The Social Costs of Hydrofluorocarbons and the Large Climate Benefits from their Expedited Phasedown

Author Info

- Tammy Tan, U.S. EPA, NBER
- Lisa Rennels, University of California, Berkeley, Energy and Resources Group
- Bryan Parthum, U.S. EPA, Office of Policy, National Center for Environmental Economics, corresponding author: parthum.bryan@epa.gov

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. The first set of estimates use methods consistent with those adopted by the U.S. Government, and a second set incorporates recent scientific advances in climate science, socioeconomic projections, damage functions, and discounting methodologies. Both results show that damage approximations based on global warming potentials are a poor proxy for direct estimation in an integrated assessment framework. Applying the updated SC-HFCs to the Kigali Amendment – the first global agreement to phasedown HFC production and consumption – produces climate benefits on the order of $37 trillion (2020USD) over the lifetime of the agreement. More aggressive reduction pathways could yield additional economic benefits to society, totaling $41 trillion (2020USD).

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

JEL Codes: Q51, Q54, Q58

Introduction

The most recent observations suggest that global average surface temperatures are already 1.1°C higher than pre-industrial levels (IPCC 2021). Even if society achieves the Paris Agreement goal of keeping temperatures at or below 1.5°C (UNFCC, 2015), countries will require various adaptation strategies to cope with a warmer world. The widespread adoption of air conditioning and improved building insulation represent two important adaptation strategies. These defensive mechanisms offer an indoor reprieve as high temperatures become more common and can reduce the health consequences of global warming (Carleton et al., 2022; Cromar et al., 2021). 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 themselves 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 combination with the growing demand for cooling products such as refrigerators and air-conditioners, 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 air conditioning 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, so HFC emissions were not explicitly controlled until the adoption of the Kigali Amendment to the Montreal Protocol in 2016. Owing to the strong potency of HFCs and the forecasted dramatic increase in their emissions rates under a business-as-usual scenario, it is estimated that the Kigali Amendment will prevent 0.2-0.4 °C of global

warming by 2100 (Purohit et al., 2022). We include a more comprehensive discussion of the Kigali Amendment and the phasedown of HFCs under this regulation in the Methods section.

As with any policy, it is important to have a means of quantifying the expected social and economic impact of regulatory efforts such as the Kigali Amendment, as well as other HFC emissions-related interventions. The U.S. Government (USG) publishes official estimates of the social cost of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) which estimate the social costs of these greenhouse gases (SC-GHGs) to quantify associated societal impacts in a benefit-cost framework. Various entities use these estimates, most recently updated in February of 2021, to value changes in emissions of these gases in benefit-cost analyses of policy alternatives (USG, 2021). To date, the methodology used to calculate these estimates by the USG does not extend to other greenhouse gases like hydrofluorocarbons. Instead, estimates of the damages associated with the emission of HFCs rely on approximations using the global warming potential (GWP) anchored to the SC-CO_2 (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).

The 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

Model estimation and the social cost of hydrofluorocarbons. We calculate SC-HFCs for eleven HFCs using 10,000 simulations of each IAM in a Monte Carlo framework. 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. We carry out this process for four distinct integrated assessment

models, three of which are averaged to constitute the current USG approach for SC-GHG estimation (DICE, FUND, and PAGE), and the last of which (GIVE) that incorporates recent scientific advances across climate science and socioeconomic dimensions. We present more details on these models and their estimation in the Methods section, and henceforth use the specific software package names of MimiIWG for the packaged USG methodology implementation, and MimiGIVE for the more recent GIVE implementation. This approach results in one SC-HFC for each of the eleven HFCs for MimiIWG and MimiGIVE, calculated for nine emissions years from 2020 to 2100 (Extended Data Table 1).

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). One immediate advantage of MimiGIVE, aside from the updated modeling inputs and components, is that the model uses an annual timestep resulting in a much smoother and more continuous SC-HFC path. In contrast, the MimiIWG models use timesteps ranging from 1 (FUND) to 100 years (PAGE). Long timesteps can pose issues for accurate calculation of climate benefits due to the "averaging" over these timesteps that is 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 global mean surface temperature anomaly resulting from a pulse of a given HFC noticeably differs under the USG methodology as compared to the updated MimiGIVE model (Fig. 2) while 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 increase more rapidly and peak earlier in time, peak at higher levels, and decay much more quickly than they do under MimiIWG (Fig. 2). Recent literature on CO_2 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 models respond much more quickly to a CO_2 emissions impulse than DICE, FUND, and PAGE, 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). Because discounting affects how society values the stream of damages resulting from an extra tonne of HFC emissions, accurate representations of temperature dynamics greatly improve SF-HFC estimates. Failing to accurately capture these near-term temperature responses could have a substantial impact on the estimated welfare effects of reducing HFC emissions; potentially underestimating the near-term benefits of abatement and international policy agreements.

Comparison to global warming potential methods. Past attempts to quantify the impact of HFC and other non-CO_2 gas emissions most frequently involved the consideration of GWPs. 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 CO_2 (US EPA, 2023). The most-cited GWPs are given for 100-year time periods (GWP100), although alternative time scales (e.g., 20 years) are also sometimes used. The GWP-based methodology for calculating the social cost of a greenhouse gas involves multiplying the GWP of a greenhouse gas by the SC-CO_2 for a chosen discount rate and year. This gives an approximation of the social cost of that gas for that discount rate and year. Research shows that GWP100s are most consistent with a discount rate of 3 percent, while GWP20s align best with a discount rate of 7 percent (Sarofim et al., 2018).

While simple to apply, the GWP has been subject to a variety of criticisms. GWPs are based on physical measures of radiative forcing, rather than any economic measure of cost or welfare or of temperature change, so differences in GWPs between gases do not accurately capture differences in welfare impacts from their emissions (Waldhoff et al, 2014; Shine et al., 2005). As a result, GWP-based estimates are sub-optimal for valuation in policy analyses like benefit-cost analyses, which prevalently use social costs, and have been shown to unreliably measure the social cost of greenhouse gases relative to other methods such as direct estimation (Marten and Newbold, 2012; Errickson et al., 2021; Schmalensee, 1993). Phrased another way, the GWP may not mirror "global damage potential", a more direct economic damage calculation of the SC-CO_2 and the social cost of another gas (Mallapragada and Mignone, 2019). Investigation of the theoretical settings under which the GWP matches the global damage potential finds several important factors in the comparison of the two metrics including the relationship between the discount rate used in the economic damage calculations and the time horizon used to calculate the GWP and assumptions around state-dependence in GHG feedback cycles (Mallapragada and Mignone, 2019).

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. To this end, we calculate the ratio between the SC-HFC estimates for each of the eleven species and for both the USG and GIVE methodologies (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-CO_2 and the SC-HFCs (Marten and Newbold, 2012; Mallapragada and Mignone, 2020). These 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. The Kigali Amendment went into effect in 2019 and outlined reduction pathways through 2047 for eleven HFCs: HFC-23, HFC-32, HFC-125, HFC-134a, HFC-143a, HFC-152a, HFC-227ea, HFC-236fa, HFC-245fa, HFC-365mfc, and HFC-4310mee (Extended Data Table 2). We use our SC-HFC estimates for each of the eleven gases and their respective phasedown schedules to estimate the total climate benefits realized over the lifetime of the agreement. The total 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, an increase of approximately 130% when using GIVE relative to the USG modelling framework (Fig. 3, Panel A). Under expedited phasedown schedule, the maximum technologically feasible reduction, 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

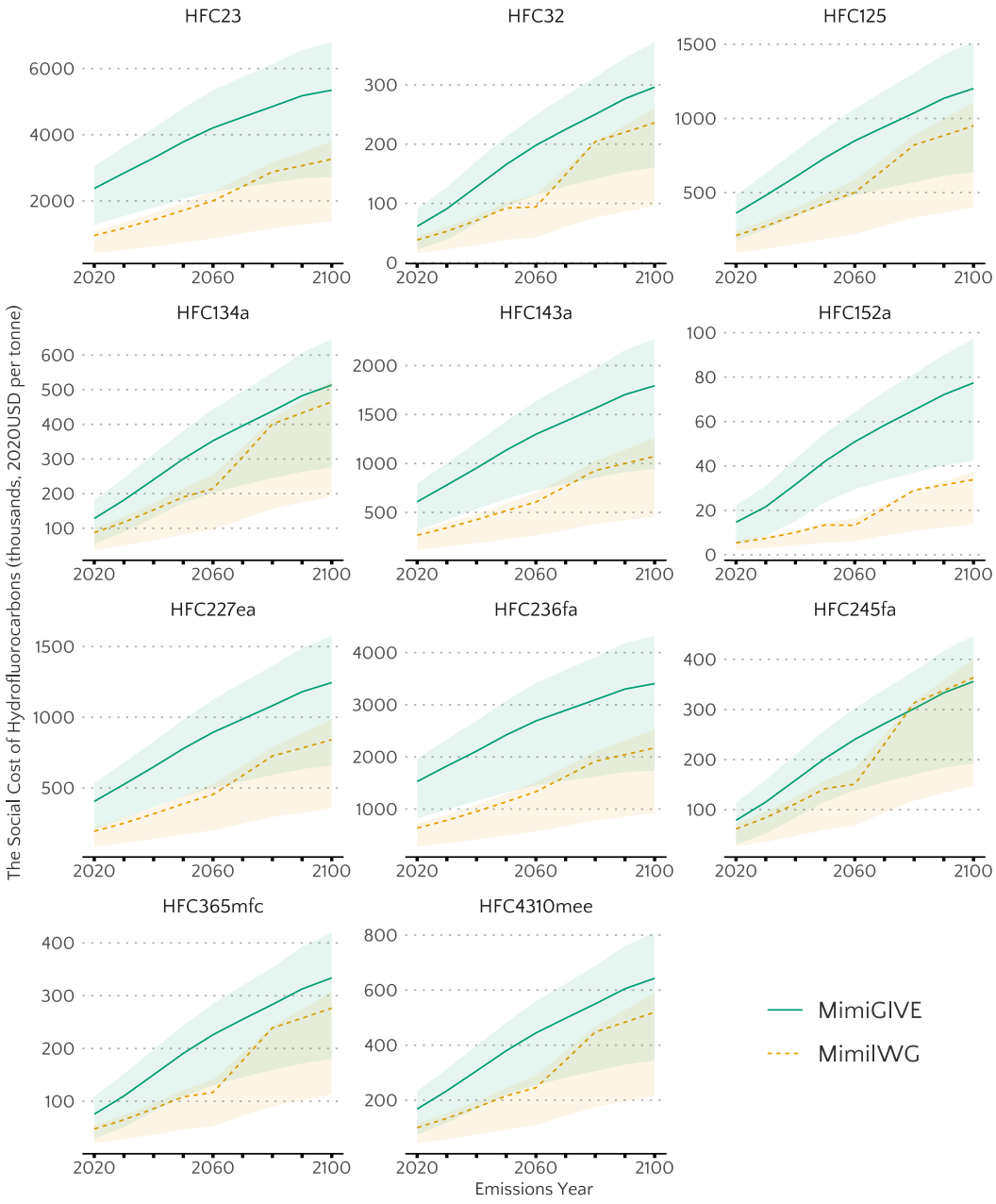


Fig. 1 | The Social Cost of Hydrofluorocarbons. The direct estimates developed in this study are noticeably different under the USG approach (MimiIWG) compared to the updated GIVE model (MimiGIVE). The mean SC-HFCs (lines) along with their 5th to 95th percentile ranges are shown. The SC-HFCs from MimiIWG 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. 2022b).

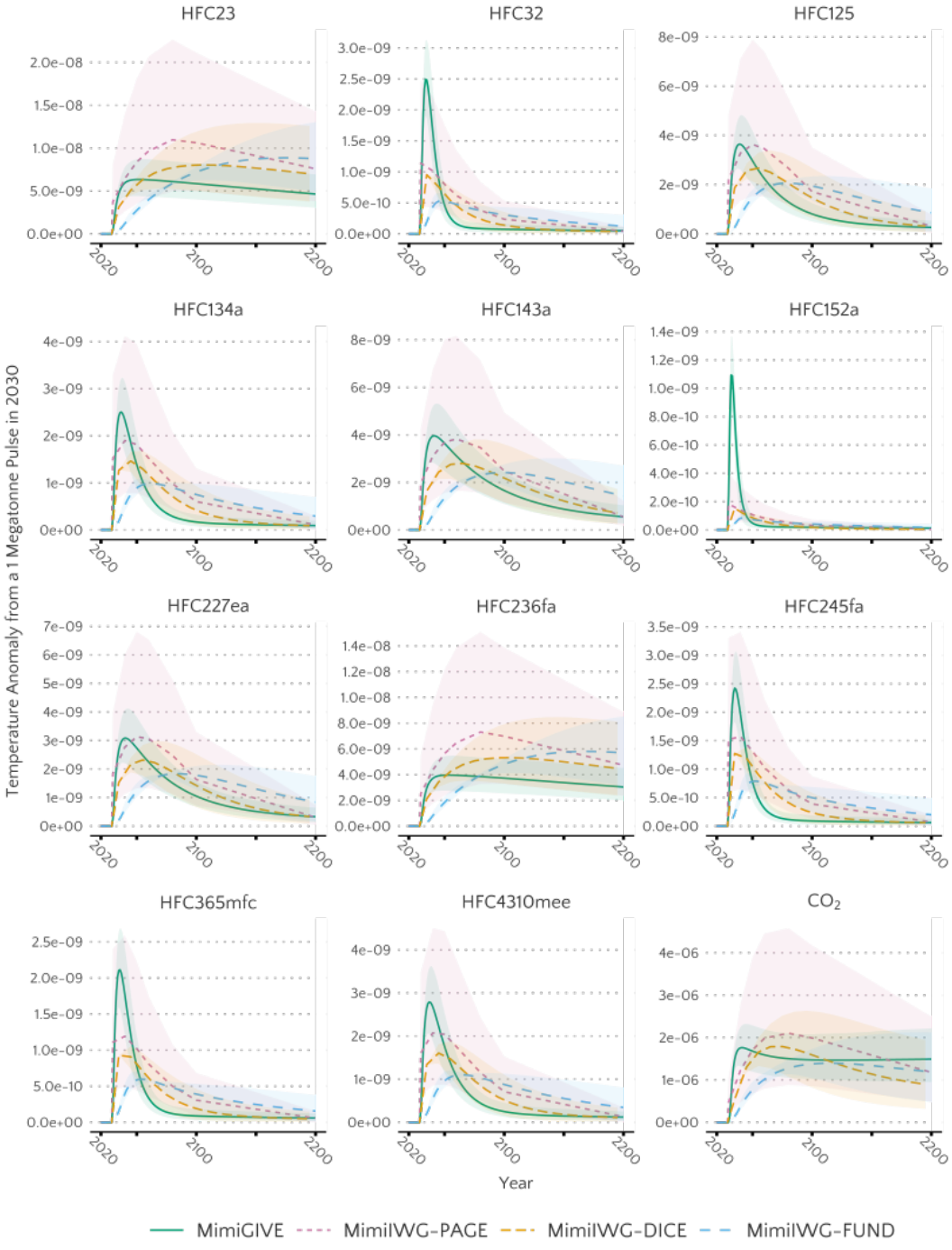


Fig. 2 | Global surface temperature anomaly from one tonne of hydrofluorocarbon gas. The climate representations underlying DICE, PAGE, and FUND fail to capture the sudden near-term response and expedited decay from HFC emissions relative to the simple climate model underlying MimiGIVE (FaIR1.6.2). The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

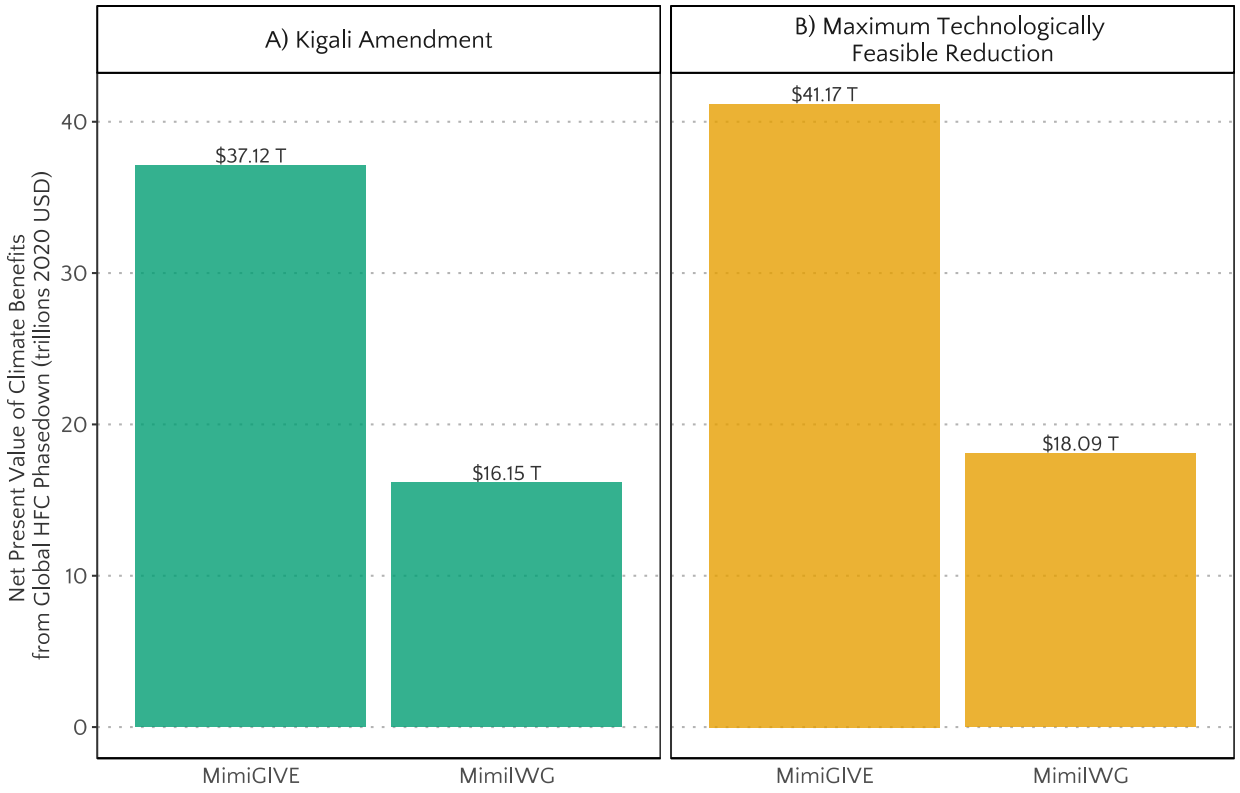


Fig. 3 | The total climate benefits from phasedown of hydrofluorocarbons. Total climate benefits discounted to a base year of 2023, realized relative to a baseline without the Kigali Amendment. MimiGIVE estimates are calculated assuming a calibrated Ramsey-like discount rate using a near-term target 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

The three integrated assessment models underlying the current USG methodology. Beginning in 2010, the 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 – CO_2. 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 CO_2, the FUND model explicitly represents emissions of CH_4, N_2O, and SF_6. 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 CH_4 and SF_6 alongside its representation of CO_2. 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.

Methods underlying the current USG methodology. The SC-GHG estimates for CO_2, CH_4, and N_2O currently published by the USG for use in benefit-cost analysis use 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). 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-CO_2 to include simple representations of CH_4 and N_2O (Marten et al., 2015). To date, none of the three IAMs have been extended to explicitly consider HFCs. As a result, direct estimate of the SC-HFCs have never been published and, instead, any estimates of the damages associated with the emission of HFCs relied on approximations using each species' GWP relative to CO_2 (Sarofim and Giordano, 2018; Mallapragada and Mignone, 2020).

Direct estimation of the SC-HFCs under the USG framework is feasible using an approach like that used by Marten et al. (2015) for CH_4 and N_2O. The study circumvents the need for explicit representation of CH_4 and N_2O in the IAMs by directly perturbing the model's exogenous radiative forcing projections with additional forcing vectors from an additional tonne of the non-CO_2 gases. From this, the study calculates streams of marginal damages associated with the additional perturbation of emissions and, hence, recovers 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 CO_2, CH_4, and N_2O 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.[1] 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

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

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

[1] 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).

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

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-CO_2, SC-CH_4, and SC-N_2O.

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 MimiIWG 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-CO_2 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 to the model's exogenous radiative forcing projection in the emissions year (Extended Data Fig. 1). 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 for as the present value of the difference in damages estimated in steps 1 and 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-CH_4 and SC-N_2O estimates. That is, we take the average radiative forcing over each timestep. 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.

The Greenhouse 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. 2022b). 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-CO_2 using the GIVE model, finding that the SC-CO_2 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-CH_4 and SC-N_2O, 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).

Methods underlying the GIVE model. The 2017 NASEM report recommended that calculations of the SC-CO_2 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 CO_2, CH_4, and N_2O 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. 2014) 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 effect the radiative forcing path (Extended Data Figure 1).
3. Re-estimate the model to compute damages in the perturbed scenario.
4. Compute the SC-HFC for as the present value of the difference in damages estimated in steps 1 and 3.

Estimating social costs using global warming potentials. In order to assess how close GWP-based methodologies come to replicating the values of SC-HFCs as calculated through direct estimation methodologies, we calculate GWP-based SC-HFCs for each of the eleven gases and compare these GWP-based estimates with our direct estimates by calculating the ratio of GWP-based estimates to the direct SC-HFC estimate (Extended Data Fig. 2). To estimate the social cost of a given HFC based on its global warming potential, we multiply the directly calculated SC-CO_2 by the global warming potential of the HFC. We then calculate the ratio of these estimates to the direct SC-HFC estimate, 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 underestimate the social costs relative to the direct estimates (Extended Data Fig. 2).

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). In October of 2021, the United States implemented a phasedown schedule for HFCs under the American Innovation and Manufacturing Act that 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. 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. 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 2)

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.

Kigali Amendment ratifying parties are split into two groups: Article 5 Parties, and non-Article 5 Parties, as specified under Article 5 of the Montreal Protocol. Article 5 Parties include primarily developing

countries, which are further divided into Group 1 and Group 2 countries. Group 1 countries have their baseline HFC production/consumption levels calculated from 2020-2022 averages and are required to reduce production/consumption by 80 percent of this baseline by 2045. Group 2 countries are categorized separately due to their high ambient air temperatures, and include Bahrain, India, Iran, Iraq, Kuwait, Oman, Pakistan, Qatar, Saudi Arabia, and the United Arab Emirates. Group 2 countries have their baselines calculated from 2024-2026 averages and are expected to reduce production/consumption by 85 percent by 2047. For both groups, the baseline calculation is to also include 65 percent of HCFC baseline production/consumption, to account for the fact that whilst HCFCs are already being phased out, HFCs are still used as alternatives for some HCFCs. Non-Article 5 parties include primarily developed countries, and are also further divided into two separate groups, with 45 countries in the first group, and 5 in the second (Extended Data Fig. 3).

The maximum technologically feasible reduction of hydrofluorocarbons. The climate benefits associated with the Kigali Amendment were estimated to be substantial, yet some criticize it for not going far enough. Whilst a full phase-out of HFCs may be difficult to enforce in the short-term, the existence of HFC substitutes such as HFOs and low-GWP refrigerants such as ammonia and CO_2 may enable a more aggressive and accelerated phasedown schedule than that outlined under Kigali.

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 Kigali Amendment and 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 valueNPV in 2023 of the stream of future benefits in year t of emissions reductions ϕ for HFC j and discount rate ρ is

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

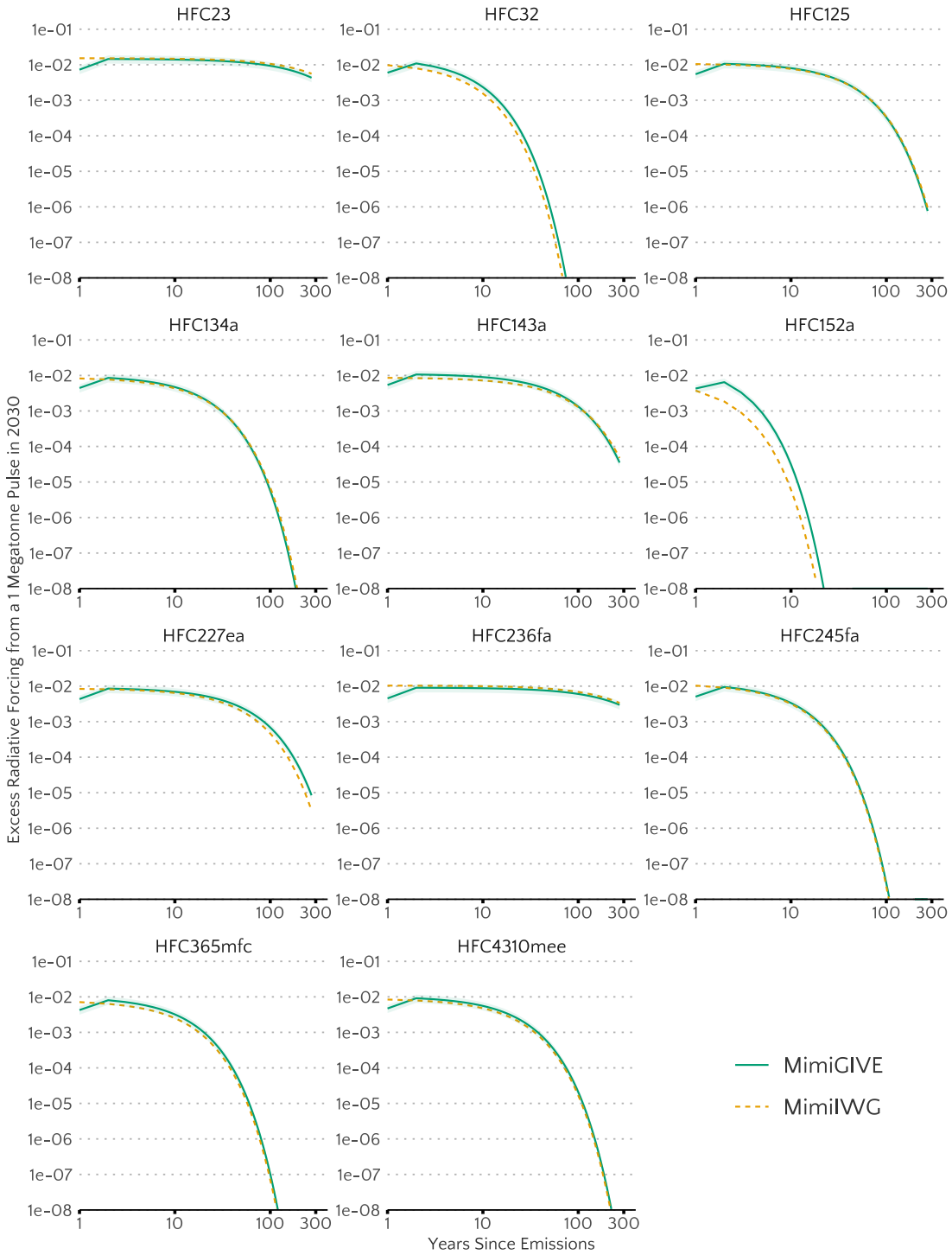
The net present value represents the total climate benefit from HFC emissions reductions under each scenario (Fig. 3). The total climate benefits are realized relative to a baseline without the Kigali Amendment, discounted to a base year of 2023, and reported in 2020 USD. Both the Kigali phasedown schedule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

The Mimi.jl integrated assessment framework. One of the key conclusions from 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). In response, 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*).

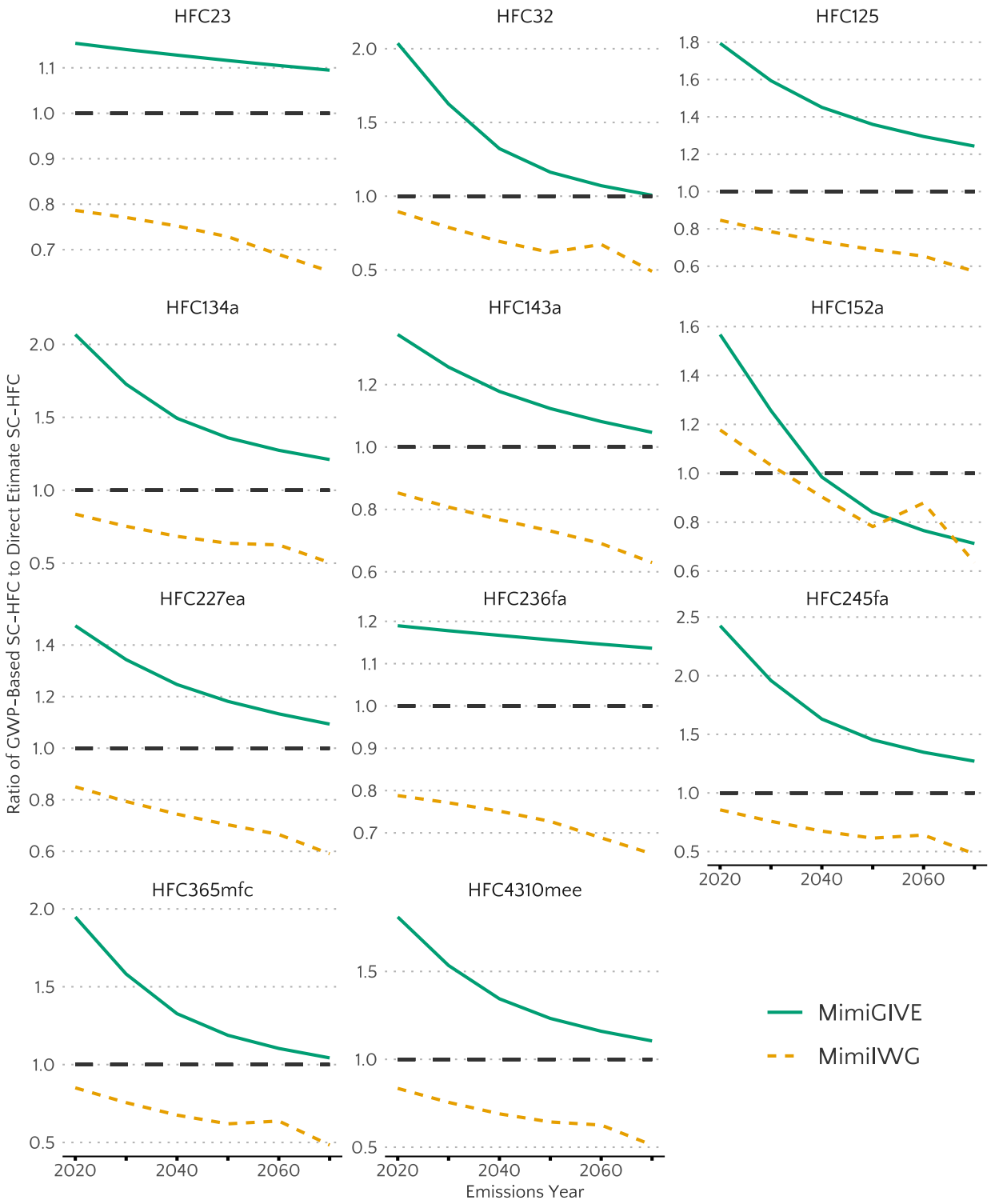
Mimi is a Julia package that provides a component model for IAMs, allowing them to be run using the same platform with a common programming language (Julia). For this analysis, we work within the *Mimi* versions of DICE, PAGE, and FUND that were converted from their original forms (in GAMS, Excel, and 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.

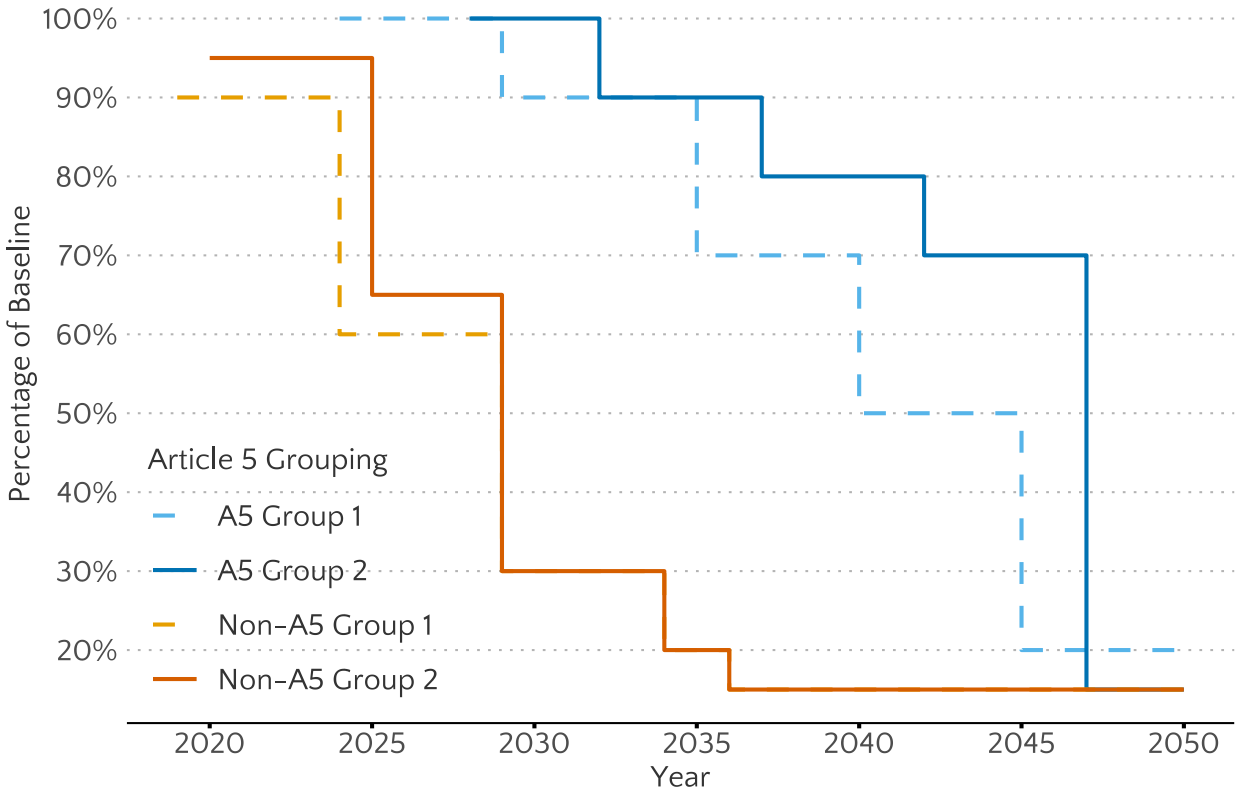
Extended Data Figures



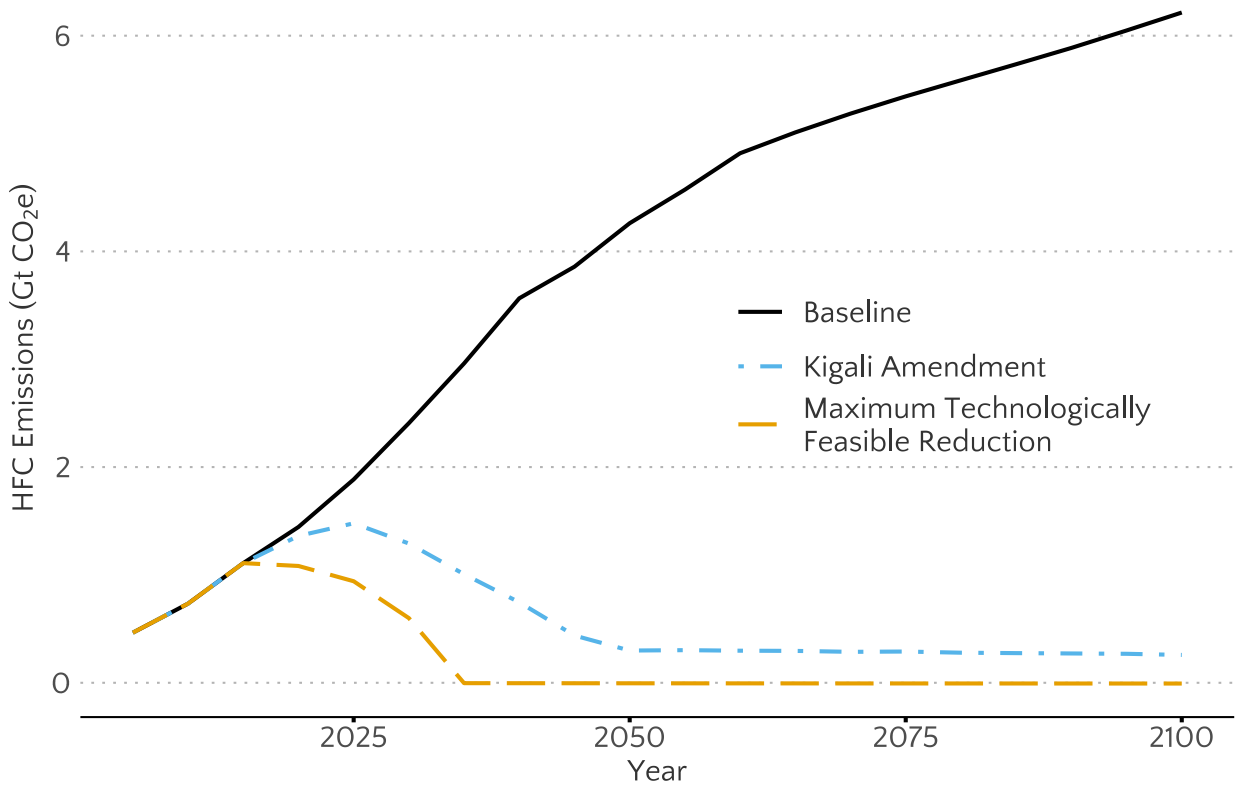
Extended Data Fig. 1 | Additional radiative forcing from 1 tonne pulse of hydroflourocarbons in 2030. Paths of additional radiative forcing for under MimiIWG are the result of the one-box model. The paths shown for MimiGIVE includes the mean (solid line) and the 5th to 95th percentile ranges that account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



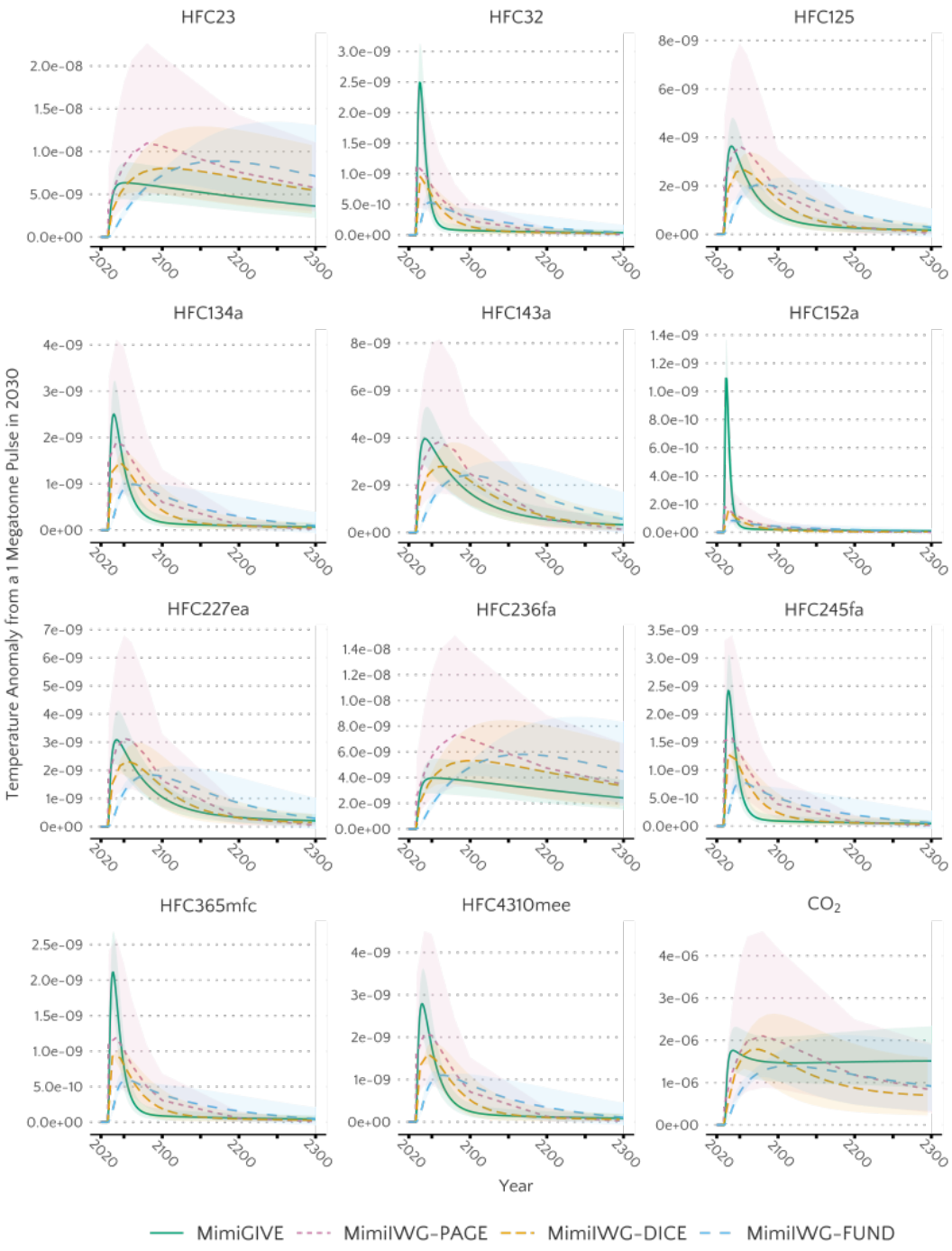
Extended Data Fig. 2 | The ratio of SC-HFC to global warming potential estimation. Direct estimation of the social cost of greenhouse gases pairs time-dependent growth, total forcing, climate warming, damages, and discounting, allowing for more refined estimates of the SC-HFCs. The ratio of GWP-based estimates to directly estimated SC-HFCs is estimated as $ratio = \mathcal{SC}\text{-}CO_2 \times GWP_{HFC} \,/\, \mathcal{SC}\text{-}HFC$ 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 Hydrofuorocarbon 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 Fig. 5 | Global surface temperature anomaly from one tonne of hydrofluorocarbon gas from 2020 to 2300. This figure extends Fig. 1 to include the full time horizon. 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.

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., 2021). 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.

GWP	23	32	125	134a	143a	152a	227ea	236fa	245fa	365mfc	4310mee
100	14,800	675	3,500	1,430	4,470	124	3,220	9,810	1,030	794	1,640

Extended Data Table 2 | Global warming potential of hydrofluorocarbons regulated under the Kigali Amendment. The GWP estimates presented here are the values used to produce comparisons between the directly estimated SC-HFCs and GWP-based methods.

HFC Species	(1) Lifetime $\tau(yr)$	(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 this paper are drawn from AR4 (column 3). This was chosen to maintain consistency throughout the models with other parameters underlying the U.S. Government's estimation of SC-CO_2, SC-CH_4, and SC-N_2O. 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.).

Data and Code Availability

The replication code and data for this paper are available at: https://github.com/bryanparthum/schfc-paper

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Author Contributions

All authors contributed equally to the programming and modifications of the integrated models. BP estimated the models, BP and LR developed the replication code and data. All authors contributed equally to evaluating the results and writing of the paper.

Competing Interests

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