Sustained Neutralization of the Warming Response to Emissions through Multiple Mitigation Strategies

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Abstract

Emissions abatement and carbon dioxide removal (CDR) are critical to achieving a global net-zero scenario under which temperatures are stabilized. In the near term, organizations pursuing net-zero targets may compensate for remaining emissions by combining short-lived climate pollutant (SLCP) abatement with CDR. Because these mitigation strategies have climate impacts across distinct timescales, they provide complementary tools to address both near-term and long-term warming. However, the distinct timescales mean that, to ensure emissions remain compensated, accounting approaches must evaluate each strategy's impact across time. We propose an approach based on sustained warming neutralization. By translating emission and mitigation impacts into a single metric - the continuous global mean surface temperature response - it ensures the warming response to an emission is neutralized in the near- and long-term. We then introduce a method to design mitigation portfolios using the approach. Ultimately, the approach structurally aligns emission compensation claims with global temperature stabilization goals.

Main

Greenhouse gas (GHG) mitigation plays a critical role in achieving a net-zero scenario under which global temperatures are stabilized (Riahi et al. 2023). In the near term, 'credits' for GHG mitigation achieved outside of the scope of an organization's operations provide important instruments for organizations to compensate for their remaining emissions and, in so doing, help to scale the long-term mitigation strategies that will be essential in global net-zero or overshoot scenarios (UNEP 2026). These credits include carbon dioxide removal (CDR) with storage durability comparable to the atmospheric lifetime of CO_2 (hereafter 'durable' CDR); CDR with shorter or more uncertain storage durability (hereafter 'shorter-durability' CDR); and superpollutant emission abatement. Superpollutants are a class of GHGs that possess significantly higher near-term warming potentials compared to CO_2 (Table 1). The subset of superpollutants with atmospheric lifetimes shorter than CO_2 – including methane and some F-gases – are commonly referred to as short-lived climate pollutants, or SLCPs.

One way to use GHG mitigation to compensate for hard-to-abate emissions is on a like-for-like mass basis (Allen et al. 2022). For example, long-lived fossil CO_2 emissions would be paired with an equivalent number of tonnes of durable CDR, and CH_4 emissions would be paired with an equivalent number of tonnes of CH_4 abatement. However, organizations commonly seek to compensate for hard-to-abate emissions – most often a 'residual' of fossil CO_2 emissions – through a portfolio of GHG mitigation strategies that are not strictly matched to the GHG composition of the emissions. A portfolio can incorporate superpollutant abatement and shorter-durability CDR alongside durable CDR.

Within such a portfolio, durable CDR remains essential in addressing the warming driven by fossil CO_2 emissions. Due to the dynamics of ocean heat uptake, this warming persists significantly beyond the atmospheric residence of the CO_2 itself for timescales reaching into millennia (Solomon et al. 2009; MacDougall et al. 2020). However, the projected supply of durable CDR is not expected to meet the quantity of hard-to-abate emissions in time to limit peak warming over the coming decades (S. M. Smith et al. 2024). Inclusion of SLCP mitigation and shorter-durability CDR can help to address this near-term capacity constraint, as both strategies can be delivered through comparably mature and scaled technologies. Shorter-durability CDR, including many nature-based pathways, can fully neutralize the warming response to CO_2 emissions for the duration of their storage relative to a non-intervention counterfactual. Concurrently, because SLCPs have higher warming potentials and shorter atmospheric lifetimes than CO_2, the destruction of a given mass of SLCP emissions can have a greater impact on acute near-term warming than a CO_2-equivalent mass of CDR (Szopa et al. 2023), including the potential tipping points and rate-based system risks that near-term net-zero goals seek to avoid (Wang et al. 2023; Fischer et al. 2021). SLCP mitigation and shorter-durability CDR therefore form complementary strategies to durable CDR, neutralizing near-term warming while durable CDR achieves the scale ultimately required to neutralize long-term equilibrium warming (Matthews et al. 2022; Ocko et al. 2021; Streck et al. 2025; UNEP 2026).

Many organizations therefore select portfolios combining SLCP mitigation and shorter-durability CDR with durable CDR. However, because their impacts are shorter lived than the warming response to a fossil CO_2 emission, these strategies require careful accounting (Figure 1) (Allen et al. 2022; Pierrehumbert 2014). Conventional accounting relies on Global Warming Potentials to convert radiative forcing into CO_2-equivalence over static 20- or 100-year horizons (GWP20 and GWP100; Table 1). However, using a single time horizon obscures variation in the impact of emissions and mitigation through time. In the near term, SLCP mitigation over-compensates for a GWP-equivalent CO_2 emission. Conversely, as the RF of SLCP mitigation dissipates at longer horizons, the persistent RF of the CO_2 emission is left uncompensated (Hausfather 2025). Similarly, while shorter-durability fully CDR compensates for emissions while storage remains durable, subsequent CO_2 release would leave the emission uncompensated (Cullenward 2023). Conventional accounting approaches based on a single time horizon can therefore mean that emissions are not compensated across time. This creates a structural inconsistency between emission compensation claims and the Paris Agreement's goal of long-term stabilization of global surface temperatures (Brunner et al. 2024).

Alignment between carbon accounting and global temperature goals instead requires an approach that explicitly represents the climate impact of each mitigation strategy across time. In this work, we propose to achieve this alignment through a 'warming neutralization approach'. We then describe a method through which organizations can use the approach to design mitigation portfolios.

The Warming Neutralization Approach

The warming neutralization approach is built on two core components: a physically representative metric for the climate impact of emissions and mitigation, and the continuous evaluation of this impact across time. The selected metric is the global mean surface temperature (GMST) response (see Supplementary Information for discussion of alternatives). GMST is selected because, as a measure of the Earth system's integrated thermal response, it is directly coupled to climate outcomes, serves as a proxy for climate damage and reversibility, and provides a state variable aligned with global temperature goals (Lynch et al. 2020). The combined GMST response to emissions and each mitigation strategy is evaluated across time, allowing their distinct climate outcomes to be accounted for through a single metric. Organizations can then achieve emissions compensation through any combination of mitigation strategies that ensures the warming response to the emissions is neutralized across time. Ultimately, this enables emission compensation claims that represent the sustained neutralization of warming (or 'net-zero warming') - regardless of the number and type of mitigation strategies used - and that are structurally consistent with global goals for long-term temperature stabilization.

A consequence of this approach is that, to neutralize the long-term warming response to a CO_2 emission, SLCP mitigation or shorter-durability CDR would need to be replaced – either by additional and repeated SLCP mitigation or shorter-durability CDR, or by a single instance of durable CDR – as their impacts dissipate. This requirement creates choices regarding the quantity of SLCP mitigation or shorter-durability CDR to purchase, the schedule on which it is replaced with more SLCP mitigation, shorter-durability CDR, or durable CDR, and the governance through which this replacement is managed. Here, we introduce one method for designing mitigation portfolios under the approach that enables these choices (see Supplementary Information for alternative methods).

A Method for Implementing the Warming Neutralization Approach

Under the method, mitigation portfolios can be designed that combine any set of mitigation strategies, either concurrently or sequentially, that together achieve sustained warming neutralization. The method first uses a reduced-complexity climate model (RCCM) to simulate the continuous GMST response to the combination of emissions and any existing mitigation. It thereby determines the quantity and timing of any additional mitigation required to ensure that the sustained GMST response to emissions and mitigation is ≤ 0°C, meaning that warming is neutralized across time. We use the Finite-amplitude Impulse Response (FaIR) RCCM for GMST simulations (see Methods).

Because the method considers the response to emissions and mitigation across successive years, it ensures the warming response to the emissions remains neutralized without requiring year-by-year mass-based accounting. In practice, however, because a significant fraction of the warming response to a fossil CO_2 emission persists for > 1,000 years, long-term neutralization of these emissions will ultimately require an equivalent quantity of durable CDR (Solomon et al. 2009; Joos et al. 2013; Archer et al. 2009). While repeat use of shorter-lived GHG mitigation could also be used for long-term neutralization, this is unlikely to be practicable on long timescales.

The method therefore enables two primary scenarios for portfolio design: 'stacking' and 'bridging'. First, if the quantity and timing of shorter-lived GHG mitigation is known, the method can determine the schedule of replacement (or stacking) with durable CDR that ensures the long-term warming response to CO_2 emissions remains neutralized. Conversely, if the schedule of durable CDR is already defined but delayed relative to the time of an emission, the method can determine the quantity of shorter-lived mitigation required to neutralize the warming response to emissions in the interim (bridging). We outline these stacking and bridging scenarios in turn.

Stacking: Scheduling durable CDR to Replace Shorter-Lived Mitigation

To demonstrate stacking, consider an organization using a 2030 pulse of CH_4 mitigation (1 Gt CO_2e at GWP20; 12.3 Mt CH_4) to initially neutralize a 1 Gt fossil CO_2 emission in 2030 (Figure 2). The method uses the RCCM to evaluate the continuous GMST response to this combination. Initially, CH_4 mitigation drives net cooling (combined GMST response < 0°C). As its cooling effect dissipates, the combined GMST response crosses 0°C, defining the year when durable CDR must be added to sustain neutralization (evaluated at p95 to ensure conservatism; see Methods). Because the CH_4 continues to provide partial cooling, durable CDR can be added progressively. The model calculates the minimum annual CDR required to maintain GMST ≤ 0°C until the cumulative mass of durable CDR equals the mass CO_2 emitted. Any CDR replacement that meets, or exceeds, this schedule is then sufficient to achieve warming neutralization across time.

Beyond this example, multiple types of shorter-lived mitigation could be used to initially compensate for a CO_2 emission. For SLCP mitigation, the specific properties of the SLCP determine the time over which it can neutralize the warming response to an emission. Shorter-durability CDR can fully neutralize the warming response to an equivalent quantity of CO_2 emissions for the duration of its storage relative to a non-intervention counterfactual. Shorter-durability CDR is typically assigned a durability claim (also referred to as an estimated durability, a permanence period, or storage term) representing the time over which storage is assured, and so this can be used as a proxy for the latest time at which it needs to be replaced with an equivalent quantity of durable CDR (see Methods).

Bridging: Scheduling Shorter-Lived Mitigation to Bridge to Delayed CDR

Shorter-lived mitigation can provide a temporary ‘bridge’ to ensure the warming response to emissions remains neutralized across a delay in net CO_2 drawdown by CDR. Such delays may occur at project level (for example, due to the physical process of CO_2 drawdown) (Cabiyo et al. 2026) or at portfolio or planetary scale, where the expansion in CDR capacity cannot yet match hard-to-abate CO_2 emissions (S. M. Smith et al. 2024).

To demonstrate bridging, consider an organization compensating for a 1 Gt CO_2 emission in 2030 using durable CDR that begins in 2040 and ramps linearly to 1 Gt over 10 years. The method uses the RCCM to calculate the minimum quantity of CH_4 mitigation required per year across the delay such that the combined GMST response to the CH_4 mitigation and emission (evaluated at p95 to ensure conservatism) remains < 0°C. CH_4 mitigation continues to be required until the year in which the cumulative quantity of durable CDR is equivalent to the CO_2 emission. Through the combination of the CH_4 mitigation and durable CDR, the warming is then neutralized across time (Figure 2).

As previously, portfolio design under a bridging scenario could use multiple types of shorter-lived mitigation. For SLCP mitigation, the quantity required to bridge a delay will depend on the specific properties of the SLCP. For shorter-durability CDR, a quantity equivalent to the CO_2 emission will be sufficient, provided that its durability claim exceeds the time required for the durable CDR to ramp up to an equivalent cumulative quantity.

Standardized Relationships for Stacking and Bridging

Calculating the optimal (minimum) annual mitigation required in a stacking or bridging scenario requires bespoke model execution, which may be operationally impractical for many organizations. To address this, the same RCCM-based method can be used to calculate standardized relationships for stacking and bridging scenarios (see Methods).

As above, multiple types of SLCP mitigation and shorter-durability CDR can be used for stacking or bridging. For shorter-durability CDR, standardized relationships are not strictly necessary: the quantity required equals the quantity of CO_2 emitted, and the replacement time is determined by the durability claim. For SLCP mitigation, the method can be used to calculate a standardized relationship between a quantity of CO_2 emitted, a quantity of mitigation used, and a time at which durable CDR must replace it. Here, we report these relationships for common types of SLCP mitigation (Table 2). The relationships apply to stacking or bridging under a simple scenario: CO_2 emissions are initially neutralized using an equivalent quantity of SLCP mitigation (in tCO_2e at GWP20), and this SLCP mitigation is then replaced by an equivalent quantity of durable CDR. In a stacking scenario, the year reported in Table 2 represents the latest possible time at which the SLCP mitigation can be replaced by durable CDR, and any replacement that meets or precedes this will be sufficient to sustain neutralization of the emission's warming response. In a bridging scenario, the year reported in Table 2 reflects the time by which the delayed CDR must have fully 'ramped up' to a quantity equivalent to the CO_2 emission to ensure that the initial SLCP mitigation is sufficient to neutralize the warming response in the interim.

Organizations could use different time horizons for replacement with durable CDR in a stacking or bridging scenario: longer replacement times will simply require larger initial quantities of SLCP mitigation to ensure the warming response to the emission remains neutralized prior to replacement. A table reporting the standardized relationships between the quantity of SLCP mitigation and the quantity of CO_2 emitted for replacement times between 1 and 20 years is provided in the Supplementary Information.

The simplifying assumptions used to produce the standardized relationships mean that the relationships are more conservative than strictly required in stacking or bridging scenarios. In a stacking scenario, the SLCP mitigation will continue to partially neutralize the warming response to an emission following replacement with durable CDR. In a bridging scenario, a progressive ramp-up of CDR prior to replacement would provide partial cooling on top of the SLCP mitigation. However, by accepting minor compromises on strict optimality, the relationships eliminate the need for model execution, making them widely operable.

Discussion

This paper proposes a warming neutralization approach as an alternative to the conventional GWP framework used in carbon accounting. The approach accounts for the combined climate impact of mitigation and emissions through the continuous global mean surface temperature (GMST) response. This explicitly represents the value of SLCP mitigation in addressing near-term warming, shorter-durability CDR in fully compensating for CO_2 emissions over decades to centuries, and durable CDR in addressing millennial-scale warming. This enables emission compensation claims that, by explicitly considering time-dependent warming impacts, are structurally aligned with global goals for long-term temperature stabilization.

A specific method is introduced to enable the design of mitigation portfolios under the approach. The method uses a reduced-complexity climate model (RCCM) to evaluate the continuous GMST response to emissions and mitigation. In a stacking scenario, the method calculates the durable CDR required to sustain neutralization of the warming response to emissions as the impact of shorter-lived mitigation dissipates. In a bridging scenario, the method calculates the shorter-lived mitigation required to neutralize warming across a delay in the timing of durable CDR relative to emissions.

Full model execution can be used to design 'optimised' portfolios, where the minimum quantity of mitigation is added per year while ensuring the warming response to emissions remains neutralized. To make this more operable, the method is resolved into standardized relationships that can be used to design portfolios under stacking and bridging scenarios without requiring model execution.

The latter is likely to be how many organisations implement the approach. To demonstrate this, consider an organisation compensating for a 1 Gt CO_2 emission in 2030 using CH_4 mitigation and CDR. Following Table 2, a total of 1 Gt (CO_2e at GWP20) of CH_4 mitigation is required by 2030, and this must be replaced by 1 Gt of durable CDR at latest 12 years after the CH_4 mitigation. Multiple portfolios can be built that adhere to these relationships and achieve sustained warming neutralization (Figure 3). For example, most simply, an organization could use 1 Gt CH_4 mitigation issued in 2030, and replace this with 1 Gt durable CDR in 2042. Alternatively, an organization could use CH_4 mitigation issued across 2026 (0.4 Gt CO_2e) and 2027 (0.6 Gt CO_2e), and replace this with 1 Gt CDR issued across 2037 (0.2 Gt) 2038 (0.3 Gt) and

2039 (0.5 Gt). In a more realistic case, an organization can apply the same relationships to neutralize consecutive years of CO_2 emissions by using multiple types of shorter-lived mitigation, each of which may also be issued across multiple years (Figure 4).

Governance of the approach must also be operable. Emission compensation claims will be most defensible if organizations establish contractual commitments to replace shorter-lived mitigation with durable CDR before, or at, the time of the claim. In addition, while shorter-lived mitigation strategies are highly effective in addressing acute near-term warming at scale and low cost, durable CDR also requires near-term support to reach the scale ultimately required to address long-term equilibrium warming.

At a portfolio level, the warming neutralization approach will therefore be most impactful when organizations support durable CDR in parallel to shorter-lived mitigation. Multiple financial structures could achieve this. One possibility is that an organization establishes independent contracts for shorter-lived mitigation and durable CDR, and these are then paired to achieve sustained warming neutralization. Alternatively, organizations could contribute to an independently-managed fund from which committed dollars appreciate and are used to procure durable CDR as the impact of shorter-lived mitigation dissipates. Such a fund could also act as an early off-taker to support the scale-up of CDR.

This overview does not provide an exhaustive list of financial structures that could be used. These will require further development and are beyond the scope of this paper. Ultimately, the objective would be for organizations to take action before the year of claim that ensures the climate impact underlying that claim is as long lived as the emission. We invite future work to consider how the approach could be used to produce robust emission compensation claims based on ‘net-zero warming’ that support near-term progress towards global temperature stabilization goals.

Table 1. *Atmospheric lifetimes and Global Warming Potentials (GWPs) of major greenhouse gases (Forster et al. 2023). GWP is a metric used to compare the integrated radiative forcing of a specific mass of a greenhouse gas to an equivalent mass of CO_2. GWP100 and GWP20 represent this integrated forcing relative to CO_2 over 100-year and 20-year time horizons, respectively. *No single atmospheric lifetime can be defined for CO_2 because it is removed via multiple processes operating on different timescales. Based on current ocean and land carbon sink strength, approximately 50 percent is removed within 30 years, an additional 30 percent within a few centuries, and the remaining 20 percent persists for thousands of years (Joos et al. 2013). Note that, at the scale of corporate emissions, the processes that remove atmospheric CO_2 apply approximately symmetrically to CDR (see Methods) (Zickfeld et al. 2021).*

Greenhouse Gas (GHG)	Atmospheric Lifetime (Years)	GWP20	GWP100
Carbon dioxide (CO_2)	Multiple*	1	1
Methane (CH_4)	11.8	81.2	27.9
HFC-134a (CH_2FCHF_3)	14	4140	1530
HFC-32 (CH_2F_2)	5.4	2690	771
Nitrous oxide (N_2O)	109	273	273

Table 2. *The maximum number of years for which SLCP mitigation can sustain full neutralization of the warming response to a CO_2-equivalent quantity (CO_2e at GWP20) of CO_2 emissions before requiring replacement with a CO_2-equivalent quantity of durable CDR. GWP20 was chosen because it provides the closest conventional GWP representation of near-term impact, but the quantity of SLCP mitigation is also shown as a mass of gas and in tCO_2e at GWP100. Replacement years were calculated using the p95 estimate. Equivalent values can be calculated for all major SLCPs; those shown here are for illustration only. GWP values from IPCC AR6 are listed in Table 1.*

SLCP mitigation	Latest year of replacement with durable CDR	Ton SLCP mitigation as CO_2e (GWP20) per ton CO_2 emitted	Ton SLCP mitigation as CO_2e (GWP100) per ton CO_2 emitted	Ton SLCP mitigation per ton CO_2 emitted
Methane (CH_4)	**12**	**1.0**	0.34	0.012
HFC-134a (CH_2FCHF_3)	**10**	**1.0**	0.36	0.00024

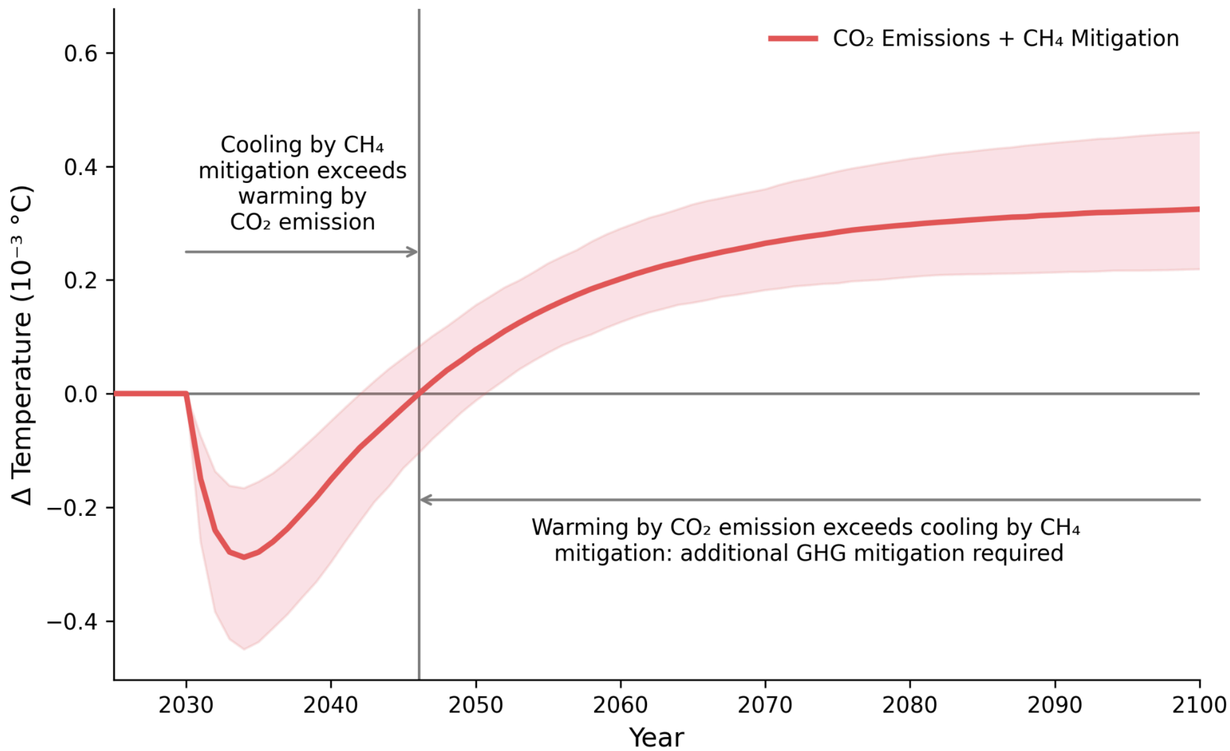

Figure 1. *Modeled global mean surface temperature response to the combination of a 1 Gt CO_2 emission pulse in 2030 and a CO_2-equivalent pulse of CH_4 mitigation in 2030 (1 Gt CO_2e at GWP20, or 12.3 Mt CH_4). The thick line is the median (p50) estimate of GMST response, and shaded regions are the p05 to p95 range.*

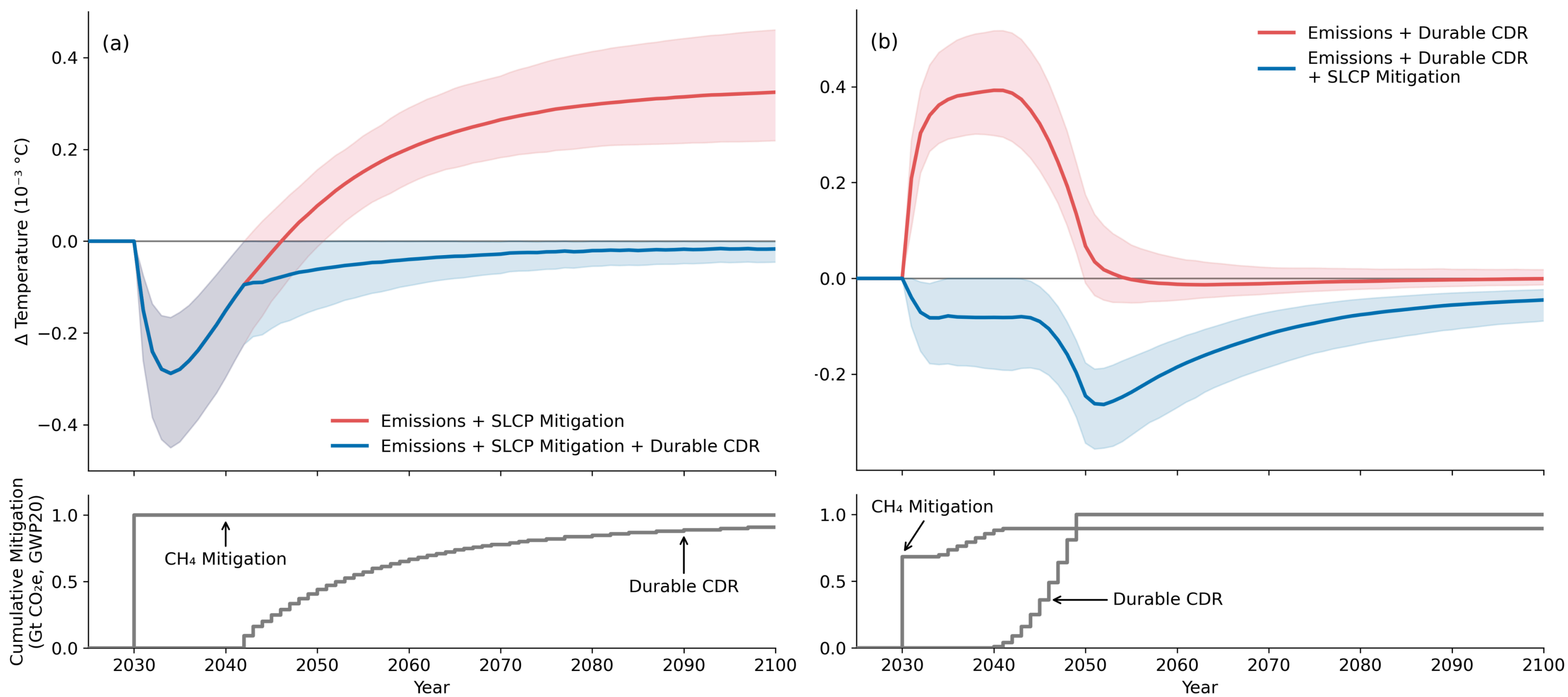

Figure 2. *Application of the warming neutralization approach to (a) stacking and (b) bridging scenarios.* ***(a). Top.*** *Modeled global mean surface temperature response to the combination of: 1 Gt CO_2 emission and 1 Gt CO_2e (GWP20) of CH_4 mitigation, both in 2030 (red); 1 Gt CO_2 emission in 2030, 1 Gt CO_2e (GWP20) of CH_4 mitigation in 2030, and the successive additions of durable CDR required to fully neutralize the warming response to the emission (blue). The schedule of CDR additions was calculated using the 95th percentile of the model's ensemble members to account for uncertainty in the GMST response (see Methods). The thick lines are the median (p50) estimates of GMST response, and shaded regions are the p05 to p95 range.* ***Bottom.*** *The cumulative schedules of CH_4 mitigation and CDR additions required to achieve warming neutralization using the p95 estimate. Note that the CDR schedule represents the latest time at which durable CDR must be added.* ***(b). Top.*** *Modeled global mean surface temperature response to the combination of: 1 Gt CO_2 emission in 2030 and 1 Gt delayed CDR, where the CDR is arbitrarily assumed to begin 10 years after the emission and then ramp up linearly over 10 years to a cumulative mass of 1 Gt (red); 1 Gt CO_2 emission in 2030, 1 Gt delayed CDR, and the successive additions of CH_4 mitigation required to fully neutralize the warming response to the emission across the CDR delay (blue). The schedule of CH_4 mitigation was calculated using the 95th percentile of the model's ensemble members to account for uncertainty in the GMST response (see Methods).* ***Bottom.*** *The cumulative schedules of the delayed CDR and CH_4 mitigation required to achieve warming neutralization using the p95 estimate.*

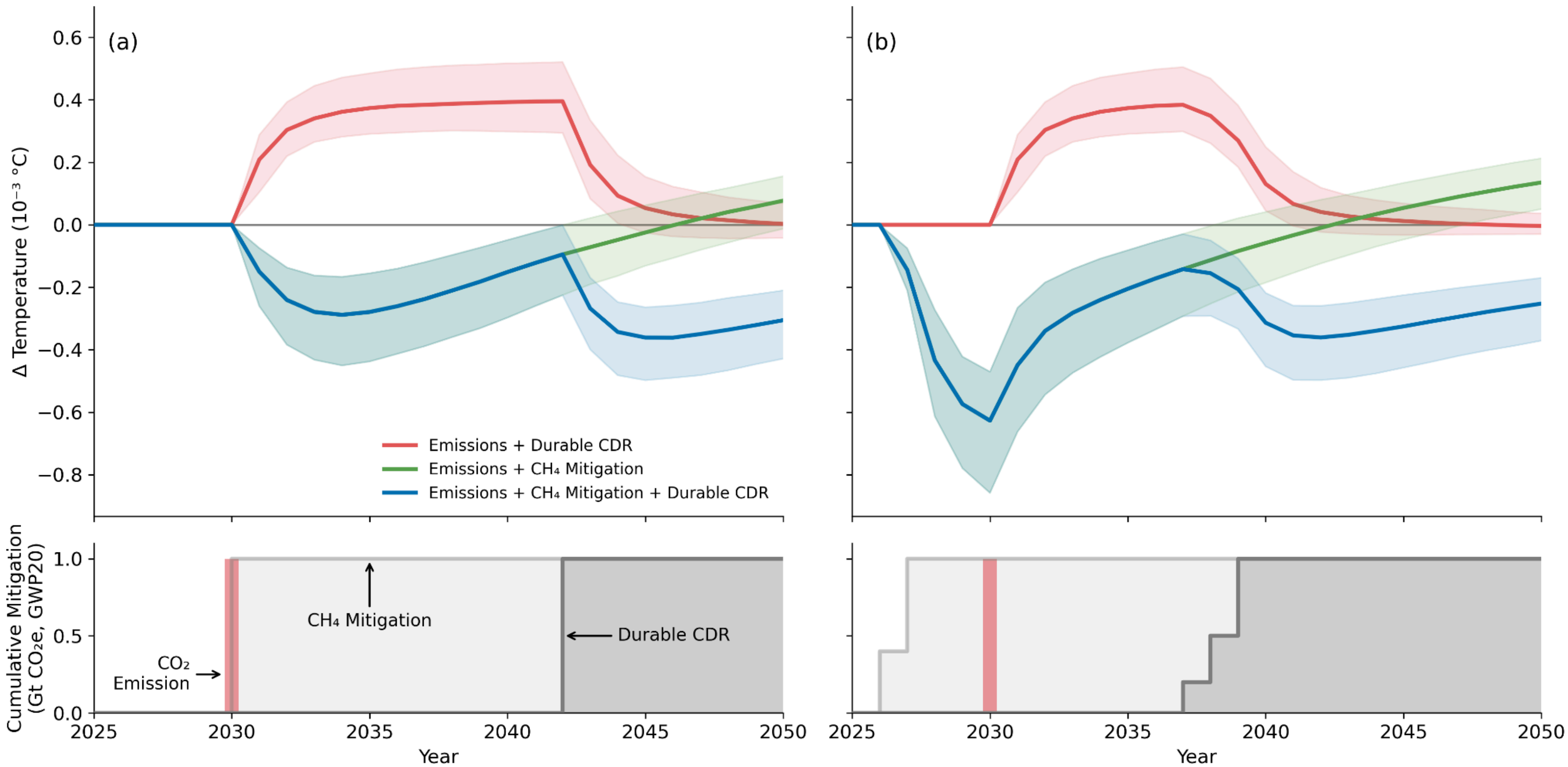

Figure 3. *Use of the standardized relationships in Table 2 to neutralize the warming response to 1 Gt CO_2 emissions in 2030.* ***(a).*** *1 Gt CO_2e (GWP20) CH_4 mitigation is issued in 2030 and replaced with 1 Gt durable CDR in 2042.* ***(b).*** *CH_4 mitigation is issued across 2026 (0.4 Gt CO2e) and 2027 (0.6 Gt CO_2e) and replaced with 1 Gt CDR issued across 2037 (0.2 Gt), 2038 (0.3 Gt), and 2039 (0.5 Gt). In both cases the portfolio maintains T < 0°C across all years, verifying sustained warming neutralization is achieved without bespoke model execution.* ***Top.*** *Modeled global mean surface temperature response to the combination of: the CO_2 emission and CDR (red); the CO_2 emission and CH_4 mitigation (green); the CO_2 emission and CH_4 mitigation and CDR issuances (blue). The thick lines are the median (p50) estimates of GMST response, and shaded regions are the p05 to p95 range.* ***Bottom.*** *The CO_2 emission, and the cumulative schedules of CH_4 mitigation and CDR.*

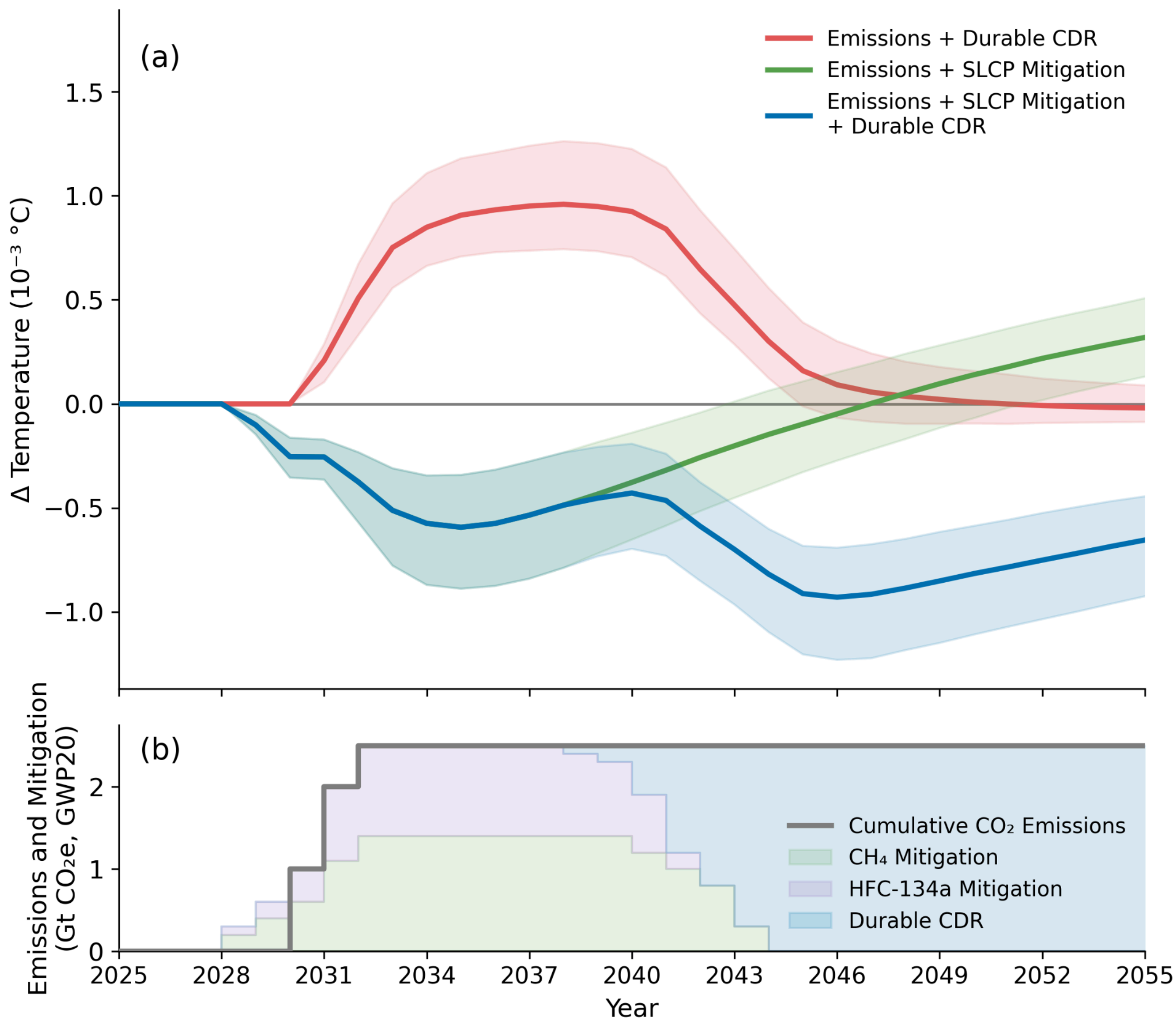

Figure 4. *Use of the standardized relationships in Table 2 to neutralize a multi-year emission profile (1 Gt CO_2 in 2030, 1 Gt in 2031, and 0.5 Gt in 2032) using a portfolio of CH_4 mitigation, HFC-134a mitigation, and durable CDR. The portfolio maintains T < 0°C across all years, verifying that sustained warming neutralization is achieved.* ***(a).*** *Modeled global mean surface temperature response to the combination of: the CO_2 emissions and CDR (red); the CO_2 emissions and SLCP (CH_4 and HFC-134a) mitigation (green); the CO_2 emissions, SLCP mitigation, and CDR (blue). The thick lines are the median (p50) estimates of GMST response, and shaded regions are the p05 to p95 range.* ***(b).*** *The active composition of the mitigation portfolio is plotted alongside the cumulative CO_2 emissions.*

Methods

Here we describe the method for designing mitigation portfolios under the warming neutralization approach. Alternative methods and models, with different tradeoffs between computational efficiency, uncertainty, and operational simplicity, could also be used without changing the underlying accounting framework.

Model Basis

The method uses the calibrated constrained version (1.4.1) of the Finite Amplitude Impulse Response (FaIR) reduced-complexity climate model v2.2 (C. Smith et al. 2024; Leach et al. 2021). FaIR is configured as a generalised impulse response model designed to simulate the Earth system's response to anthropogenic GHG emissions with high computational efficiency. The model is run in an ensemble configuration of 841 calibrated members under an SSP1-2.6 baseline, and again as an 841 member ensemble under the various perturbations to CO_2 emissions and GHG mitigation activities considered throughout the work. These ensemble members incorporate a range of climate sensitivity and carbon cycle feedback parameters that are statistically consistent with the probabilistic assessments provided in the IPCC Sixth Assessment Report (AR6). Global mean surface temperature responses (Δ Temperature) were determined from the difference between the set of ensemble runs under the baseline SSP1-2.6 emissions pathway run and the set of ensemble runs under each perturbation scenario. Projected changes in the CH_4 temperature anomaly are modeled using the 1.4.0 values for unperturbed lifetime, lifetime temperature sensitivity, and lifetime chemical sensitivities to NO_x, VOC, HC, and N_2O to better reflect standard literature values rather than empirically-derived calibrations.

Application of the Method to Stacking and Bridging Scenarios

The method first uses FaIR to construct a temporal profile representing the GMST response to the combination of GHG emissions and any existing mitigation, relative to a non-perturbed baseline run. The stacking application can evaluate CO_2 emissions and multiple types of mitigation including, but not limited to, CH_4 emissions destruction, F-gas emissions destruction, shorter-durability CDR, and durable CDR. The bridging application can evaluate emissions including, but not limited to, CO_2, CH_4, and N_2O, and mitigation including, but not limited to, CH_4 emissions destruction, F-gas emissions destruction, shorter-durability CDR, and durable CDR. For each emission and mitigation component, the forcing is assumed to occur in yearly pulses. For mitigation, the forcing year corresponds to the year that the credit for the activity was issued (rather than delivered or retired).

The GMST response to the combination of emissions and any existing mitigation is represented as a series of yearly ΔT (°C) values. To ensure conservatism, the ΔT values are evaluated at p95 of the model's constrained parameter ensemble. Where the ΔT is positive, the existing mitigation is not sufficient to neutralize the emissions in that year. In the stacking scenario, the method then requires that durable CDR is added to the portfolio. The minimum quantity that must be added in a given year is determined by the minimum pulse of CO_2 required to neutralize the ΔT (p95) in that year. In the bridging scenario, the method requires that additional SLCP mitigation is added. The minimum quantity that must be added is determined by the minimum pulse of SLCP that neutralizes the ΔT (p95) in that year.

A binary search algorithm is used to calculate these minimum GHG pulses. The model neutralizes the ΔT for each year in turn, starting from the first year of emissions. This builds a 'schedule' representing the minimum quantity of additional mitigation required in a given year. When moving forward by one year, the new target year's ΔT is re-calculated based on any additions of mitigation in the previous year. This ensures that the non-linear effects of accumulating mitigation are accounted for in the GMST response. The tolerance of the binary search is arbitrarily set as 0.01 Gt CO_2, 0.01 Mt CH_4, and 0.01 kt HFC-134a, but these can be updated according to the level of precision required for a given mitigation portfolio.

In the stacking application, for consistency with existing mass-based accounting approaches, the quantity of durable CDR additions is capped when the combined total of existing and added durable CDR is equivalent to the cumulative mass of CO_2 emitted. When the difference between CO_2 emitted and total durable CDR becomes less than the tolerance, the difference is allocated to the current year's CDR requirement and the schedule is concluded. Alternatively, if the schedule concludes with unused CDR (for example where shorter-lived mitigation maintains the temperature below 0°C until the final modeled year of 2500 without requiring use of all CDR), this residual mass is retroactively assigned to the final year in which CDR was used in the portfolio.

Calculation of Standardized Relationships for Stacking and Bridging

Supplementary Table S1 provides standardized relationships, calculated using the method, that represent the minimum quantity of SLCP mitigation required to sustain full neutralization of the warming response to a CO_2 emission across time periods of 1 to 20 years. Table 2 reports these relationships for the specific case where the quantity of SLCP mitigation required is equivalent (in tCO_2e at GWP20) to the quantity of CO_2 emitted. To produce these values, FaIR was used to simulate the combined GMST response to a 1 Gt CO_2 emission pulse in 2030, a 1 Gt CO_2 removal pulse at discrete delay periods ranging from 1 to 20 years, and an SLCP mitigation pulse in 2030. A binary search algorithm with a tolerance of 0.01 Mt CH_4 or 0.01 kt HFC was used to identify the minimum SLCP pulse that ensured the maximum GMST anomaly remained less than or equal to zero from the year of the SLCP pulse to the end of the delay period. To ensure conservatism, the algorithm evaluated the GMST response at p95 of the model's constrained parameter ensemble.

While the SLCP quantities are calculated assuming a 1 Gt CO_2 emission in 2030, these results have minimal scale- and time-dependence, and the p95 values reported in Table 2 and Supplementary Table S1 remain conservative across the range of probable scenarios for the scale and timing of corporate emissions.

As a useful approximation, a replacement time equal to the atmospheric lifetime of an SLCP minimizes the quantity of SLCP mitigation required. For example, if a universal 20-year replacement time were chosen, then SLCPs with shorter lifetimes would require exponentially larger quantities of mitigation to sustain warming neutralization across those 20 years. This effect is normalized where the atmospheric lifetime of each SLCP aligns with the replacement time, corresponding to the most efficient use of a given type of SLCP mitigation on a mass basis.

Method and Model Assumptions

Uncertainty in Temperature Projections

Simulation of temperature responses must account for a wide range of possible future climate scenarios and varying Earth system responses. Temperature projections in FaIR capture this uncertainty using ensemble configurations that incorporate a broad spectrum of climate sensitivity parameters and carbon cycle feedbacks (Leach et al. 2021; C. Smith et al. 2024). To ensure that the method suggests additions of GHG mitigation under stacking or bridging scenarios that remain highly conservative in the context of this uncertainty, ΔT values are calculated at the 95th percentile of the 841 member ensembles. This means that the yearly GMST response is over-estimated relative to the median outcome. In turn, the method effectively over-estimates the total quantity of SLCP mitigation required to 'bridge' a delay, and accelerates the schedule on which durable CDR must be added in a stacking scenario, relative to the median outcome.

Selection of SSP Baseline

The choice of SSP baseline can influence the quantity and timing of GHG mitigation required to compensate for emissions. The SSP1-2.6 scenario was selected because it represents a trajectory consistent with deep, near-term mitigation coupled with the large-scale deployment of CDR in the latter half of the 21st century; in keeping with the approach presented in this work, which prioritises GHG mitigation followed by the larger-scale deployment of durable CDR, and ultimately aligns with Paris Agreement goals (Riahi et al. 2023; UNEP 2026).

Under a higher-emissions baseline more consistent with current policy trajectories (e.g., SSP2-4.5) (Hausfather and Peters 2020), background saturation dampens the marginal radiative forcing – and by extension the GMST response – to both emissions and mitigation. Because this saturation scales non-linearly according to a specific GHG, its effect on the mitigation required to compensate for a given emission is not straightforward. For CO_2, the dampening effect of background saturation is also partially moderated by the reduced efficiency of ocean and terrestrial carbon sinks (Canadell et al. 2021). Together, these effects typically result in marginally more SLCP mitigation being required to compensate for a given mass of CO_2 emitted under a higher-emissions baseline. This is demonstrated in Supplementary Table S2, which compares the standardized relationships between SLCP mitigation, CO_2 emissions, and replacement timescales under SSP1-2.6 and SSP2-4.5 scenarios.

At the scale of corporate emissions, this overall baseline effect remains small relative to the uncertainty bounds of the temperature projections themselves. At the p50 and p95 likelihoods, the standardized ratios for CH_4 mitigation in stacking or bridging scenarios under SSP1-2.6 and SSP2-4.5 baselines differ by no more than 0.001 ton CH_4 per ton CO_2 emitted (Supplementary Table S2). While a less mitigated baseline scenario may therefore be more conservative in some cases, most outcomes remain accommodated by the choice to use p95 outputs under SSP1-2.6.

Replacement of shorter-durability CDR

In principle, the replacement time for shorter-durability CDR under a stacking or bridging scenario is set by the time at which CO_2 storage is no longer assured: either because a 'reversal' (partial or complete return of CO_2 to the atmosphere) is observed, or because active monitoring of the storage reservoir ceases and so the absence of a reversal can no longer be verified. When physical reversals do occur, CO_2 may return to the atmosphere either abruptly or progressively, with the potential for a fraction of the CO_2 to remain stored over centuries to millennia in certain reservoirs (Piñeiro-Juncal et al. 2025). In practice, the schedule for replacement of shorter-durability CDR is therefore determined by project-specific factors, including the time at which a reversal occurs or at which monitoring for reversals ceases, and the rate at which CO_2 is subsequently returned to the atmosphere.

Given these project-specific influences on CO_2 storage, credits originating from shorter-durability CDR projects are typically assigned a durability claim (also referred to as an estimated durability, a permanence period, or storage term) representing the time over which CO_2 storage is assured. For example, for nature-based CDR, durability claims often correspond to the duration of active monitoring; biogenic carbon storage reservoirs are vulnerable to reversal risks like land use change, and when monitoring ceases it is no longer possible to verify that a reversal has not occurred. Within the duration of the durability claim, projects may still be vulnerable to reversals, but in this case the risk can be managed by independent frameworks (e.g. buffer pools, monetary permanence reserves, or financial instruments) that are beyond the scope of this paper.

Durability claims are therefore used in the method as a convenient and conservative proxy for the time at which shorter-durability CDR needs to be replaced to sustain the neutralization of the warming response to emissions. This ensures that, even if full 'reversal' of shorter-durability CDR occurred immediately, the warming response to the CO_2 emission would remain neutralized. Organizations may choose to partially or completely replace shorter-durability CDR on shorter timescales, and further work to standardize reservoir- or project-specific reversal rates could ultimately enable replacement schedules distributed across multiple years (Arcusa and Hagood 2024).

Replacement by durable CDR

Under the stacking scenario, additions of durable CDR to a portfolio are capped when the cumulative mass of durable CDR equals the cumulative mass of CO_2 emitted. In reality, where the net atmospheric drawdown by a CDR deployment occurs later than the CO_2 emission, the quantity of durable CDR required to fully neutralize the warming response may be different to the quantity of CO_2 emitted. This is because the efficiency of natural carbon sinks is state-dependent – responding to varying atmospheric CO_2 concentrations and transient warming levels – meaning that the climate system's response to adding CO_2 and subsequently removing it is not perfectly symmetric (Zickfeld et al. 2021; Koven et al. 2023).

However, assuming a 1:1 mass equivalence between the durable CDR and the initial CO_2 emission is an acceptable approximation for corporate GHG accounting. The asymmetry between positive and negative emissions is heavily scale-dependent; it becomes pronounced primarily at large scales (e.g., 100s Gt of CO_2) and over long delay times (Canadell et al. 2021; Zickfeld et al. 2021). At the scale of individual corporate GHG perturbations, the forcing effect of a CO_2 emission is quasi-linear. For example, a 1 Gt CO_2 emission and delayed CDR pulse in years 2030 and 2050 respectively produces a deviation from a symmetric response that is within the p95 likelihood used to estimate quantities of GHG mitigation through the method.

Note that the avoided CO_2 resulting from the atmospheric oxidation of mitigated fossil CH_4 is not explicitly subtracted from the final mass of durable CDR, since this mass is typically negligible relative to the scale of the CO_2 emission being compensated (e.g., ≤ 2% of the CO_2 emission for delay periods up to 20 years; Supplementary Table S1). This simplification is inherently conservative in that it marginally over-estimates the CDR required.

Model Stability and Future IPCC Assessments

The modeling of GMST response in FaIR uses physical climate parameters – including radiative efficiencies, atmospheric lifetimes, and climate-carbon feedbacks – primarily derived from the Intergovernmental Panel on Climate Change (IPCC) Assessment Reports. IPCC reports are released on a 5 - 10 year cycle, and so it is possible that the standardized relationships in Tables 2 and S1 could change between publication cycles. The standardized relationships will therefore be updated on a cadence reflecting this publication cycle.

Regardless, the physical relationships governing the rapid decay of short-lived climate pollutants and the long-term persistence of CO_2 are generally well established. For example, between the IPCC's Fifth (2013) and Sixth (2021) Assessment Reports, the evaluated atmospheric perturbation lifetime of CH_4 changed from 12.4 to 11.8 years, and its base GWP100 changed from 28 to 27.9 (Myhre et al. 2014; Forster et al. 2023). Barring a major scientific reassessment of the transient climate response or the specific effective radiative forcing of major greenhouse gases following AR6, the values in Tables 2 and S1 are therefore expected to remain stable. If there are changes in these parameters, they will most likely reflect a narrowing of the present-day uncertainty. Because the p95 output used to estimate quantities of mitigation is at the extreme upper bound of present-day uncertainty, future updates will most likely reduce the quantity of mitigation required relative to this output. Irrespective of small changes, the standardized relationships reported in this work are therefore likely to remain conservative.

Data & Code Availability

Source code for the FaIR model is available at https://github.com/OMS-NetZero/FAIR.

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E. R. H., Z. H., R. S., and C. V. A. conceived of the ideas in this work. E. R. H. conducted the analysis, prepared all outputs, and wrote the manuscript. All authors contributed during editing.

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Ethics declarations

Competing interests

Z. H. helps manage Frontier, an advanced market commitment on the part of corporate carbon removal buyers. E. R. H., R. S., and C. V. A. participate in the procurement of carbon removal and superpollutant abatement to meet Google's climate targets.

Supplementary Information

Supplementary Text

S1 Alternatives to the Warming Neutralization Approach

Measures and Models of Climate Impact

Multiple approaches for accounting for the time-dependent climate impact of GHG emissions and mitigation are possible. The warming neutralization approach proposed in this paper uses GMST response as the measure of impact. Here we consider the primary alternative: use of radiative forcing (RF). A neutralization approach based on RF is directly analogous to warming neutralization, except that RF is used now to represent the climate impact of emissions and mitigation across time. Provided that the forcing response to the combination of emissions and mitigation remains less than or equal to zero across all time periods, the impact of the emissions would be fully compensated.

As for the warming neutralization approach, an 'RF neutralization approach' can be implemented through a method that uses an RCCM to simulate RF responses relative to a baseline across time. For RF, it is also possible to derive a simpler analytical method to describe the neutralization of emissions. This is possible because a forcing response can be linked directly to GHG mass through well-constrained physical constants such as specific radiative efficiency. We briefly outline this derivation below, and then discuss the results of each accounting approach (based on GMST or forcing response) and method of implementation (RCCM-based or analytical).

An Analytical Method to Implement an 'RF Neutralization Approach'

In a neutralization approach based on RF, the aim is ultimately to ensure that the instantaneous radiative forcing (ΔRF) through a combination of GHG mitigation strategies (e.g. CDR and SLCP mitigation) is equivalent to, or exceeds, the ΔRF of a CO_2 emission across time. In a single inequality:

$$\Delta RF_{SLCP}(t)\ +\ \Delta RF_{CDR}(t) \geq \Delta RF_{CDE}(t)$$

where $SLCP$ = SLCP mitigation, CDR = durable CDR, CDE = the CO_2 emission to be compensated, t is the time since the CO_2 emission pulse, and all ΔRF are absolute values. ΔRF is a function of many variables, including the mass (M) of the emission or mitigation. The first inequality can therefore be rewritten as:

$$M_{SLCP}(t)\ \cdot\ i(t,\ \ldots)\ +M_{CDR}(t)\ \cdot\ j(t,\ \ldots) \geq M_{CDE}(t)\ \cdot\ j(t,\ \ldots)$$

where i and j are functions representing the relationships between M and RF for the SLCP and CO_2 respectively. The decay in atmospheric mass of an SLCP ($M(t)$) can be modeled assuming a pseudo-first order exponential decay from its initial mass M_0 using the IPCC AR6 perturbation lifetime (τ):

$$M(t)\ = M_0 \cdot\ e^{-t/\tau}$$

The decay in atmospheric mass of CO_2 can be modeled using the standard IPCC AR6 methodology for GWP, which represents the remaining fraction of a CO_2 pulse through an impulse response function, $IRF(t)$ (Joos et al. 2013; Forster et al. 2023). Therefore:

$$M_{0,SLCP} \cdot e^{-t/\tau_{SLCP}} \cdot \frac{i(t,...)}{j(t,...)} + M_{0,CDR} \cdot IRF_{CDR}(t - t_r) \geq M_{0,CDE} \cdot IRF_{CDE}(t)$$

Here, t_r is the time following the CO_2 emission at which CDR replaces the SLCP mitigation. $\frac{i(t,...)}{j(t,...)}$ expresses the relative effect of a change in mass of the SLCP and CO_2 on RF, and can be approximated by the relative radiative efficiency (RE) and molecular mass of each gas (MW) through the constant α (Supplementary Table S3). This approximation assumes that the relationship between M and ΔRF for each GHG is linear, which is acceptable for GHG perturbations at the scale relevant to corporate emissions.

$$M_{0,SLCP} \cdot e^{-t/\tau_{SLCP}} \cdot \alpha_{SLCP} + M_{0,CDR} \cdot IRF_{CDR}(t - t_r) \geq M_{0,CDE} \cdot IRF_{CDE}(t)$$

$$\text{where } \alpha_{SLCP} \approx \frac{RE_{SLCP}}{RE_{CO_2}} \cdot \frac{MW_{CO_2}}{MW_{SLCP}}$$

To further simplify the inequality, it can be assumed that $M_{0,CDE} = M_{0,CDR}$ (since the quantity of CDR is independently set to equal to the quantity of CO_2 emitted), meaning that $M_{0,CDR} \cdot IRF_{CDR}(t - t_r) \geq M_{0,CDE} \cdot IRF_{CDE}(t)$. Therefore, until the time at which CDR replaces SLCP mitigation (t_r):

$$M_{0,SLCP} \cdot e^{-t/\tau_{SLCP}} \cdot \alpha_{SLCP} \geq M_{0,CDE} \cdot IRF_{CDE}(t) \text{ for } 0 \leq t < t_r$$

and so the minimum quantities of SLCP mitigation (M_0) required to neutralize the CO_2 emission across the interval between $t = 0$ and $t = t_r$ can be found at t_r:

$$M_{0,SLCP} \cdot e^{-t_r/\tau_{SLCP}} \cdot \alpha_{SLCP} = M_{0,CDE} \cdot IRF_{CDE}(t_r)$$

Finally, neglecting the fact that the forcing effect of a CO_2 emission degrades with time following the IRF (an implicitly conservative assumption):

$$M_{SLCP} / M_{CDR} = e^{t_r/\tau_{SLCP}}/\alpha_{SLCP} \quad \textbf{(1)}$$

Equation (1) provides a simple relationship between the quantity of SLCP mitigation, quantity of CDR, and time of CDR replacement that ensures that the forcing response to the CO_2 emission remains neutralized across all time periods.

An even simpler single ratio representing the relative quantities of SLCP mitigation and CDR required to neutralize the forcing response to a CO_2 emission across time can be derived by independently setting the timescale over which CDR replacement occurs. As an arbitrary example, if the timescale is assumed to equal the atmospheric lifetime of the SLCP – meaning that CDR replacement must occur within, or at, one lifetime – the simple relationship is reduced to the species-specific ratio β_{SLCP}, where $\beta_{SLCP} = e/\alpha_{SLCP}$ (Equation (2)).

$$M_{SLCP} / M_{CDR} = \beta_{SLCP} \quad (2)$$

Comparison of Accounting Approaches Based on Temperature and Radiative Forcing

Supplementary Table S3 reports standardized ratios representing the quantity of CH_4 mitigation required to fully neutralize the climate impact of a CO_2 emission across 5- to 20-year time horizons. These ratios are calculated using three distinct methods: (a) the warming neutralization approach, implemented through the RCCM-based method introduced in this work; (b) an RF neutralization approach, implemented through an analogous RCCM-based method; and (c) an RF neutralization approach, implemented through the analytical method (Equation (1)).

The RF-based approach, whether implemented through an RCCM or analytical solution, consistently requires larger initial quantities of SLCP mitigation when compared to the GMST-based approach. This is because a pulse of CO_2 immediately exerts a positive radiative forcing, but the Earth's thermal inertia, driven primarily by the heat capacity of the ocean's mixed and deep layers, means that the resulting GMST increase is delayed and dampened (Lynch et al. 2020; Forster et al. 2023). An approach that requires that the instantaneous RF from SLCP mitigation strictly equals or exceeds the RF of the CO_2 emission therefore requires a large upfront quantity of SLCP mitigation to match the acute, initial energy flux of the CO_2 emission.

The analytical method for implementing the RF-based approach consistently requires a larger initial quantity of SLCP mitigation when compared to the RCCM-based method for RF. This is because a number of simplifying assumptions were made in deriving the analytical method. Ultimately, the RCCM-based method is a more realistic representation of the climate system, and so the higher values produced by the analytical method should be understood as a product of simplification rather than a strict physical requirement. In addition, the mathematical precision of the analytical equations does not necessarily imply greater certainty. There remains inherent uncertainty in the radiative efficiencies and atmospheric lifetimes used within the analytical approach, which are explicitly captured in the RCCM-based method through a probabilistic ensemble. A choice to implement the analytical or RCCM-based method would therefore depend on an organization's preference for simple equations versus RCCM execution, rather than a straightforward tradeoff of conservatism or certainty.

Because an RF neutralization approach requires larger investment in near-term SLCP mitigation to balance immediate energy fluxes, the choice of RF or GMST within a neutralization approach will influence portfolio design. When comparing RF and GMST as impact metrics, the larger upfront volumes of SLCP mitigation required by an RF-based approach could be viewed as more conservative. On the other hand, the physical outcomes of climate change are primarily driven by temperature, rather than a strict neutralization of instantaneous energy fluxes, as highlighted by the development of temperature-aligned approaches like GWP* in recent literature (Lynch et al. 2020). Ultimately, an approach targeting the sustained neutralization of the impact of emissions could therefore defensibly use either RF or GMST as an impact metric. In this work, we propose GMST to enable corporate emission neutralization claims that are structurally consistent with global goals to stabilize long-term temperatures. However, neutralization of RF remains a valid and complementary approach. We acknowledge that neither RF nor GMST explicitly represents every biogeochemical consequence of emissions, such as CO_2-induced ocean acidification. Use of a single metric to account for multiple GHGs – whether RF or GMST – inherently requires a compromise between operational utility and representation of all possible climate impacts.

In future work, we welcome an exploration of the alternative metrics and methods and their inherent tradeoffs in computational efficiency, uncertainty, and operational simplicity.

Supplementary Tables

Table S1. *The minimum quantity of SLCP mitigation required to sustain full neutralization of the warming response to a CO_2 emission across time periods from 1 to 20 years, shown in mass of SLCP gas and in tCO_2e using GWP20 and GWP100. The quantity of SLCP mitigation is shown relative to the CO_2 emission, which is itself equivalent to the quantity of durable CDR required at the time of replacement. SLCP quantities were calculated at the p95 estimate of the GMST response. Equivalent values can be calculated for all major SLCPs; those shown here are for illustration only. GWP values from IPCC AR6 are listed in Table 1.*

Latest year of replacement with durable CDR	Ton CH_4 mitigation per ton CO_2 emitted	Ton CH_4 mitigation (CO_2e, GWP20) per ton CO_2 emitted	Ton CH_4 mitigation (CO_2e, GWP100) per ton CO_2 emitted	Ton HFC-134a mitigation per ton CO_2 emitted	Ton HFC-134a mitigation (CO_2e, GWP20) per ton CO_2 emitted	Ton HFC-134a mitigation (CO_2e, GWP100) per ton CO_2 emitted
1	0.008	0.68	0.23	0.00022	0.90	0.33
2	0.008	0.68	0.23	0.00022	0.90	0.33
3	0.008	0.68	0.23	0.00022	0.90	0.33
4	0.008	0.68	0.23	0.00022	0.90	0.33
5	0.009	0.69	0.24	0.00022	0.90	0.33
6	0.009	0.72	0.25	0.00022	0.90	0.33
7	0.009	0.76	0.26	0.00022	0.90	0.33
8	0.010	0.79	0.27	0.00022	0.92	0.34
9	0.010	0.84	0.29	0.00023	0.95	0.35
10	0.011	0.89	0.30	0.00024	0.98	0.36
11	0.012	0.94	0.32	0.00025	1.01	0.37
12	0.012	1.00	0.34	0.00025	1.06	0.39
13	0.013	1.06	0.36	0.00026	1.10	0.41
14	0.014	1.13	0.39	0.00028	1.14	0.42
15	0.015	1.21	0.41	0.00029	1.20	0.44
16	0.016	1.29	0.44	0.00030	1.25	0.46
17	0.017	1.37	0.47	0.00032	1.31	0.48
18	0.018	1.46	0.50	0.00033	1.37	0.51
19	0.019	1.55	0.53	0.00034	1.43	0.53
20	0.020	1.66	0.57	0.00036	1.49	0.55

Table S2. *The minimum quantity of CH_4 mitigation required to sustain full neutralization of the warming response to a CO_2 emission across various time periods, calculated under SSP1-2.6 and SSP2-4.5 scenarios. The quantity of CH_4 mitigation is shown relative to the CO_2 emission, which is itself equivalent to the quantity of durable CDR required at the time of replacement. Values are calculated using the p50 and p95 estimates of the GMST response and using a 1 Gt CO_2 emission in 2030.*

Latest year of replacement with durable CDR	**Ton CH_4 mitigation per ton CO_2 emitted (SSP1-2.6, p50)**	**Ton CH_4 mitigation per ton CO_2 emitted (SSP1-2.6, p95)**	**Ton CH_4 mitigation per ton CO_2 emitted (SSP2-4.5, p50)**	**Ton CH_4 mitigation per ton CO_2 emitted (SSP2-4.5, p95)**
5	0.007	0.009	0.007	0.009
10	0.009	0.011	0.009	0.011
15	0.012	0.015	0.012	0.015
20	0.015	0.020	0.016	0.021

Table S3. *Constants for select SLCPs for use in Equations (1) and (2). All β_{SLCP} values assume the replacement time is equivalent to τ_{SLCP}. Radiative efficiencies from IPCC AR6 (Forster et al. 2023).*

SLCP	**τ_{SLCP} (yr)**	α_{SLCP}	β_{SLCP}
Methane (CH_4)	11.8	117.6	0.023
HFC-134a (CH_2FCHF_3)	14	5513	0.0005

Table S4. *The minimum quantity of CH_4 mitigation required to sustain full neutralization of the climate impact of a CO_2 emission across various time periods, as determined using radiative forcing (RF) and global mean surface temperature (GMST) as the measures of climate impact, and using an analytical or RCCM-based method for RF. The quantity of SLCP mitigation is shown relative to the CO_2 emission, which is itself equivalent to the quantity of durable CDR required at the time of replacement. Equivalent values can be calculated for all major SLCPs; those shown here are for illustration only. For the RCCM-based methods, values are calculated using the p95 estimates of the forcing and GMST responses, and using a 1 Gt CO_2 emission in 2030.*

Latest year of replacement with durable CDR	**Ton CH_4 mitigation per ton CO_2 emitted (RCCM-based method for warming neutralization)**	**Ton CH_4 mitigation per ton CO_2 emitted (RCCM-based method for RF neutralization)**	**Ton CH_4 mitigation per ton CO_2 emitted (analytical method for RF neutralization)**
5	0.009	0.009	0.013
10	0.011	0.013	0.020
15	0.015	0.019	0.030
20	0.020	0.029	0.046

Supplementary Information References

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