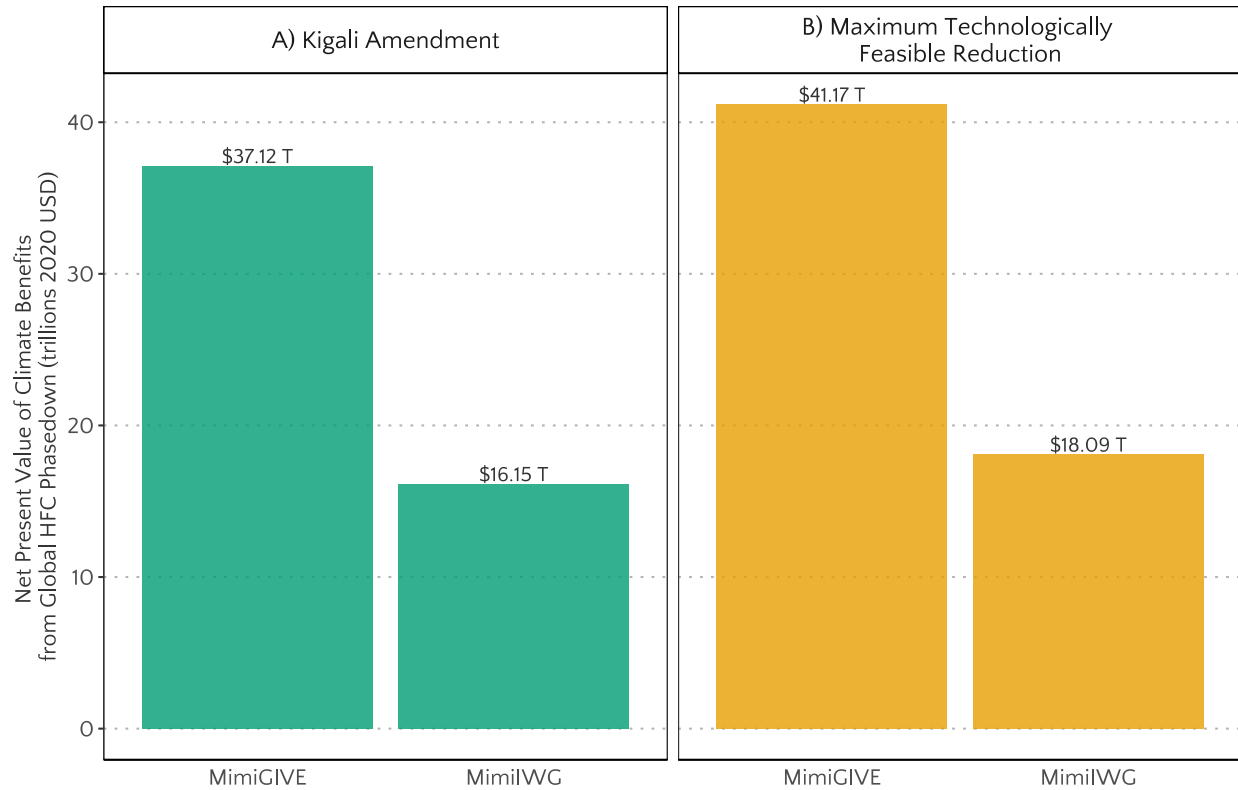


Fig. 3 | The total climate benefits from phasedown of hydrofluorocarbons. Total climate benefits under each phasedown schedule are discounted to a base year of 2023, realized relative to a baseline without the Kigali Amendment. MimiGIVE estimates are calculated assuming a calibrated Ramsey-like discount rate using a near-term target of 2 percent; MimiIWG assumes a 3 percent constant discount rate. Climate benefits range from \$16.15 trillion using the SC-HFC estimates under the as-published Kigali Amendment phasedown schedule and outdated USG methodology (Panel A), to \$41.17 trillion under the maximum technologically feasible reduction and accounting for updated methodologies (Panel B).

Methods

Estimation using the current USG methodology.

Beginning in 2010, the U.S Government (USG) adopted three primary integrated assessment models (IAMs) to estimate its social costs of greenhouse gases. The first IAM, and perhaps the most-commonly used in the literature for its simplicity and transparent design, is the Dynamic Integrated Climate Economy (DICE; Nordhaus and Boyer, 2000; Nordhaus, 2008). Dr. William Nordhaus created DICE in 1990 and the numerous revised versions exist today. The USG used version DICE2010 for the 2021 SC-GHG estimates, although the latest version at time of publication is DICE2016R2. DICE is a single-region globally aggregated model that approaches the economics of climate change from the perspective of neoclassical economic growth theory (Nordhaus 2017). DICE extends the neoclassical approach by including the “natural capital” of the climate system as an additional form of capital, whereby investments in emissions reduction reduce consumption today but prevent future economic harm from climate change. The DICE2010 model runs in five-year timesteps from 2005 to 2595. The climate system modelled by DICE is highly simplified, and only explicitly represents one greenhouse gas – CO₂. A single exogenous radiative forcing projection captures the impact of all other greenhouse gases. It is to this exogenous radiative forcing vector that we add the additional radiative forcings.

The second IAM used in the USG methodology is the Climate Framework for Uncertainty, Negotiation, and Distribution model (FUND; Tol 2002a, Tol 2002b, Anthoff et al. 2009). Dr. Richard Tol originally developed FUND in the early 1990s, and the USG used version FUND 3.8 (2014) for the 2021 SC-GHG estimates. FUND links simple models of population, technology, economics, emissions, atmospheric chemistry, climate, and sea level to determine impacts under various scenarios. FUND defines 16 distinct regions and runs in one-year timesteps from 1950 to 2300. In addition to CO₂, the FUND model explicitly represents emissions of CH₄, N₂O, and SF₆. HFCs, however, are not explicitly modelled. Therefore, we add estimates of HFC radiative forcing directly to the component of FUND that aggregates radiative forcing from each greenhouse gas.

The third IAM used is the Policy Analysis of the Greenhouse Effect model (PAGE; Hope et al. 1993, Hope 2006, Hope 2008). Dr. Chris Hope originally developed the PAGE model in 1991. PAGE projects future increases in global mean temperature, the economic costs of damages caused by climate change, costs of mitigation policies, and impact of adaptation measures. PAGE has an irregular timestep (years are 2000, 2001, 2002, 2010, 2200, 2040, 2060, 2080, 2100, 2150, 2200), and is globally aggregated across 8 regions.

The USG used version PAGE 2002 for its SC-GHG estimates, which includes an atmospheric model for CH₄ and SF₆ alongside its representation of CO₂. A single exogenous radiative forcing projection captures all other greenhouse gases. We add estimates of the additional radiative forcing from HFC emissions to this radiative forcing projection.

The SC-GHG estimates for CO₂, CH₄, and N₂O published by the USG use these three widely cited integrated assessment models (DICE, PAGE, and FUND). The USG modified these models to run using a common set of input assumptions for future population, economic, and emissions growth based on five scenarios developed under the Stanford Energy Modeling Forum (EMF-22) (Clarke et al. 2009, Fawcett et al., 2009). The USG also adopted a distribution for the equilibrium climate sensitivity (ECS) parameter—the Roe and Baker distribution (USG, 2010).

In 2016, the USG extended their estimation of the SC-CO₂ to include simple representations of CH₄ and N₂O (Marten et al., 2015). To date, none of the three IAMs have been extended to explicitly consider HFCs. Direct estimation of the SC-HFCs under the USG framework is feasible using an approach similar to that used by Marten et al. (2015) for CH₄ and N₂O. The study circumvents the need for explicit representation of CH₄ and N₂O in the IAMs by directly perturbing the model's exogenous radiative forcing projections with additional forcing vectors from an additional tonne of the non-CO₂ gases. From this, one can easily calculate streams of marginal damages associated with the additional perturbation of emissions and, hence, recover the social cost of each gas.

We extend this direct estimation approach to HFCs by using a one-box gas cycle model to calculate HFC atmospheric concentrations and estimate the resulting paths of additional radiative forcing under the assumption that forcing from atmospheric concentrations of HFCs is proportional to its concentration. Because the background level of HFCs existing in the atmosphere is relatively low, it is not necessary to explicitly represent the HFCs with EMF-22 scenario-consistent baseline emissions projections.

The paths of additional radiative forcing from hydrofluorocarbon emissions underlying the current USG methodology.

To calculate marginal radiative forcing contributions for a gas, one would ordinarily require a projection of baseline emissions. This baseline emissions projection is needed to calculate both the gas' baseline radiative forcing contribution, as well as account for potentially non-linear effects of an emission perturbation on radiative forcing due to interaction with pre-existing, background emissions.

The need for a baseline emissions projection, however, poses an issue for the calculation of USG-consistent SC-HFC estimates, as the SC-GHG estimates for CO₂, CH₄, and N₂O rely on EMF-22 emissions projections. The five EMF-22 scenarios used by the USG for these SC-GHG estimates, however, do not explicitly model HFCs. While other emissions projections exist for HFCs, use of these alternate emissions paths would cause inconsistency between the assumptions driving HFC emissions, and emissions of gases already present in the models. For example, the International Institute for Applied Systems Analysis' Greenhouse gas – Air pollution Interactions and Synergies model (IIASA GAINS) has been used to estimate additional short and long-lived climate forcings (Heyes et al. 2011, Purohit and Hoglund-Isaksson 2016, Wagner et al., 2013). This paper exploits the fact that baseline emissions of HFCs are relatively low (when compared to the total atmospheric concentrations of all other GHGs) to circumvent the need for these projections. At low levels of HFC atmospheric concentrations, the interaction effect between marginal emissions of HFCs and these background concentrations becomes negligible, and hence the effect of marginal HFC emissions on radiative forcing can be assumed to be linear (Myhre et al, 2013).

Given the independence of marginal radiative forcing contribution from baseline emissions, one can directly "shock" the models' exogenous radiative forcing projections with an estimate of the additional radiative forcing associated with a one tonne perturbation of a given HFC in a particular year. To compute this change in radiative forcing, one must first model the change in atmospheric concentration associated with the increase in gas emissions. The change in radiative forcing can then be calculated from this change in atmospheric concentration.

In this paper we utilize a "one-box" gas cycle model to calculate HFC atmospheric concentrations, assuming one representative sink with a constant decay rate. For a pulse of HFC emissions E in year $t = 0$, the concentration remaining in the atmosphere at time $C(t)$ is

$$C(t) = E \times e^{-rt} \tag{1}$$

where r is the rate of decay. $C(t)$ is in volume (parts per billion, or ppb) and not mass (tons), and therefore E also needs to be adjusted. In the case of a 1 megaton (Mt) pulse, E then represents the mass to volume conversion for Mt to ppb. This equation assumes that atmospheric concentrations of the HFC decay towards their background levels at an exponential rate.

After calculating atmospheric concentrations of each HFC, we calculate additional radiative forcing by assuming that forcing from atmospheric concentrations of HFCs is proportional to its concentration. In other words, we assume that each additional molecule of HFC in the atmosphere reflects an equal amount

of radiation back to the Earth as the previous molecule. Since the wave bands covered by HFCs are not very saturated, climate scientists believe this to be a reasonable assumption (Myhre et al, 2013). Therefore, additional radiative forcing in year t , $RF(t)$ from the pulse of HFC emissions can be calculated as

$$RF(t) = X \times C(t) \quad (2)$$

where X is the radiative efficiency of the HFC. The radiative efficiency values for each HFC are recovered from the Fourth Assessment Report (Pichauri and Reisinger 2007) (Extended Data Table 3). We also present updated values from the Sixth Assessment Report (AR6) as a comparison. The values from AR4 were selected for estimation in this paper to maintain consistency with the methods used by the USG to estimate the SC-CO₂, SC-CH₄, and SC-N₂O.

Applying formula (2) to each HFC, over a time horizon of 300 years, yield eleven different marginal radiative forcing projections (Extended Data Fig. 1). We observe a high level of consistency between the MimiWG and MimiGIVE models, the two modeling approaches showing nearly identical radiative forcing responses to a pulse of an HFC. It is important to note that these radiative forcing projections are independent of start year—i.e., the magnitude of the additional marginal radiative forcing estimate in the first year after the HFC emissions pulse is the same regardless of whether the original emissions pulse occurs in 2020, or 2050, for example. This is, again, due to the assumption that the background atmospheric concentrations of HFCs are negligible and, thus, the impact of marginal HFC emissions on radiative forcing can be assumed linear and independent of pulse year.

Calculating the SC-HFCs using the current USG methodology.

To calculate the social cost of a greenhouse gas, one must quantify the marginal economic impact of an additional pulse of emissions of that gas in an emissions year. This involves first calculating a baseline level of economic damages from greenhouse gas emissions, then re-running the models with an emissions perturbation to calculate the perturbed level of economic damages. Marginal damages are calculated as the difference between the baseline and perturbed levels of damages; the present value of these marginal damages gives the SC-GHG estimate for the emissions year. All three IAMs (DICE, FUND, and PAGE) in their original forms have the functionality to calculate SC-CO₂ estimates using this method.

However, given that the models do not include explicit representations of HFCs, one cannot perturb HFC emissions in this manner to calculate marginal damages. Instead, we utilize the following methodology to calculate the SC-HFC:

1. Estimate the model under baseline emissions scenario to calculate baseline damages.
2. Add marginal radiative forcing for HFC of interest (Extended Data Fig. 1) to the model's exogenous radiative forcing projection in the emissions year. For PAGE and DICE, which have non-annual timesteps, the average radiative forcing over each timestep was used.
3. Re-estimate the model to compute damages in the perturbed scenario.
4. Compute the SC-HFC as the present value of the difference in damages estimated in steps 1-3.

The marginal radiative forcing vector used to shock each model is calculated as an annual projection. DICE and PAGE, however, both have non-annual timesteps. To reconcile this discrepancy, we followed the same methodology used by the USG for their SC-CH₄ and SC-N₂O estimates. That is, we take the average radiative forcing over each timestep. While we recognize that using the simple average in each model's timestep may fail to fully capture the additional radiative forcing if the average radiative forcing over the timestep is not representative of the actual path of radiative forcing over that same time period, we maintained this assumption for consistency with the USG methodology.

Estimation using the Gas Impact Value Estimator (GIVE).

Whilst previous direct estimates of SC-GHGs developed by the USG and others offer numerous improvements over the GWP-based damage approximations, the modeling underlying those estimates does not incorporate subsequent advancements in climate science and economics. In 2017, the National Academies of Sciences, Engineering, and Medicine (NASEM) provided a series of recommendations for updating the SC-GHGs, including improvements to the socioeconomic projections, climate models, damage functions, and discounting methods utilized by the estimation process (NASEM, 2017).

The Greenhouse Gas Impact Value Estimator (GIVE) is an open-source integrated assessment model published in 2022 that incorporates recent advancements in climate science and economics to provide estimates of the social cost of greenhouse gases that are reflective of the current state of research in the area and largely address the module-specific, near-term suggestions put forth by a 2017 NASEM report (Rennert et al. 2022a,b). Each individual component in GIVE is based on peer-reviewed research on socioeconomic projections, climate modelling, climate impact assessments, and economic discounting. Rennert et al. (2022b) present updated estimates for the SC-CO₂ using the GIVE model, finding that the SC-CO₂ suggested by GIVE is 3.6x that of the current USG estimate (2020 USD, 2 percent near-term discount rate). The GIVE model in its current released form is also able to directly estimate SC-CH₄ and SC-N₂O, results for which are presented in the RFF Social Cost of Carbon Explorer (Prest et al., 2022). Most

recently, the U.S. Environmental Protection Agency (EPA) introduced an updated approach to estimating SC-GHGs that includes the GIVE model as one proposed line of evidence (EPA, 2022).

The 2017 NASEM report recommended that calculations of the SC-CO₂ leverage one of the available scientifically updated simple earth system models to represent the relationship between greenhouse gas emissions and average global surface temperature. Accordingly, GIVE uses the Finite Amplitude Impulse Response (FaIR) simple climate model, which includes simple models of CO₂, CH₄, and N₂O cycles and, most relevantly to this work, uses a one-box model method to represent cycles for numerous additional greenhouse gases including several species of HFCs (Smith et al., 2018; Smith et al., 2021; Forster et al., 2021). This enables the direct estimation of the SC-HFCs by perturbing the emissions forcings of each gas individually and observing the marginal effects as described in further detail in the Methods section.

Calculating the SC-HFCs using the modified GIVE model.

Methods to calculate the social cost of HFCs using the GIVE model closely follow those used in current USG methodologies as described in the previous section, with the important difference being that the FaIR climate system model does explicitly represent other greenhouse gases and climate forcings, including many species of HFCs, thus one can directly perturb emissions trajectories of those gases. Modifications to the underlying models were therefore minor.

The GIVE model employs FaIR version 1.6.2 (Millar et al. 2017) as used in the recent IPCC AR6 (IPCC, 2021) and by default uses the SSP2-4.5 scenario (Meinshausen, et al. 2020) for HFC forcings. Gas species data including lifetime, radiative efficiency, and other values needed to parameterize the one-box models were already included in the model data for all HFC species of interest. In addition, emissions of all but three HFC species of interest were explicitly included in the IPCC AR6 modeling effort, so the only addition necessary was to add baseline emissions paths for the missing three HFC species (HFC152a, HFC236fa, and HFC365mfc) to enable direct perturbation of the path. We obtain these paths from the RCMIP emissions protocol used to force the Leach et al. (2021) FaIR publication modeling. For consistency we use the SSP2-4.5 scenario for all HFCs. After this augmentation, the following steps were taken to enable estimation of the SC-HFC:

1. Estimate the model under baseline emissions scenario to calculate baseline damages.
2. Add marginal emissions forcing for HFC of interest to the model's emissions forcing projection in the year of the emissions, which in turn effects radiative forcing (Extended Data Fig. 1).
3. Re-estimate the model to compute damages in the perturbed scenario.

4. Compute the SC-HFC as the present value of the difference in damages estimated in steps 1-3.

The Mimi.jl integrated assessment framework.

A team of researchers at UC Berkeley, in connection with Resource for the Future's Social Cost of Carbon Initiative, developed the Modular Integrated Modeling Interface (*Mimi*) in response to the need for a common computing platform for IAMs that would ease barriers to entry for researchers and policy-makers, seeking to promote collaboration and novel research. Additionally, one of the key conclusions of the 2017 National Academies of Sciences report was that the development of an integrated, modular approach for modelling SC-GHGs would increase the transparency of the process and provide a mechanism through which the models can be updated more regularly with new scientific evidence and expert opinion (NASEM, 2017).

Mimi is a Julia package that provides a component model for IAMs, allowing them to be run using the same platform with a common programming language (Julia). For this analysis, we work within the *Mimi* versions of DICE, PAGE, and FUND that were converted from their original forms (in GAMS, Excel, and Python, respectively) into the Mimi Framework. The models are available for public download from the Mimi model registry and can be run under their default specifications as individual packages (DICE2010, FUND, PAGE09). For this analysis, we utilized a modified package that incorporated changes to make the models consistent with USG assumptions around timestep, socioeconomic scenarios, and parameter distributions. In addition, we work with the *Mimi* implementation of the GIVE model, which was originally constructed on the platform and is also publicly available.

Approximating social costs using global warming potentials.

To approximate the social cost of an HFC based on the global warming potential of the gas, we multiply the directly calculated SC-CO₂ by the global warming potential of each HFC (Extended Data Table 2) such that

$$ratio = \frac{SCCO_2 \times GWP_{HFC}}{SCHFC} .$$

Ratios closer to 1 indicate closer alignment between GWP-based estimates and direct estimates of each SC-HFC, while ratios less than 1 indicate that GWP-based methods underestimate the social costs relative to the direct estimates and, inversely, ratios larger than 1 indicate that GWP-based methods overestimate the social costs relative to the direct estimates. This equation provides the ratios displayed in Extended Data Fig. 2. The most-cited GWPs are given for 100-year time periods (GWP100), although alternative time

scales (e.g., 20 years) are also sometimes used. For this exercise we use the GWP100 as published in the Fourth Assessment Report (AR4) as listed in Extended Data Table 1. While slightly updated GWPs have been published under both the Fifth (AR5) and Sixth (AR6) Assessment Reports, we use AR4 values in this paper to maintain consistency with the USG's approach to estimating the social costs of non-CO₂ gases and the use of AR4 GWP100 in the passing of the American Innovation and Manufacturing Act (2021). The results of the ratio exercise are qualitatively very similar when using values from AR5 and AR6.

The Kigali Amendment.

The Kigali Amendment to the Montreal Protocol represents the first internationally coordinated effort towards global reductions in HFC production and consumption; to date it has been ratified by 146 countries (UN, 2016). The Kigali Amendment to the Montreal Protocol (KA) was signed on October 15, 2016, at the 28th Meeting of the Parties in Kigali, Rwanda, and extended the Montreal Protocol to address the phasedown of HFC consumption and production (Clark and Wagner, 2016). The agreement went into force on 1 January 2019. It wasn't until October of 2021 that the United States implemented a phasedown schedule for HFCs consistent with the Kigali Amendment. This was done under the American Innovation and Manufacturing Act and satisfies the Kigali Amendment without explicit ratification. The Kigali Amendment provides specific targets for the phasedown of HFCs by ratifying countries and is expected to avoid an increase in atmospheric temperature of about 0.2-0.4°C by the end of the century (UNIDO, 2017; Purohit, 2022). This is an important component for meeting the Paris Agreement goal of limiting global warming to below 2°C, although some argue that the phasedown schedule proposed by the Kigali Amendment is not aggressive enough in its speed or scale for reducing HFC emissions (Purohit et al., 2020; Purohit et al., 2022).

The phasedown schedule of hydrofluorocarbons under the Kigali Amendment and its climate benefits.

The HFCs controlled under the Kigali Agreement include HFC-23, HFC-32, HFC-125, HFC-134a, HFC-143a, HFC-152a, HFC-227ea, HFC-236fa, HFC-245fa, HFC-365mfc, and HFC-4310mee. Annex F of the Kigali Amendment presents the GWP100 of each of these eleven HFCs (Extended Data Table 3). While the Kigali Amendment represents progress towards the reduction of global greenhouse gas emissions, some criticize it for not doing more. Unlike the Montreal Protocol, which involves a complete phaseout of ODS, the Kigali Amendment is only a phase down of HFC production and consumption, reaching a maximum of an 85 percent reduction in baseline levels. Furthermore, the phasedown timelines for Kigali take place over several decades, whereas research by Purohit et al. (2020) suggests that a more accelerated schedule

would be feasible. Given the time sensitivity of preventing climate change and achieving climate-related goals such as the Paris Agreement, reducing emissions on as fast of a timeline as possible is crucial.

The Kigali Amendment's phasedown schedule of HFCs takes place over the course of several decades. The 146 ratifying parties are split into two category: Article 5 and non-Article 5. The first category, Article 5, includes primarily developing countries and is allotted a slower phasedown schedule, reaching either an 80% reduction (Group 1) or an 85% reduction (Group 2) by 2045 relative to 2020-2022 averages. Non-Article 5 parties include primarily developed countries and are allotted a slightly more strict schedule, being required to achieve an 85% reduction by 2035, a full ten years earlier (Extended Data Fig. 3).

The maximum technologically feasible reduction of hydrofluorocarbons.

To estimate the additional climate benefits resulting from a more ambitious phasedown schedule, we use the maximum technologically feasible reduction (MTFR) schedule as calculated by Purohit et al. (2020). They estimate the MTFR for the eleven Kigali Amendment HFCs and show that following this schedule would lead to a full phaseout of HFCs by 2035.

In their paper, Purohit et al. (2020) use data on HFC consumption reported by countries to the United Nations Framework Convention on Climate Change (UNFCCC) combined with derived data from the IIASA GAINS model (Purohit and Höglund-Isaksson, 2017), and extrapolate these to 2100 using socioeconomic indicators consistent with the assumptions in the Shared Socioeconomic Pathways (SSPs). Specifically, they use projections consistent with SSP3, though projections based on SSP1 are also used as an optimistic sensitivity case. While these projections were created with the goal of investigating the content of the MTFR, rather than the magnitude of the reduction per se, this serves our purposes well as the species and order of HFC reduction are important for accurately calculating the magnitude of climate benefits associated with the phasedown.

Purohit et al. (2020) developed two sets of alternative phasedown assumptions, one based on "technical" energy efficiency potentials, and one based on "economic" energy efficiency potentials. We use the projections based on technical energy efficiency potentials for these calculations since these represent the maximum efficiency improvements considered technically possible and is the primary motivation of our alternative phasedown analysis.

Climate benefits calculation.

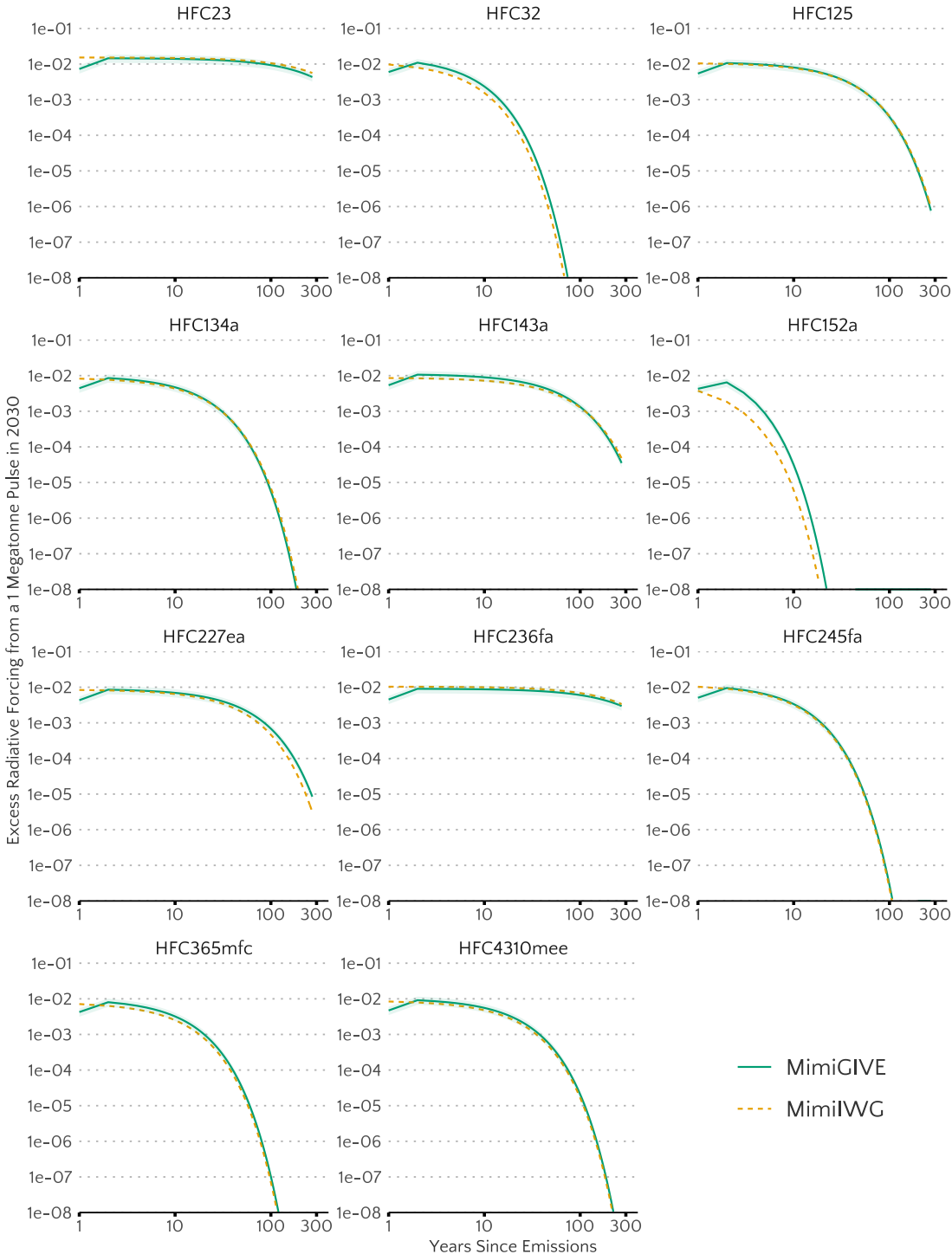
Climate benefits were calculated based on emissions projections from Purohit et al. (2020). Emissions reductions for each HFC were calculated for the (1) the as-adopted Kigali Amendment and (2) the

maximum technologically feasible reduction (MTFR) scenarios, relative to a baseline “business-as-usual” scenario in which the Kigali Amendment was not implemented (Extended Data Fig. 4). Because projections from Purohit et al. are in ten-year timesteps, each emissions trajectory was annualized using linear interpolation. Emissions reductions were then calculated for each gas under each scenario and multiplied by their respective SC-HFCs to get a stream of undiscounted benefits for each phasedown year (2023 to 2100). This stream of undiscounted benefits was then summed across all gases for each year, then discounted to a base year of 2023 using a constant discount rate of 3 percent for MimiIWG and a constant discount rate of 2 percent for MimiGIVE. The net present value NPV in 2023 of the stream of future benefits in year t of emissions reductions ϕ for HFC j and discount rate ρ is

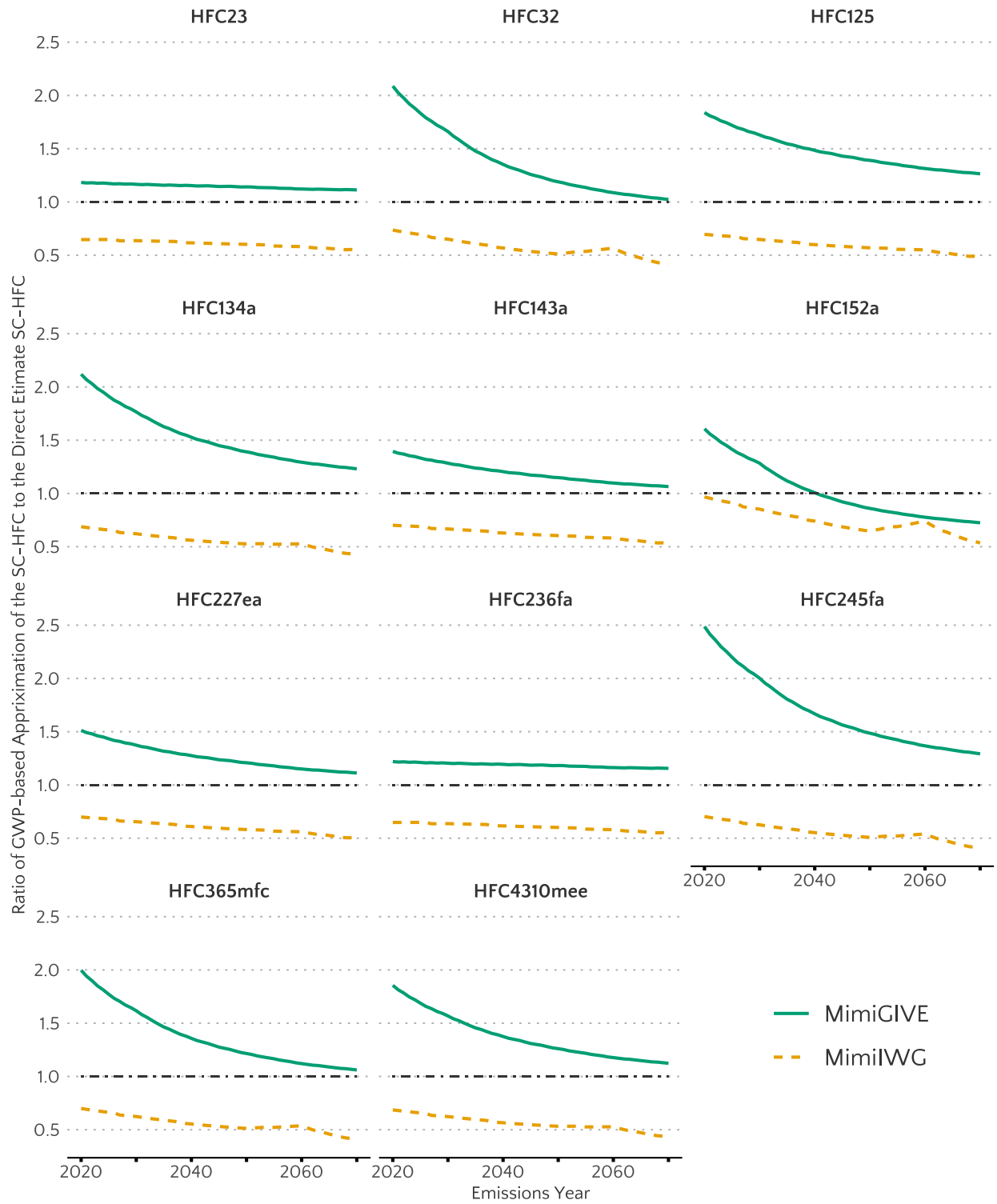
$$NPV_{2023} = \sum_{t=2023}^{2100} \frac{\sum_{j=HFC} (SCHFC_{tj} \times \phi_{tj})}{(1 + \rho)^{t-2023}}$$

The net present value represents the total climate benefit from HFC emissions reductions under each scenario (Fig. 3). The total climate benefits are realized relative to a baseline without the Kigali Amendment, discounted to a base year of 2023, and reported in 2020 USD. Both the Kigali phasedown schedule and maximum technologically feasible reductions are evaluated.

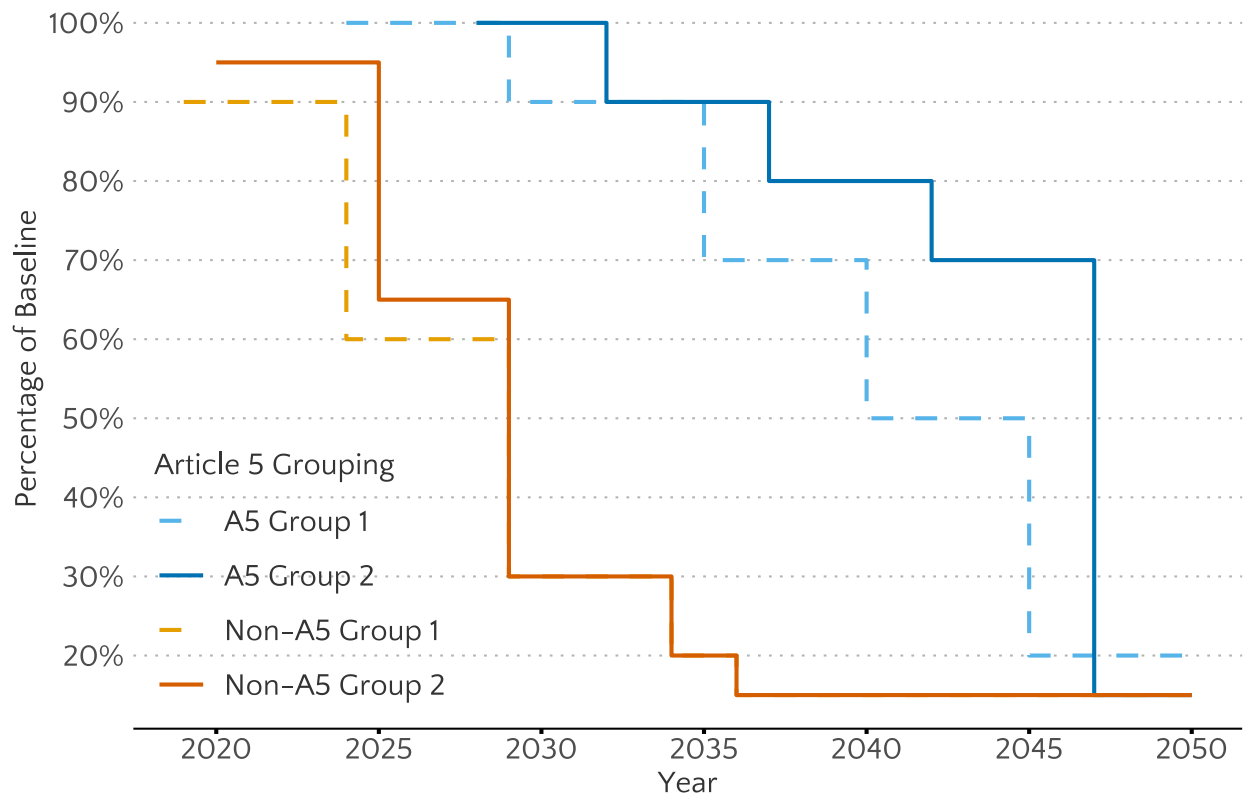
Extended Data Figures



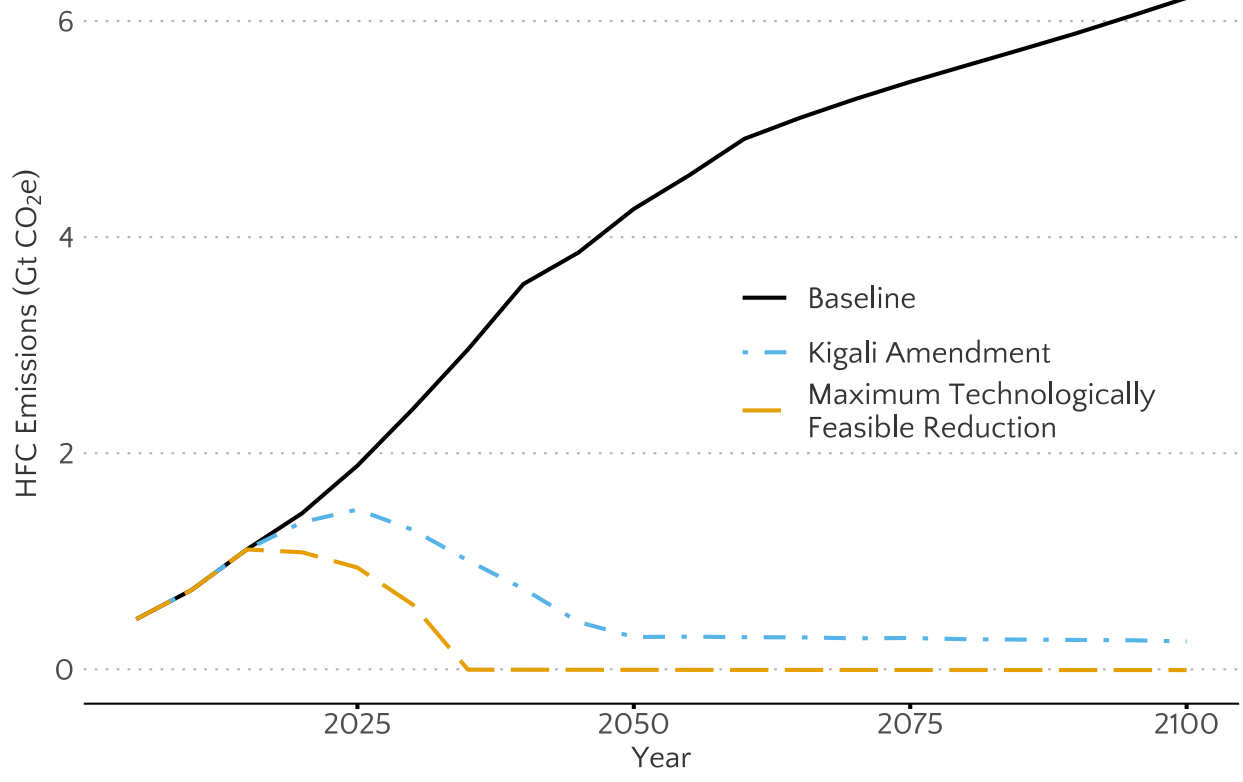
Extended Data Fig. 1 | Additional radiative forcing from 1 tonne pulse of hydrofluorocarbons in 2030. Paths of additional radiative forcing for under MimiIWG are the result of the one-box model. The paths shown for MimiGIVE includes the mean (solid line) and the 5th to 95th percentile ranges that account for uncertainty underlying its simple climate model (FaIR1.6.2).



Extended Data Fig. 2 | The ratio of SC-HFC to global warming potential estimation. Direct estimation of the social cost of greenhouse gases pairs time-dependent growth, total forcing, climate warming, damages, and discounting, allowing for more refined estimates of the SC-HFCs. The ratio of GWP-based estimates to directly estimated SC-HFCs is estimated as $ratio = SC-CO_2 \times GWP_{HFC} / SC-HFC$ and varies by HFC species and direct estimation methodology—underscoring the importance of the direct estimation of social costs and the suite of improvements contained within our modified MimiGIVE.



Extended Data Fig. 3 | Kigali Amendment Hydrofluorocarbon Phasedown Schedule. The Kigali Amendment defines different phasedown schedules for each of the four Article 5 groupings. Article 5 Group 1 countries have their baseline HFC production/consumption levels calculated from 2020-2022 averages and are required to reduce production/consumption starting in 2029, reaching 20 percent of baseline levels by 2045. Article 5 Group 2 countries have their baselines calculated from 2024-2026 averages and are expected to decrease production/consumption by 85 percent by 2047, starting reductions in 2028. Non-Article 5 parties have their baseline levels calculated from 2011-2013 averages and must reduce production/consumption by 85 percent by 2036. Reductions start in 2019 for Non-Article 5 Group 1 and 2020 for Non-Article 5 Group 2.



Extended Data Fig. 4 | Hydrofluorocarbon emissions projections under various scenarios from Purohit et al. (2020). HFC emissions were projected out to 2100 as per the methodology described in Purohit et al. (2020). Three scenarios are presented: emissions under a baseline, “business-as-usual” scenario, emissions under full compliance with the Kigali Amendment phasedown schedule and emissions under a maximum technologically feasible reduction schedule.

Extended Data Tables

Emissions Year	Hydrofluorocarbon Species										
	23	32	125	134a	143a	152a	227ea	236fa	245fa	365mfc	4310mee
Panel A: MimiGIVE											
2020	2377	61	362	128	609	15	405	1528	79	76	168
2030	2844	91	481	181	780	22	525	1825	115	110	234
2040	3296	128	606	241	953	32	649	2112	159	150	306
2050	3785	166	735	300	1136	42	778	2422	202	191	380
2060	4208	198	849	353	1299	51	893	2690	240	226	444
2070	4532	225	944	396	1431	58	987	2894	272	255	498
2080	4852	250	1037	438	1564	65	1082	3096	302	283	550
2090	5180	277	1136	483	1704	72	1180	3302	333	313	605
2100	5348	296	1202	514	1794	77	1245	3406	356	334	643
Panel B: MimiIWG											
2020	961	39	211	87	268	5	193	636	61	48	100
2030	1186	53	275	117	342	7	251	786	84	65	134
2040	1440	71	350	153	426	10	317	956	112	86	174
2050	1720	92	430	190	518	13	388	1142	142	108	216
2060	2013	94	502	214	607	13	454	1336	151	117	246
2070	2448	149	660	306	766	21	588	1627	231	177	345
2080	2894	204	822	401	930	29	727	1925	314	239	448
2090	3081	220	885	433	1001	31	783	2049	338	257	484
2100	3273	236	952	465	1074	34	842	2179	364	276	520

Extended Data Table 1 | The Social Cost of Hydrofluorocarbons. Panel A presents estimates from MimiGIVE using the central near-term target discount rate of 2 percent with calibrated Ramsey parameters (Newell et al., 2022). Panel B presents estimates from MimiIWG using the central constant discount rate of 3 percent (USG, 2021). All estimates are in thousands of 2020 United States dollars per tonne of the gas. Values in between each perturbation year (each decade as listed) are recovered by linearly interpolating between each ten-year perturbation.

Source	23	32	125	134a	143a	152a	227ea	236fa	245fa	365mfc	4310mee
AR4	14,800	675	3,500	1,430	4,470	124	3,220	9,810	1,030	794	1,640
AR6	14,600	771	3,740	1,530	5,810	164	3,600	8,690	962	914	1,600

Extended Data Table 2 | Global warming potential of hydrofluorocarbons regulated under the Kigali Amendment. The GWP100 estimates presented here are published in the Fourth Assessment Report (AR4) (Forster et al., 2007) and the Sixth Assessment Report (AR6) (Smith et al., 2021). To maintain consistency with the modeling underlying the MimiIWG methods, we use the AR4 estimates to produce comparisons between the directly estimated SC-HFCs and GWP-based methods.

HFC Species	(1) Lifetime τ (yr)	(2) Molecular Weight	(3) Radiative Efficiency (AR4)	(4) Radiative Efficiency (AR6)
23	270	70.01	0.19	0.19
32	4.9	52.02	0.11	0.11
125	29	120.02	0.23	0.23
134a	14	102.03	0.16	0.17
143a	52	84.04	0.13	0.17
152a	1.4	66.05	0.09	0.10
227ea	34.2	170.03	0.26	0.27
236fa	240	152.04	0.28	0.25
245fa	7.6	134.05	0.28	0.25
365mfc	8.6	148.07	0.21	0.22
4310mee	15.9	252.06	0.40	0.36

Extended Data Table 3 | Lifetime, Weight, and Radiative Efficiency of Hydrofluorocarbons. The lifetime, molecular weight, and radiative efficiency values used in the MimiWG implementation of this paper are drawn from the Fourth Assessment Report (AR4, column 3) (Forster et al., 2007). This was chosen to maintain consistency throughout the models with other parameters underlying the U.S. Government’s estimation of SC-CO₂, SC-CH₄, and SC-N₂O. Values from AR6 are presented as a comparison and drawn from Table 7SM in Smith et al. (2021).

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Software

All our results are computed using open-source software tools. We use the Julia programming language for the entire replication code of this paper (Bezanson et al., 2017). All models used in this study are implemented on the Mimi.jl computational platform for integrated assessment models (Anthoff et al., 2017).

Data and Code Availability

Complete replication code, data, and software accompanying this study are freely available at: <https://github.com/bryanparthum/schfc-paper.git>.

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Author Contributions

TT and BP developed the study idea, the application, and implemented the modifications into the three MimiIWG integrated assessment models (DICE/FUND/PAGE). BP and LR developed and implemented the modifications to the MimiGIVE integrated assessment model. BP estimated the integrated assessment models, BP and LR developed the replication code and data. TT, LR, and BP contributed equally to evaluating the results and writing of the paper.

Competing Interests

The authors have no competing interests to report. Research was done independently without funding.