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

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Abstract

Hydrofluorocarbons are a potent greenhouse gas, yet there remains a lack of quantitative estimates of their social cost. 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 a 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 social cost approximations based on global warming potentials to show that the latter is a poor proxy for direct calculation of hydrofluorocarbon emissions impacts using IAMs. Applying our SC-HFCs to the Kigali Amendment, a global agreement to phase down HFCs, we estimate that it provides $37 trillion (2020USD) in climate benefits over its lifetime. Expediting the phasedown could increase the estimated climate benefits to $41 trillion (2020USD).

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Introduction

The most recent observations suggest that global average surface temperatures are already 1.1°C higher than pre-industrial levels[1]. In response to this trend, many are considering adaptation strategies, including 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[2,3]. 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[4,5]. 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[6,7]. 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[1]. 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 interior space conditioning and foam building insulation, has the potential to substantially contribute to global warming[8]. Experts forecast that global warming itself will exacerbate and accelerate this demand for cooling products around the globe, creating a dangerous feedback loop[9]. The Scientific Assessment of Ozone Depletion (2018) reported that HFC emissions increased by 23% from 2012 to 2016 alone, and without policy intervention, escalated growth is projected to continue, especially in developing countries[6,8].

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. The Kigali Amendment 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[10].

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 CO_2 (SC-CO_2), CH_4, (SC-CH_4), and N_2O (SC-N_2O), 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[11]. 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-CO_2[12,13]. This GWP-based methodology enjoys widespread use but has several limitations that can be addressed with direct estimation methodologies[14]. 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 provide an updated quantification of the benefits from their phasedown as dictated by international climate agreements. We develop a direct estimation methodology (Fig. 1) to calculate SC-HFCs for the suite of three models currently 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 thorough exploration of the potential benefits and costs of climate strategies that include HFCs as part of the technology underlying their implementation.

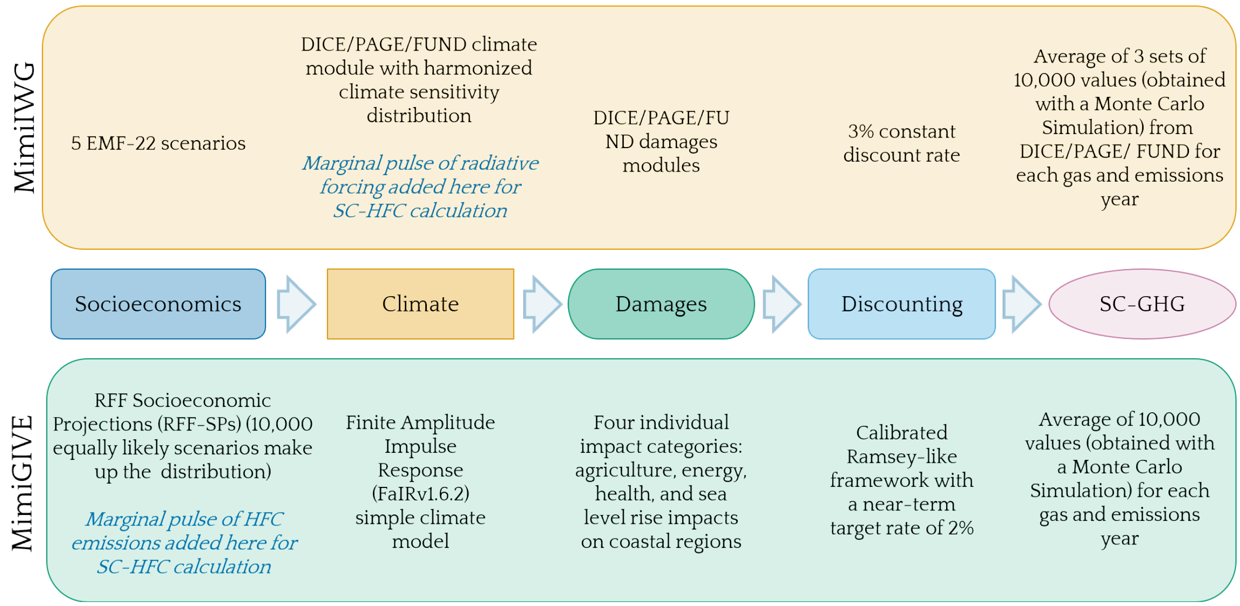


Fig. 1 | Differences in Estimating the Social Cost of Hydrofluorocarbons. The four primary components in estimating the Social Cost of Hydrofluorocarbons (SC-HFCs): Socioeconomics (population, gross domestic product, and greenhouse gas emissions), Climate (used to translate greenhouse gas emissions into physical changes in climate variables), Damages (used to translate changes in climate variables into economic damages), and Discounting (used to recover a net present value from a stream of accounted for future economic damages). The approaches developed in this study to recover the SC-HFCs differ at each of the four components.

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 our updated GIVE model (MimiGIVE) (Extended Data Table 1). Each simulation of the model draws from the set of random parameters underlying each model, 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 central discount rate for each model.

The estimated SC-HFCs for an emissions pulse in 2023 from MimiIWG range from between 24-65% lower than the updated estimates under the MimiGIVE model (Fig. 2, Extended Data Table 1). For example, HFC-134a, which is the most prevalent HFC in the atmosphere, is estimated at $144,000 per tonne (2020 USD) under MimiGIVE and just $96,000 per tonne (2020 USD) under MimiIWG, a 33% increase with a model that incorporates recent scientific advances. MimiGIVE not only incorporates recent scientific advances, but also provides a much smoother and more realistic SF-HFC path due to its annual timestep. In contrast, the USG models use HFC gas cycle models with timesteps ranging from one to one-hundred years.

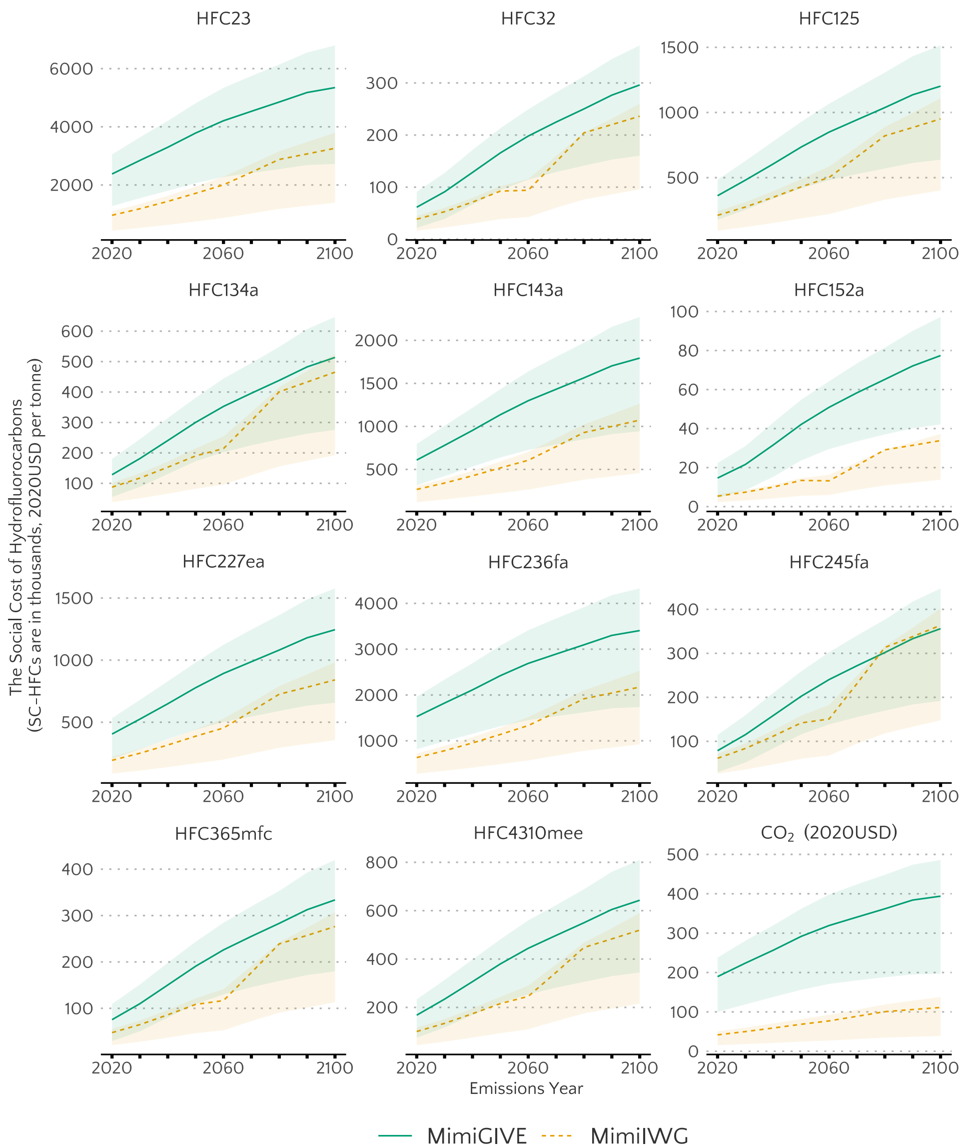


Fig. 2 | The Social Cost of Hydrofluorocarbons. The direct estimates developed in this study are noticeably different under the USG approach (MimiIWG) compared to the updated GIVE model (MimiGIVE). The mean SC-HFCs (lines) along with their 5th to 95th percentile ranges (shaded ribbons) are shown, representing the distribution of estimated SC-HFC values over the 10,000 Monte Carlo simulations. The SC-HFCs from MimiIWG adopt a 3% 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%, the central value in Rennert et al. (2022b)[25]. 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[26,25]. MimiGIVE SC-HFC estimates are certainty-equivalent estimates, as outlined in EPA (2023)[19].

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. 2, Extended Data Fig. 1) stems from advances in the climate system representation (Extended Data Fig. 2), 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, as do the interactions between these factors.

For example, the resulting global mean surface temperature anomaly is noticeably different under MimiIWG and the MimiGIVE methodologies (Fig. 3). By comparison, the radiative forcing responses hardly differ, as further detailed in the Methods section (Extended Data Fig. 3). This suggests differences between how radiative forcing perturbations translate to temperature anomalies in each model. The impulse responses under MimiGIVE occur much faster, peak at higher levels, and decay more quickly than they do under MimiIWG (Fig. 3). 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[15]. We expect that an accurate characterization is similarly important 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)[16], who show that climate science models respond much more quickly to a CO_2 emissions impulse than climate models underlying IAMs, 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. Studies such as Rickels and Schwinger (2021)[17] further show that inaccurate representations of the temperature impulse response have important consequences for climate policy analysis, including that of zero-emissions commitments and potential temperature overshoots.

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[18]. Since the stream of damages resulting from an extra tonne of emissions and its discounting is time-dependent, accurate representations of temperature dynamics greatly improve 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.

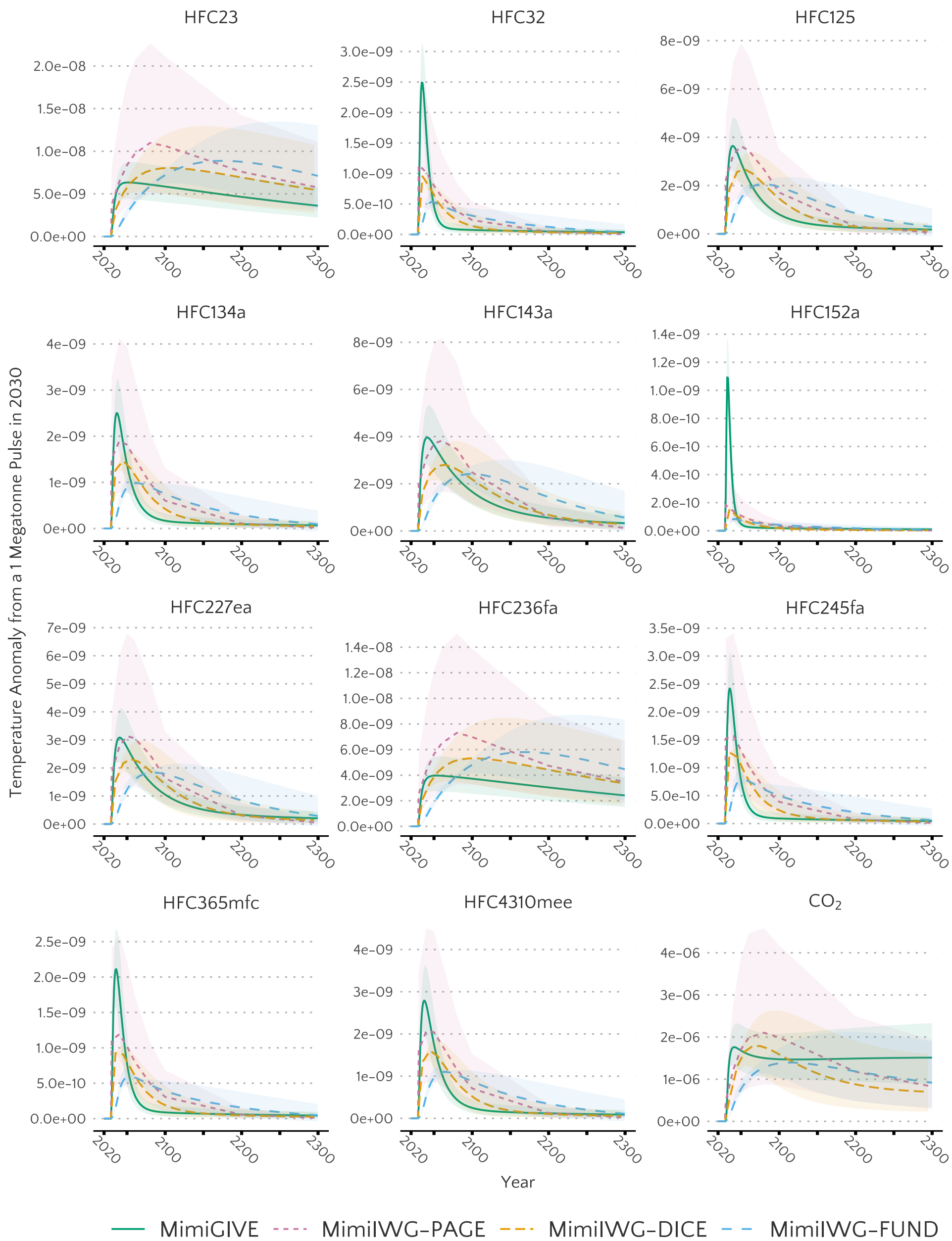


Fig. 3 | Global surface temperature anomaly from one tonne of hydrofluorocarbon gas. The climate representations underlying DICE, PAGE, and FUND predict a much slower near-term response and gradual decay compared to the simple climate model underlying MimiGIVE (FaIR1.6.2). The mean (lines) and 5th to 95th percentile ranges (shaded ribbons) are shown representing the distribution of estimated temperature anomaly values over the 10,000 Monte Carlo simulations.

A comparison to GWP-based damage approximations. Past attempts to quantify the impact of HFC and other non-CO_2 gas emissions most frequently involved the use of GWPs[13]. 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[19]. GWP-based damage approximations simply multiply the GWP of a greenhouse gas by the SC-CO_2 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%, while those derived from a time period of 20 years (GWP20s) align best with a discount rate of 7%[20]. While simple to apply, the GWP has been subject to a variety of criticisms such as their applicability in benefits-cost analyses[14], their sensitivity to the time horizon and discount rate[13], and the imperfect relationship between forcing and damages[21,22]. Despite these well-documented downsides, GWPs remain a popular way for policy makers to evaluate the relative tradeoffs when substituting between GHGs, effectively acting as a proxy for their social costs[7]. 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 species' GWP100, a time-invariant scalar, with the SC-CO_2 from each model. That is, the GWP-based approximations under MimiIWG use the SC-CO_2 from MimiIWG, while the SC-CO_2 from MimiGIVE is used to estimate the GWP-based damage approximations under MimiGIVE. We calculate the SC-CO_2 under each model using the same probabilistic setting as the SC-HFC—a Monte Carlo simulation with 10,000 trials. 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. 4).

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 (i.e., ratios are less than 1), while estimates with the MimiGIVE methodology overestimate the social costs. (i.e., ratios are greater than 1). For example, comparing the 2030 SC-HFCs we find that the ratios estimated using MimiIWG underestimate the direct estimates by 10%-38%, while the ratios estimated using MimiGIVE overestimates the direct estimates 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[14,13]. 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 climate benefits from phasing down 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 CO_2) may enable a more aggressive and accelerated phasedown schedule than that outlined under Kigali (Extended Data Fig. 5). To assess the additional gains from following a more ambitious timeline, we estimate climate benefits under a maximum technologically feasible reduction (MTFR) schedule[23], which would entail a full phaseout of HFCs by 2035 (Extended Data Fig. 6). We estimate the total climate benefits under (1) the Kigali phasedown schedule and (2) expedited MTFR phasedown schedule using results from both our modified MimiIWG and MimiGIVE models (Fig. 4 and Extended Data Table 2). Climate benefits from the as-published Kigali Amendment range from $16.13 trillion ($15.24T–$17.06T, 5%–95% range, 2020 US dollars) using the SC-HFCs from the MimiIWG framework, to $37.14 trillion ($35.93T–$38.31T, 5%–95% range, 2020 US dollars) using the MimiGIVE SC-HFC estimates. This is an increase of approximately 130% when using MimiGIVE relative to MimiIWG (Fig. 4, Panel A).

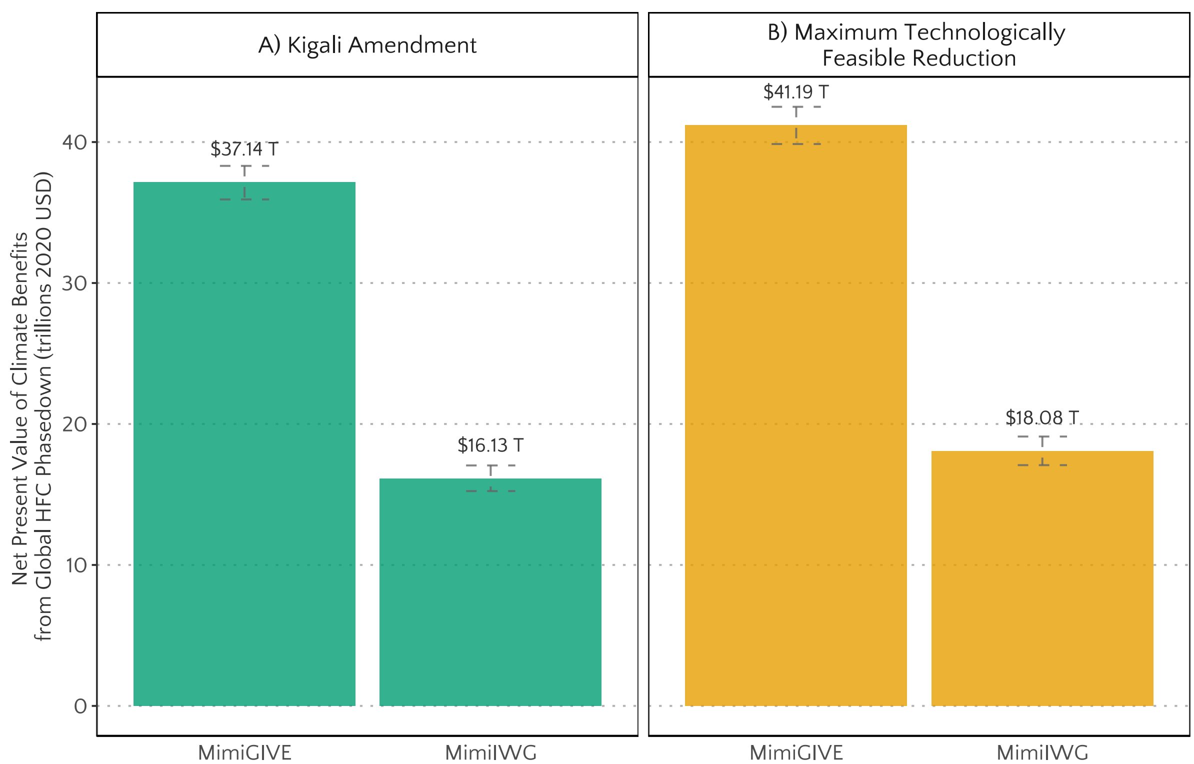


Fig. 4 | The total climate benefits from phasedown of hydrofluorocarbons. Total climate benefits under each phasedown schedule are discounted to the present (2023), realized relative to a baseline without the Kigali Amendment. MimiGIVE estimates are calculated assuming a calibrated Ramsey-like discount rate using a near-term target of 2%, while MimiIWG assumes a constant 3% discount rate. Climate benefits range from $16.13 trillion ($15.24T–$17.06T, 5%–95% range, 2020 US dollars) using the SC-HFC estimates under the as-published Kigali Amendment phasedown schedule and outdated USG methodology (Panel A), to $41.19 trillion ($39.86T–$42.50T, 5%–95% range, 2020 US dollars) under the maximum technologically feasible reduction and accounting for updated methodologies (Panel B). Uncertainty around the climate benefits under each policy (dashed error bars) is derived using a bootstrap simulation across the distributions of SC-HFCs and propagating the empirical distributions through to the final estimates (n = 50k). The error bars represent the 5th and 95th percentiles of the simulations.

Under the MFTR phasedown schedule, total climate benefits range from $18.08 trillion ($17.08T–$19.11T, 5%–95% range, 2020 US dollars) using the SC-HFCs from the MimiIWG framework, to $41.19 trillion ($39.86T–$42.50T, 5%–95% range, 2020 US dollars) using the MimiGIVE SC-HFC estimates (Fig. 4, Panel B). Under both modeling frameworks, we estimate an additional 11%-12% 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 often remain reliant on potent greenhouse gases, hydrofluorocarbons, as inputs to their production.

To contextualize the results discussed in this paper, we note that Wei et al. (2020)[24] estimate that following current emissions reductions efforts, the world would experience a washout of benefit amounting to $127-$616 trillion dollars between present and 2100 compared to a scenario where global temperature increases remain below the 1.5-2°C target laid out by the Paris Agreement. However, it is important to note that this is a cumulative measure of benefits to 2100, not a discounted present value. Calculating cumulative benefits to 2100 from the Kigali Amendment using MimiGIVE SC-HFCs yields $96 trillion (2020 USD) under a 2% near-term Ramsey rate, and $69 trillion using MimiIWG and SC-HFCs discounted at 3% constant rate. Despite differences in methodology and models between this paper and Wei et al. (2020), this approximate comparison provides some indication of the non-trivial contribution that enacting the Kigali Amendment may have towards achieving global climate goals like the Paris Agreement.

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.

Methods

Estimation using the current U.S. Government methodology. The SC-GHG estimates for CO_2, CH_4, and N_2O published by the USG use three widely cited integrated assessment models: the Dynamic Integrated Climate Economy (DICE)[27], the Climate Framework for Uncertainty, Negotiation, and Distribution model (FUND)[28,29,30], and the Policy Analysis of the Greenhouse Effect model (PAGE)[31,32,33]. 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)[34,35]. The USG also adopted a distribution for the equilibrium climate sensitivity (ECS) parameter—the Roe and Baker distribution[36].

In 2016, the USG extended their estimation of the SC-CO_2 to include simple representations of CH_4 and N_2O[37]. 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 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, 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. While this one-box approach is a simplified model that does not fully capture the atmospheric chemistry of the conversion, it is well-represented in the literature and in widely used simple climate models such as FaIR[37,14,28]. 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. 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[39,40,41]. This paper exploits the fact that baseline emissions of HFCs are relatively low (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[42].

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.

Following Myhre et al. (2013)[42] and Ramaswamy et al. (2001)[43], we use these HFC atmospheric concentration calculations to estimate additional radiative forcing from emissions of each gas. We assume that forcing from atmospheric concentrations of HFCs is proportional to its concentration. In other words, 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. Therefore, additional radiative forcing in year t, $RF(t)$ from the pulse of HFC emissions can be calculated as

$$RF(t) = X \times C(t) \tag{2}$$

where *X* is the radiative efficiency of the HFC.

Both the rate of decay values (Equation 1) and the radiative efficiency values (Equation 2) for each HFC are recovered from the Fourth Assessment Report (AR4)[44] (Table SI.1). We also present the values used by FaIR 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, yields eleven different marginal radiative forcing projections (Extended Data Fig. 3). 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. The small differences in the radiative forcing impulse response primarily reflect the differences in the (1) lifetime and (2) radiative efficiency parameters, which are kept consistent with original modeling efforts (Table SI.1). With respect to method and structure, while the addition of a marginal exogenous radiative forcing to MimiIWG peaks in the first year of emissions, the addition of a marginal pulse of emissions to MimiGIVE produces a radiative forcing impulse with a slight temporal delay before peaking. This third difference has a fairly negligible effect for most HFCs and is most pronounced for those with extremely short lifetimes (such as HFC152a). 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 (Fig. 1):

1. Estimate the model under baseline emissions scenario to calculate baseline damages.
2. Add marginal radiative forcing for HFC of interest (Extended Data Fig. 3) 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-CH_4 and SC-N_2O 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[18].

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[25,26]. 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% 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[15]. 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[18].

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[45,46,47]. This enables the direct estimation of the SC-HFCs by perturbing the emissions forcings of each gas individually and observing the marginal effects.

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[48] as used in the recent IPCC AR6[1] and by default uses the SSP2-4.5 scenario[49] 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 three missing 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)[50] 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 (Fig. 1):

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. 3).
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.

Calculating the SC-HFCs for the IWG model paired with the FaIR Climate Model. As previously discussed, the consensus in the current literature is that the climate model representations of the three IWG models do not represent key climate dynamics for the calculation of SC-GHGs, such as the temperature impulse response, as accurately as the newer generation of simple climate models used in integrated assessment models[16]. We investigate the implications of this finding by estimating the SC-HFCs using a hybrid approach we call MimiIWG-FaIR that begins with the current USG methodology, as implemented with MimiIWG, and substitutes the FaIR climate model for the individual climate models in DICE, FAIR, and PAGE to create three new models that estimate the SC-GHGs (Extended Data Fig. 2). The following steps were taken to enable this estimation:

1. Use the FaIR model with full parametric uncertainty to compute 10,000 pairs of (1) a baseline emission scenario and (2) a perturbed scenario with additional emissions for each combination of EMF-22 scenario, gas, and pulse year.
2. Compute damages under both the baseline scenario and the perturbed scenario by exogenously forcing the model (DICE, FUND, or PAGE) with the temperature trajectories computed in step 1.
3. Compute the SC-HFC as the net present value of the difference in damages estimated in step 2.

The impacts of this modification differ by individual IWG model, and by gas, as a result of the interaction between several climate response factors such as the speed of impulse response and the eventual magnitude and duration of the temperature anomaly, as well the interplay with emissions forcings, the shape of the damage function, and discounting. The SC-HFC152a and SC-CO_2 increase under MimiIWG-FaIR, while all other estimated SC-HFCs decrease under MimiIWG-FaIR (Extended Data Fig. 2). The literature provides some intuition behind these relationships. For example, Dietz et al. (2020) investigate several permutations of the DICE model and show that the combination of the DICE climate model's slow response to a pulse of CO_2 with a hotter, longer duration response anomaly resulted in a lower optimal carbon price than that calculated with an updated climate model[16]. They also emphasize that a delayed impulse response can lead to higher sensitivity to the choice of discount rate. It is important to note that this is not a full investigation of the impacts of the various modifications to socioeconomic scenarios, climate models, damages estimation, and discounting approaches, and the interactions between these different modifications, that in combination summarize the differences between MimiIWG and MimiGIVE. However, examples of similar current work can be found in literature such as Hänsel et al. (2020)[51].

The modeling constraints around this estimation methodology have a few important assumptions and consequences:

1. The MimiIWG-FaIR models do not use the USG-adopted distribution for the equilibrium climate sensitivity (ECS) parameter—the Roe and Baker distribution[36]—as used in the MimiIWG implementation and, instead, use the constrained parameter set dictated by the FaIR implementation.
2. The MimiIWG-FaiR models can only represent global mean surface temperature, so the PAGE implementation does not use regionally downscaled temperature, in contrast to the MimiIWG implementation of PAGE.
3. Temperature anomalies are bounded at a minimum of 0 degrees.

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 policymakers, 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[18].

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-CO_2 by the global warming potential of each HFC (Table SI.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 (Extended Data Fig. 4). 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)[44] (Extended Data Table 1). While slightly updated GWPs have been published under both the Fifth (AR5)[42] and Sixth (AR6)[46] Assessment Reports, we use AR4 values in this paper to maintain consistency with the USG's approach to estimating the social costs of non-CO_2 gases and the use of AR4 GWP100 in the passing of the American Innovation and Manufacturing Act (2021)[52]. 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[53]. 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[54]. The agreement went into force on 1 January 2019. It was not until October 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[10,55]. 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[10,23].

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 (Table SI.1). 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% 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[23]. 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 categories: Article 5 and non-Article 5. The first category, Article 5, includes primarily developing countries and is alloted 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 stricter schedule, being required to achieve an 85% reduction by 2035, a full ten years earlier (Extended Data Fig. 5).

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)[23]. 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[40] 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, which is often considered a relatively pessimistic future scenario. Projections based on SSP1 are provided as an optimistic sensitivity case; however, they find that differences in HFC emissions between the two scenarios are minimal. Purohit et al. (2020) further note that mitigation potential relative to the baseline is similar for different SSPs[23]. Hence, the baseline scenario assumed by the model should be of minor consequence for our analysis, which relies only on estimates of HFC reductions relative to baseline to calculate total climate benefits under each policy. That is, even if the Purohit et al. (2020) baseline emissions projections were identical to those used by our model runs in MimiGIVE and MimiIWG, it is reasonable to assume that ultimately the estimated reductions under KA and the MTFR would have been negligibly different from those made under the current SSP3 baseline assumption.

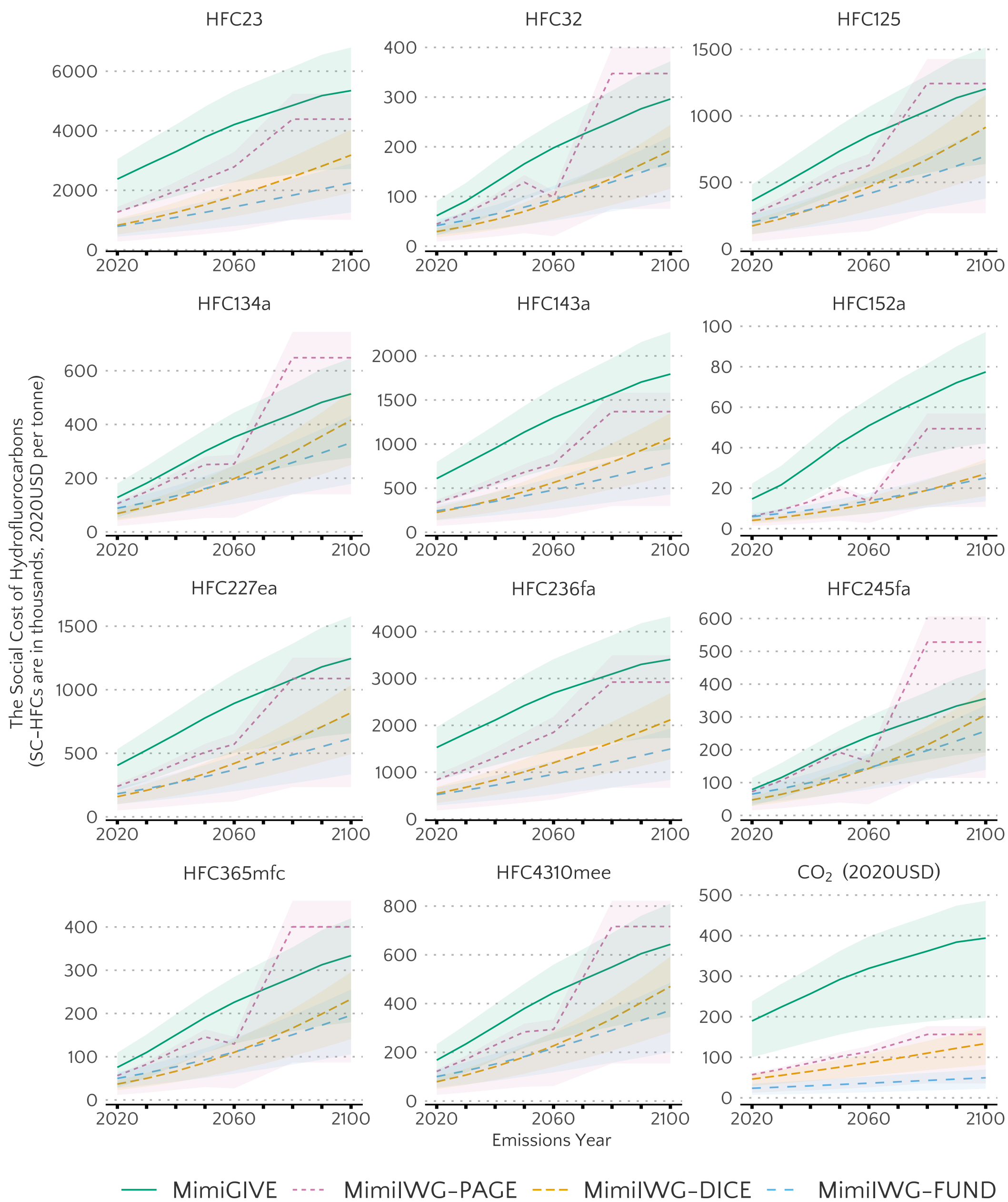
Purohit et al. (2020) developed two sets of alternative phasedown assumptions, one based on “technical” energy efficiency potentials, and one based on “economic” energy efficiency potentials[23]. We use the projections based on technical energy efficiency potentials for these calculations since these represent the maximum efficiency improvements considered technically possible and is the primary motivation of our alternative phasedown analysis.

The climate benefits calculation. Climate benefits were calculated based on emissions projections from Purohit et al. (2020)[23]. 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. 6). 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% for MimiIWG and a constant discount rate of 2% 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

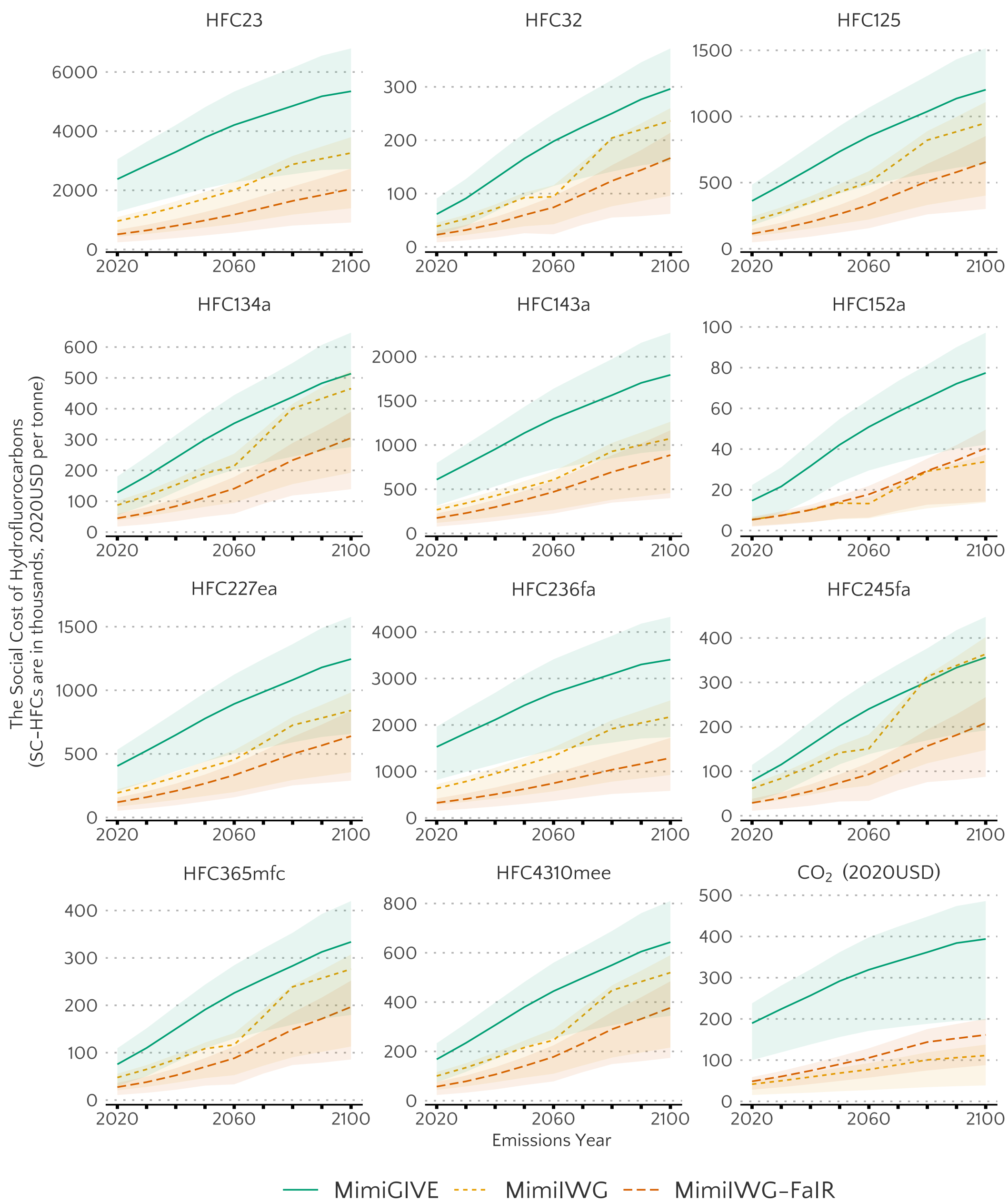
$$NPV_{2023} = \sum_{t=2023}^{2100} \frac{\sum_{j=HFC}^{J}(SCHFC_{tj} \times \phi_{tj})}{(1+\rho)^{t-2023}}.$$

The net present value represents the total climate benefit from HFC emissions reductions under each scenario (Fig. 4). 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.

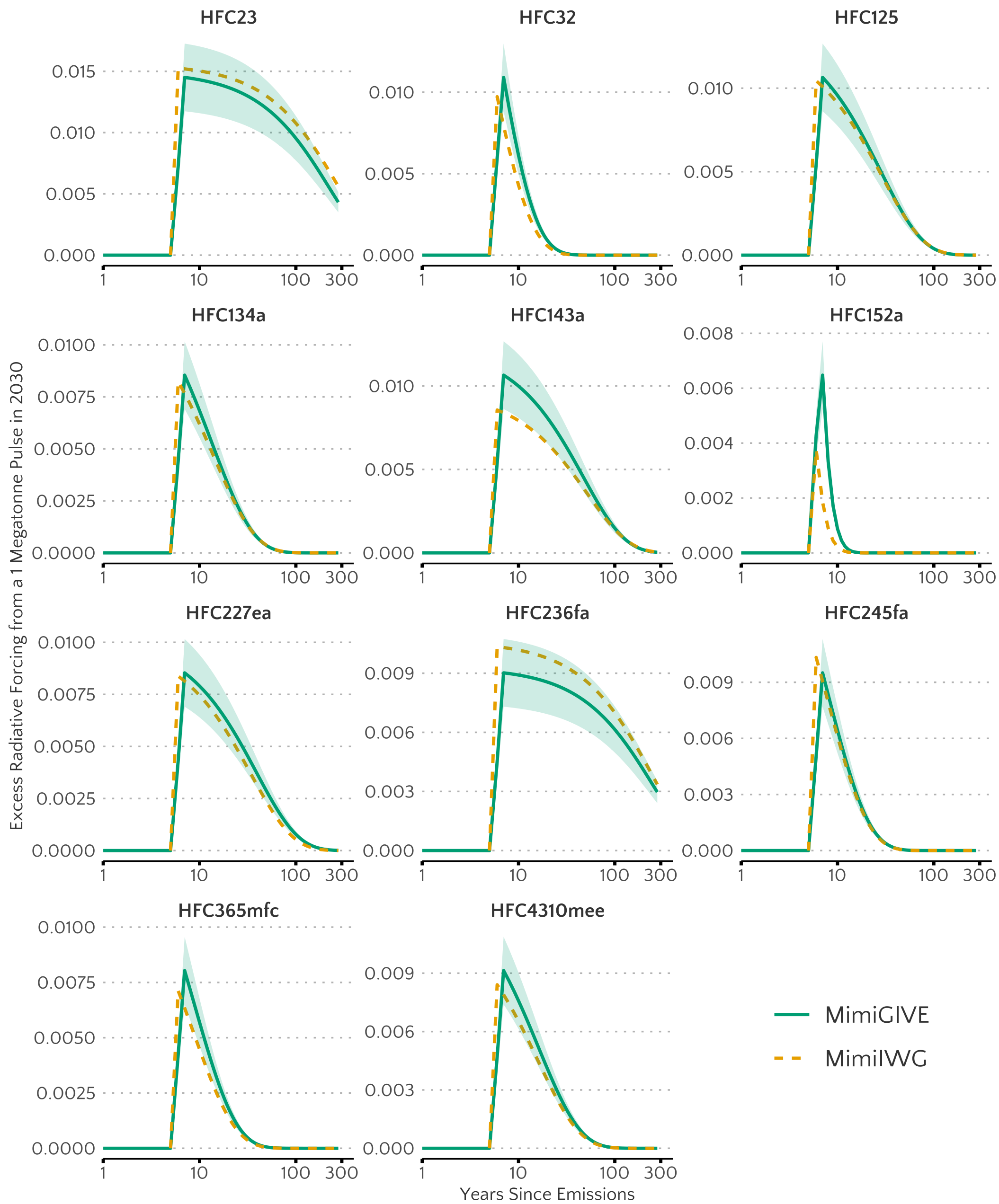
Extended Data Figures



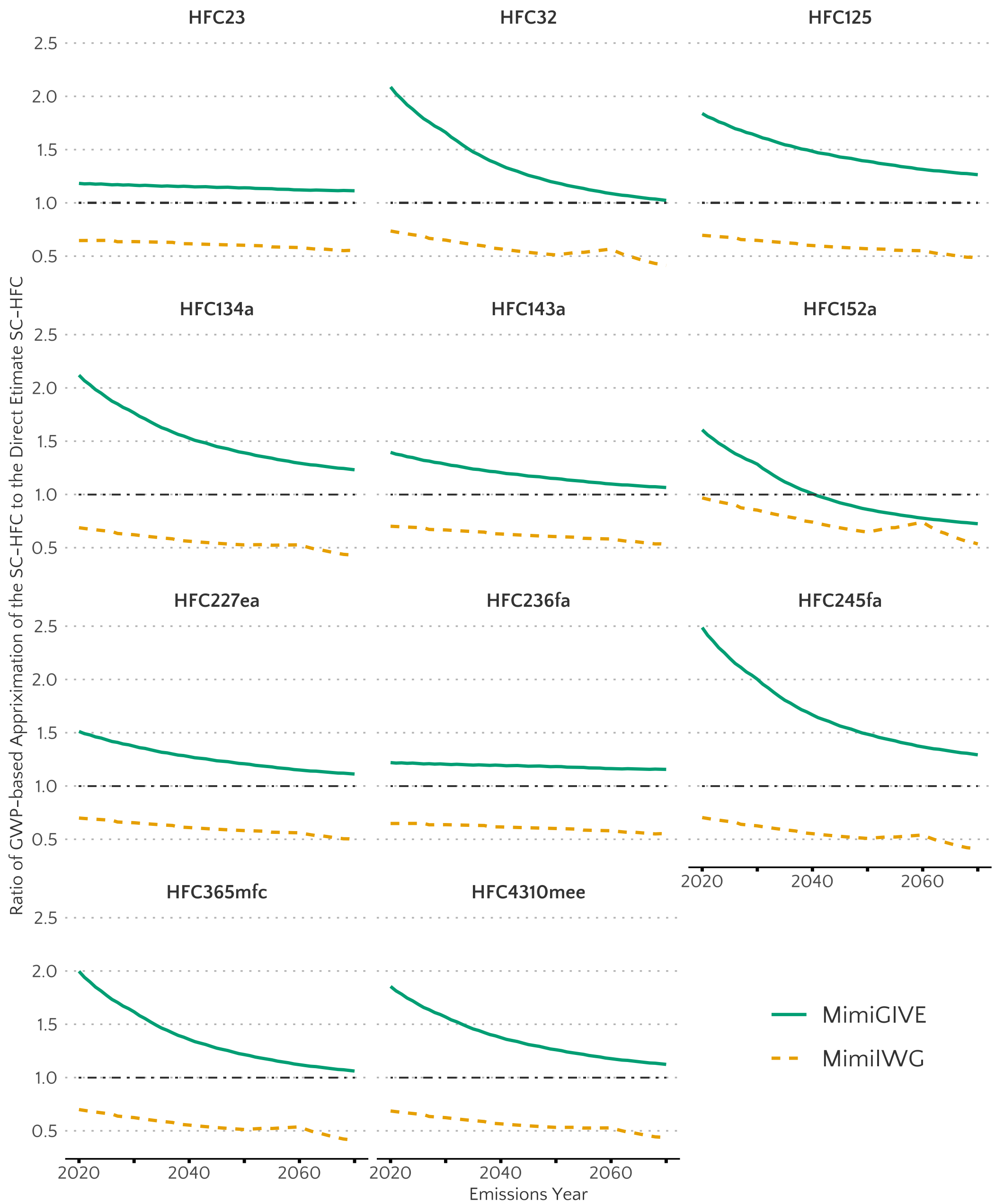
Extended Data Fig. 1 | The Social Cost of Hydrofluorocarbons by IAM. The direct estimates developed in this study are noticeably different under the USG approach (MimiIWG) compared to the updated GIVE model (MimiGIVE). The mean SC-HFCs (lines) from each of the underlying IAMs, along with their 5th to 95th percentile ranges (shaded ribbons), 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% 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%, the central value in Rennert et al. (2022b).



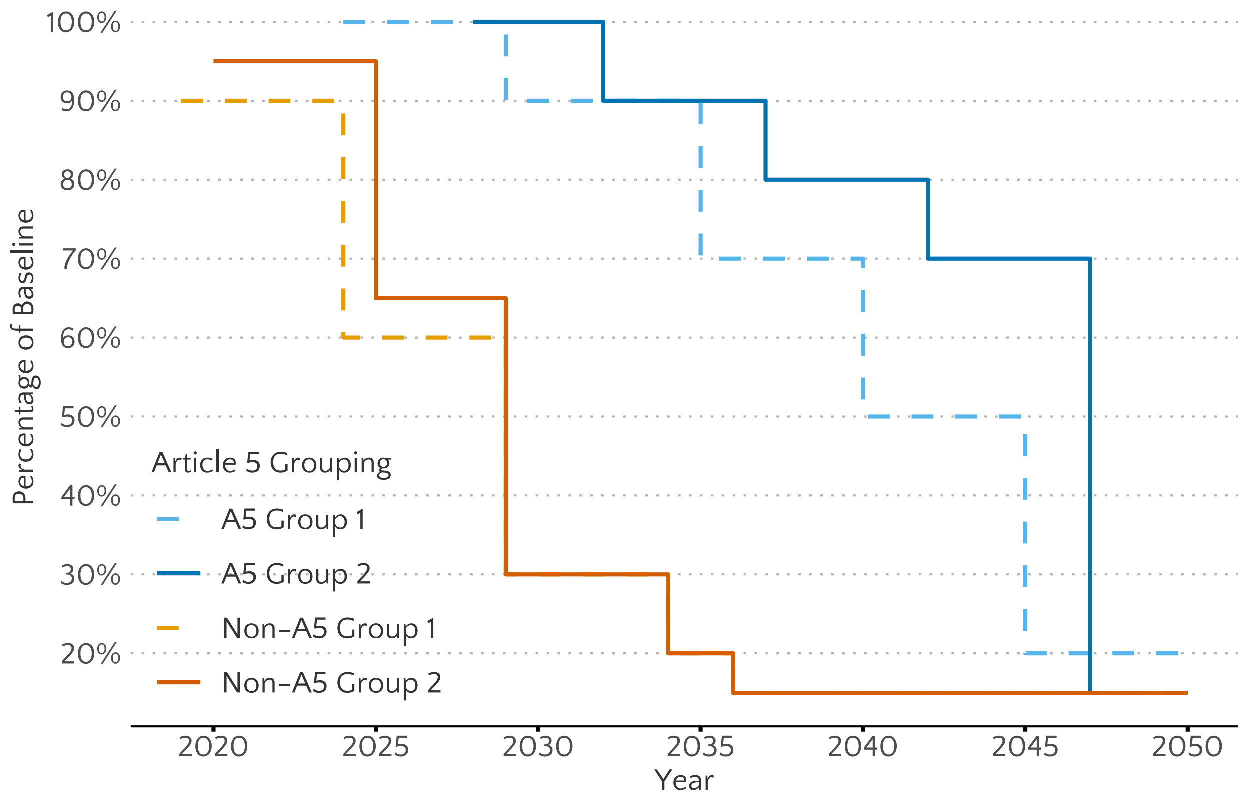
Extended Data Fig. 2 | The Social Cost of Hydrofluorocarbons with MimiIWG-FaIR Pairing. The estimates using the paired approach (MimiIWG-FaIR) differ from those using the USG approach (MimiIWG), although their relationship differs noticeably by gas. The mean SC-HFCs (lines) from each underlying approach, along with their 5th to 95th percentile ranges (shaded ribbons), are shown, representing the distribution of estimated SC-HFC values over the 10,000 Monte Carlo simulations. The SC-HFCs from MimiIWG and MimiIWG-FaIR adopt a 3% 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%, the central value in Rennert et al. (2022b).



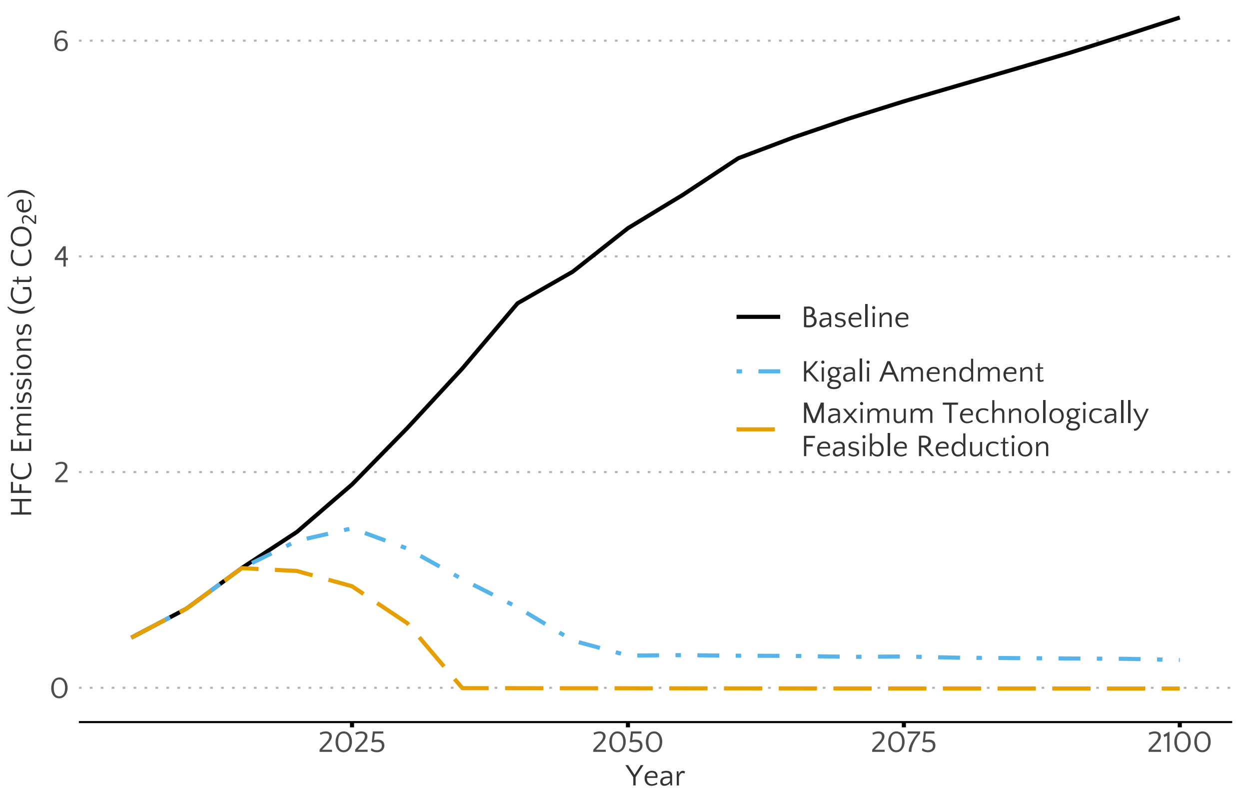
Extended Data Fig. 3 | Additional radiative forcing from 1 tonne pulse of hydrofluorocarbons in 2030. Paths of additional radiative forcing for under MimiIWG are the result of the one-box model. The paths shown for MimiGIVE includes the mean (solid line) and the 5th to 95th percentile ranges (shaded ribbons) across 10,000 Monte Carlo Simulations that account for uncertainty underlying its simple climate model (FaIRv1.6.2). The x-axis of this plot spans the years 2025-2300 for a pulse of emissions in 2030.



Extended Data Fig. 4 | 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 integrated estimates of the SC-HFCs. The ratio of GWP-based estimates to directly estimated SC-HFCs is estimated as $ratio = SCCO_2 \times GWP^{HFC} / SCHFC$ 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. 5 | 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% 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% 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% by 2036. Reductions start in 2019 for Non-Article 5 Group 1 and 2020 for Non-Article 5 Group 2.



Extended Data Fig. 6 | 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 sched ule.

Extended Data Tables

	Emissions Year	Hydrofluorocarbon Species										
		23	32	125	134a	143a	152a	227ea	236fa	245fa	365mfc	4310mee
Panel A: MimiGIVE 2% Near-term Ramsey Rate	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
3% Near-term Ramsey Rate	2020	1078	43	223	86	347	10	238	688	54	52	111
	2030	1373	68	313	128	469	16	326	874	84	80	163
	2040	1669	99	409	176	596	25	418	1061	121	114	221
	2050	1989	131	507	224	728	34	513	1264	157	147	279
	2060	2264	157	591	265	842	41	595	1438	187	175	328
	2070	2470	177	655	295	930	47	658	1568	210	196	366
	2080	2697	196	723	327	1024	52	726	1711	232	217	404
	2090	2929	216	795	360	1124	58	797	1858	256	239	446
	2100	3039	229	836	380	1178	61	836	1926	271	253	470
Panel B: MimiGIVE 2% Constant Discount Rate	2020	2436	68	411	160	558	9	383	1595	110	85	185
	2030	2835	88	508	204	675	12	470	1859	142	110	235
	2040	3266	113	616	253	802	16	566	2146	180	139	291
	2050	3719	140	726	302	932	20	665	2446	219	168	346
	2060	4177	141	820	332	1054	20	753	2747	228	177	383
	2070	4789	206	1009	441	1250	29	915	3153	324	249	502
	2080	5409	273	1202	554	1451	39	1080	3564	422	323	625
	2090	5704	294	1294	600	1558	42	1163	3760	456	348	674
	2100	5996	315	1388	643	1667	45	1247	3957	490	373	724
3% Constant Discount Rate	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 two near-term target discount rates, 2% (the central value in Rennert et al. 2022b), and 3% with calibrated Ramsey parameters (Newell et al., 2022). Panel B presents estimates from MimiIWG using two constant discount rates, 3% (the central rate in USG, 2021) and 2%. 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.

	Kigali Amendment	**Maximum Technologically Feasible Reduction**
MimiGIVE 2% Near-term Ramsey Rate	$37.14 [$35.93, $38.31]	$41.19 [$39.86, $42.50]
MimiGIVE 3% Near-term Ramsey Rate	$17.58 [$16.91, $18.29]	$19.81 [$19.06, $20.61]
MimiIWG 2% Constant Discount Rate	$38.06 [$36.32, $39.81]	$42.18 [$40.25, $44.13]
MimiIWG 3% Constant Discount Rate	$16.13 [$15.24, $17.06]	$18.08 [$17.08, $19.11]

Extended Data Table 2 | The total climate benefits from phasedown of hydrofluorocarbons. Total climate benefits under each phasedown schedule are discounted to the present (2023, trillions USD), realized relative to a baseline without the Kigali Amendment. Uncertainty around the climate benefits under each policy is derived using a bootstrap simulation across the distributions of SC-HFCs and propagating the empirical distributions through to the final estimates. The values in brackets represent the 5th and 95th percentiles of the simulations, while the central value represents the mean.

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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.

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[56]. All models used in this study are implemented on the Mimi.jl computational platform for integrated assessment models[57].

Data Availability

Complete replication code and data for this study are freely available from Parthum et al. (2023): https://zenodo.org/records/10081241[58].

Code Availability

Complete replication code and data for this study are freely available from Parthum et al. (2023): https://zenodo.org/records/10081241[58].

Supporting Information

Additional Details on the IAMs in the U.S. Government 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)[1,2]. 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[3]. 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. DICE2010 represents damages from climate change as a fractional per-period loss in (endogenous) gross domestic product (GDP). The model calculates this loss using a quadratic function of the temperature anomaly and a quadratic function of total sea level rise, both estimated using meta-analysis of the literature, thus incorporating an array of impact categories without explicitly separating each of them. 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)[4,5,6]. 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. The model estimates damages using different damage functions for each of eight distinct impact categories: agriculture, forestry, water, energy, sea level rise, ecosystems, human health, and extreme weather. 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)[7,8,9]. 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 model estimates climate damages in three main categories: economic, non-economic, and catastrophic for each of these eight regions. Damage functions in PAGE are power functions of the temperature anomaly and estimate fractional loss to (exogenous) GDP in a given period. 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.

Additional Details on the GIVE Climate Damages Representation. At present the Greenhouse Gas Impact Value Estimator (GIVE) model estimates climate damages occurring in four categories: agriculture, energy, health, and sea level rise damages to coastal regions[10]. The damage functions in each sector reflect recent scientific advancements in the peer-reviewed literature, and the underlying studies were each published independently of the GIVE model. The damages module incorporates parametric uncertainty via Monte Carlo Simulation whenever the information is available in the underlying literature to do so. We here include a brief overview of the damage estimation in the GIVE model, while a full description can be found in Rennert et al. (2022)[10] and the underlying literature for each individual damage sector.

GIVE utilizes Moore et al. (2017)[11] for the agriculture damage function. The study uses a meta-analysis of temperature-yield response estimates to review the biophysical impacts of climate change on various key crops including maize, rice, wheat, and soybeans. These studies do, to a certain extent, include the mediation of impacts using exiting adaptation measures. The authors then use a computable general equilibrium (CGE) model to estimate welfare consequences of these productivity changes while incorporating the effects of agriculture market shifts (e.g., trade patterns).

Damages in the energy sector reflect changes in building energy expenditure, for both heating and cooling, in response to changes in temperature[12]. Using the Global Change Analysis Model (GCAM), Clarke et al. (2018)[12] relates changes in temperature to changes in the regional energy expenditure of the 12 GCAM regions as a percentage of gross domestic product (GDP).

GIVE estimates damages in the health sector with a damage function developed from a meta-analysis of climate change impacts on human health[13]. The authors of the study, alongside a panel of experts in epidemiology, climatology, and economics, reviewed the literature on the impacts of increase in temperature on regionally resolved mortality. They then used this systematic review to generate a damage function that relates changes in average annual surface temperature to changes in premature mortality across nine distinct global regions. GIVE monetizes this physical impact using a country-specific measure of willingness-to-pay for mortality risk reduction.

Finally, GIVE uses the BRICK sea level rise model[14] to estimate local sea level rise for over 11,000 unique coastal segments, derived from the global mean surface temperature anomaly produced by the FaIR model. The CIAM model[15] translates these sea level rise projections into monetized damages from sea level rise as calculated based on local adaptation decision-making and the resultant sum of (1) adaptation costs (2) residual damages costs.

Supplementary Tables

HFC Species	(1) Lifetime (AR4) $\tau(yr)$	(2) Lifetime (FaIR) $\tau(yr)$	(3) Molecular Weight	(4) Radiative Efficiency (AR4)	(5) Radiative Efficiency (FaIR)
23	270.0	222.0	70.01	0.19	0.18
32	4.9	5.2	52.02	0.11	0.11
125	29.0	28.2	120.02	0.23	0.23
134a	14.0	13.4	102.03	0.16	0.16
143a	52.0	47.1	84.04	0.13	0.16
152a	1.4	1.5	66.05	0.09	0.10
227ea	34.2	38.9	170.03	0.26	0.26
236fa	240.0	242	152.04	0.28	0.24
245fa	7.6	7.7	134.05	0.28	0.24
365mfc	8.6	8.7	148.07	0.21	0.22
4310mee	15.9	16.1	252.06	0.40	0.42

Table SI.1 | Lifetime, Weight, and Radiative Efficiency of Hydrofluorocarbons. The lifetime, molecular weight, and radiative efficiency values used in the MimiIWG 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-CO_2, SC-CH_4, and SC-N_2O. Values from FaIR are presented as a comparison and drawn from the FaIRv1.6.2 implementation (Millar et al. 2017).

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

Table SI.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.

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