Supplementary Information for: Limiting warming by CO_2 and methane mitigation in an expanded scenario space

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S.1 Monte Carlo parameter sampling

This section describes in more detail the parameter ranges sampled in the Monte Carlo sampling and provides justification for the distributions used. Extended Data Table 2 summarizes the sampled parameters, their distributions, and upper and lower bounds. We sample 2000 realizations for each combination of net zero emissions target year and CH_4 pathway, and propagate parameter uncertainty through the infilling model to generate ensembles of emission scenarios. As shown in Extended Data Fig. 4, the assessed influence of uncertainty in parameters (scenario uncertainty) is much lower than the uncertainty in the climate response. This indicates that the exact parameter values are of limited importance, provided that the choice of uncertainty ranges is not unreasonably narrow.

We acknowledge that complete independence from integrated assessment models (IAMs) is difficult to achieve, as our perception of plausible parameter ranges is likely informed by literature that explicitly uses or implicitly relies on IAM results. Nevertheless, we aim to use parameter ranges that are based on current knowledge and expert judgment where possible. Parameter choices and ranges can be adapted to represent different sets of plausible emission scenarios.

S.1.1 Net negative CO_2 and GHG emissions

Maximum net negative CO_2 and GHG emissions The maximum achievable rates of net negative CO_2 emissions ($CO_{2}{}_{\max}^{\text{net neg.}}$) are sampled from truncated Gaussian distributions with mean -6 $GtCO_2$ / year, standard deviation 4 $GtCO_2$ / year, and bounds of $[-14, 0]$

$GtCO_2$ / year. The central value of -6 $GtCO_2$ / year is consistent with optimistic projections of feasible storage by mid-century[1–3] and within the constraints on geological storage potential[4] when considering additional residual CO_2 emissions to be stored. We note that this is also a typical value reached in strong mitigation scenarios by IAMs[5]. The lower bound of -14 $GtCO_2$ / year represents an extremely optimistic estimate of attainable carbon dioxide removal (CDR) deployment until 2100, considering land-use constraints, energy requirements, and geological storage capacity[2,4]. We judge uncertainty to be substantial, encapsulated by the standard deviation of 4 $GtCO_2$ / year. The upper bound of zero is an obvious choice, given that our analysis is contingent on reaching net zero CO_2 emissions.

Maximum net negative GHG emissions The maximum achievable rates of net negative GHG emissions ($\mathrm{GHG}_{\mathrm{max}}^{\mathrm{net\,neg.}}$) are sampled from truncated Gaussian distributions with mean -1 $GtCO_2eq$ / year, standard deviation 4 $GtCO_2eq$ / year, and bounds of $[-10, 0]$ $GtCO_2eq$ / year. As of 2026, we are aware of only one country (Denmark[6]) aiming for net negative GHG emissions, and we reflect this in a higher central estimate for $\mathrm{GHG}_{\mathrm{max}}^{\mathrm{net\,neg.}}$. Again, uncertainty in realized net negative GHG emissions is high. The lower bound is very optimistic and represents the net negative GHG emissions reached in a maximum sectoral effort scenario[7] (strong behavioral change and adoption of emerging technologies.

Realization factors The net negative CO_2 and GHG realization factors ($f_{\mathrm{CO_2}}^{\mathrm{net\,neg.}}$ and $f_{\mathrm{GHG}}^{\mathrm{net\,neg.}}$) are drawn from uniform distributions on $[0, 1]$. These factors scale the rate at which net fossil CO_2 and GHG emissions decrease after reaching net zero emissions, accounting for a potential slowdown in further emission reductions. The uniform distribution reflects our limited knowledge about future policy ambition, further mitigation of residual emissions, and the deployment of negative emission technologies in the time after net zero CO_2/GHG emissions are achieved.

S.1.2 Residual fossil fuel and industry emissions

Functional form We employ two functional forms for estimating gross fossil CO_2 emissions at net zero CO_2 emissions, selected with probabilities 0.75 and 0.25, respectively: (i) a smoothed functional form derived from the AR6 scenario database[5], and (ii) a constant residual emissions floor (see Methods of the main text).

Residual CO_2 emissions at net zero CO_2 Residual CO_2 emissions occur in sectors that are not fully decarbonized, including aviation, shipping, steel production, and potentially parts of the energy sector[8,9] and continue to co-emit short-lived climate forcers (SLCFs) and/or N_2O. The only reason we estimate residual CO_2 emissions in our model is to estimate the resulting emissions of co-emitted climate forcers. When the constant method is selected, residual emissions at net zero CO_2 emissions ($E_{CO_2}^{\mathrm{res,netzeroCO_2}}$) are sampled from a truncated Gaussian with mean 6 $GtCO_2$ / year, standard deviation 3 $GtCO_2$ / year, bounded by $[0, 20]$ $GtCO_2$ / year. The upper bound of 20 $GtCO_2$ / year allows in principle for scenarios with limited decarbonization progress in these sectors and widespread carbon capture and storage (CCS) deployment combined with compensatory CDR[10] with strong co-emission of SLCFs and N_2O, while the lower bound is equivalent to complete decarbonization and no emissions of non-CO_2, non-CH_4 climate forcers being produced from residual emissions. Both edge cases are unlikely, but the actual amount of residual emissions is highly uncertain[10,11] and countries' climate pledges remain vague[12,13]. This is why we include a standard deviation of 3 $GtCO_2$ / year, equivalent to a likely range of around 3-9 $GtCO_2$ / year of residual emission at net zero CO_2 emissions, comprising what is simulated by IAMs[9,14], and on the lower end of what countries currently plan for[13]. The comparatively small amount of residual CO_2 emissions reflects our less optimistic expectation concerning CCS and CDR deployment to compensate for residual emissions necessary to reach net zero CO_2 emissions and aligns closer with scenarios that prioritize strong mitigation over CDR deployment[7,10] and the Net Zero Roadmap of the International Energy Agency[15].

Smoothed functional form scaling When the smoothed method is selected, the scaling factor (f_{smoothed}) is sampled from a truncated Gaussian with mean 0.312, standard deviation 0.2, bounded by $[0, 0.910]$. f_{smoothed} represents a linear scaling factor to the smoothed relationship between $CO_2^{\mathrm{FFI,gross}}$ and $CO_2^{\mathrm{FFI,net}}$, with $f_{\mathrm{smoothed}} = 0.5$ equivalent to the mean, and 0 (1) equivalent to the minimum (maximum) of the smoothed relationship (Supplementary Fig. 1). The chosen values of f_{smoothed} correspond to residual fossil CO_2 emissions of 6 $GtCO_2$ / year (central value) and 20 $GtCO_2$ / year (upper bound). The standard deviation in f_{smoothed} of 0.2 corresponds to approximately 3-4 $GtCO_2$/year, consistent with the values chosen for the other method.

S.1.3 F-gas emissions

Emissions of F-gases are infilled by randomly selecting from five SSP scenarios that reach or approach net zero CO_2 emissions this century (out of all eight Tier 1 and Tier 2 scenarios of ScenarioMIP for CMIP6[16]): SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP4-3.4, and SSP5-3.4-over. Each scenario is selected with equal probability. This approach captures a broad range of future F-gas emission scenarios, including weak and delayed mitigation, while avoiding emission scenarios with substantially higher warming that would be inconsistent with net zero CO_2/GHG emission targets this century.

S.1.4 Air pollution co-control

Air pollution control policy Air pollution control policy is sampled as a categorical variable with 10% probability of maintaining current legislation (constant emission factors) and 90% probability of strengthening controls (convergence toward the lowest regional sector-specific emission factors averaged over the reference period). The high probability assigned to strengthening reflects our expectation of additional air pollution control due to strong co-benefits for public health[17–19] and the historical trend toward stricter regulations globally[20,21].

Target year The year by which emission factors are reduced to the regional minimum (τ_{ap}) is sampled from a truncated Gaussian with mean 2100, standard deviation 30 years, bounded by $[2050, 2200]$. With this, we aim to reflect the considerable uncertainty in the pace of implementation of air pollution control measures and include scenarios where air pollution control stringency (affecting emission factors in our model) progresses independent of GHG mitigation.

Pollutant species All non-CH_4 SLCFs (BC, NO_x, SO_2, OC, CO, VOC, NH_3) are included in the strengthening policy independently with 90% probability. This allows for heterogeneous control across pollutants, and reflects that some species may face higher barriers (for technical or regulatory reasons) to abatement than others. The species that are in principle included are the climate forcers that are also targeted by modern air pollution regulation, such as the one of the European Union[22].

S.1.5 Sectoral emission distribution at net zero emissions (CH_4)

Residual CH_4 emissions at net zero CO_2 emissions are distributed across three sectors: agriculture, waste, and energy production. While the sectoral distribution of CH_4 emissions at net zero CO_2 emissions is uncertain, the general expectation is that agricultural emissions will be the dominant source of residual CH_4 emissions due to mitigation options being comparatively more costly and technically more challenging than in other sectors, and that demand for animal protein is likely to rise[23–25]. This aligns broadly with what countries consider in their long-term strategies[12,13] and the sectoral distribution generated by IAMs[14] at net zero CO_2/GHG emissions. Therefore, we choose to sample the agricultural share ($\rho^{\mathrm{CH_4}}_{\mathrm{agr,nz}}$) from a truncated Gaussian with mean 70%, standard deviation 15%, bounded by $[40\%, 100\%]$. The waste sector share ($\rho^{\mathrm{CH_4}}_{\mathrm{wst,nz}}$) is sampled conditionally as a fraction of the non-agricultural remainder, with a mean of 50% and a standard deviation of 15% of the remainder. The upper and lower bounds are selected, such that $\rho^{\mathrm{CH_4}}_{\mathrm{wst,nz}} > 0$ and the energy sector share ($\rho^{\mathrm{CH_4}}_{\mathrm{ene,nz}}$) can be computed as the positive residual.

S.1.6 Sectoral emission distribution at net zero emissions (CO_2)

Residual CO_2 emissions are distributed across eight sectors. Solvents and waste are assigned constant small shares (0.2% and 0.1%, respectively), similar to the historical period.

International transport International transport, including aviation and shipping, is widely considered as difficult to decarbonize[15,26] and is expected to grow as a sector[27,28]. To reflect a potentially high share in residual CO_2 emissions and uncertainty about future decarbonization pathways, we sample the combined international aviation and shipping share ($\rho^{CO_2}_{\mathrm{inttrans,nz}}$) from a truncated Gaussian with mean 45%, standard deviation 20%, and bounded by $[20\%, 60\%]$. Within international transport, aviation receives $70\% \pm 10\%$ (bounded by 50–100%), with shipping as the residual, aligned with the expectation that aviation will contribute a larger share of residual emissions.

Other sectors The energy production, residential, and domestic transportation sectors are expected to contribute less to residual CO_2 emissions. Both long-term strategies of countries[12,13] and results of IAMs[14] indicate that energy production and (domestic) transportation likely contribute similar shares and more than the residential sector, but (as for other variables) variation across countries and models remains high. At the same time, decarbonization of the industrial sector depends on emergent technologies and is expected to contribute a much larger share to residual CO_2 emissions than to today's emissions[13,14]. With sampling ranges of parameters we try to consider all these factors: We sample the share of energy production, the residential sector, and the domestic transportation sector from truncated Gaussians with means of 15%, 5%, and 15% respectively, standard deviations of 10%, 3%, and 10%, and bounded by $[0\%, 30\%]$, $[0\%, 10\%]$, and $[0\%, 30\%]$. The industrial sector share is computed as the residual to ensure shares sum to 100%; if the residual is negative, all sectoral shares are resampled. The residual distribution is broad and reflects a potentially high share for industrial CO_2 emissions at net zero CO_2 emissions.

Sectoral split method. With 90% probability, the sampled sectoral splits are applied; with 10% probability, the model maintains the sectoral distribution from the reference time period.

S.1.7 Biomass burning emissions

Emissions of SLCFs and N_2O tended to globally decrease slightly over the last 20 years, but with substantial inter-annual variability[29–31]. Future changes are uncertain and depend on changes in land use, human management, and (regional) climate conditions, such as (the increase in) fire weather and other bioclimatic factors[31,32]. Considering the substantial uncertainty, we sample the fractional relative change in biomass burning emissions by 2100 (Φ_{bb}) from a truncated Gaussian distribution with mean −20%, standard deviation 50%, bounded by $[-100\%, +100\%]$. The negative central value reflects a continuation of the historical trend, and that reduced deforestation and improved fire management might decrease anthropogenic fire emissions.

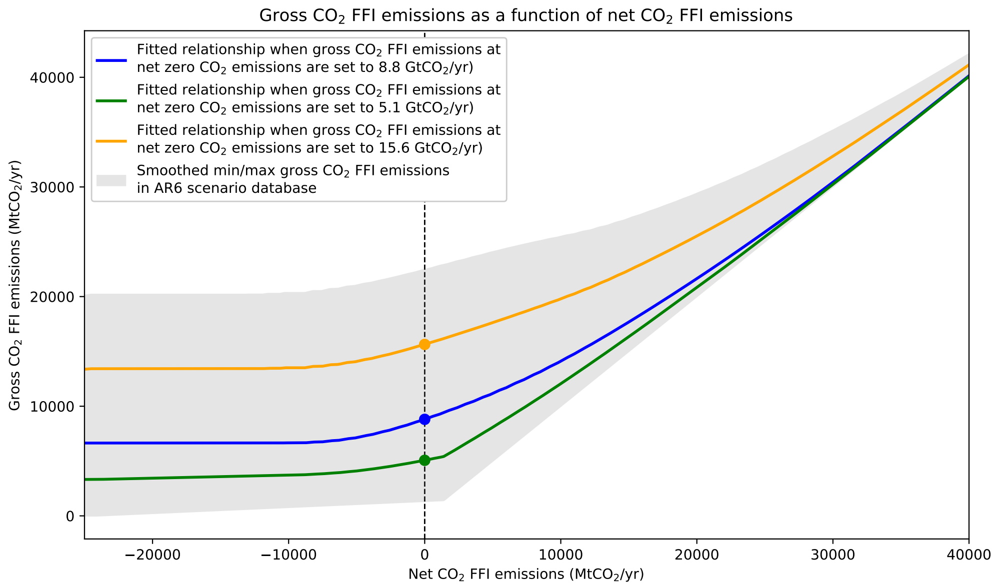
S.1.8 Reference time period selection

To make sure that our results are not biased by the selected reference time periods and account for interannual variability in the composition of emissions, we also vary the years contained in τ_{ref} and $\tau_{\mathrm{ref,bb}}$.

CEDS emissions We choose τ_{ref} to always include 2023 as the anchor year. Earlier years, back to 2004, are added probabilistically, with weights declining as 0.9^n for the nth year before 2023. Years affected by the COVID-19 pandemic (2020, 2021, 2022) receive reduced weights (0.2, 0.2, and 0.8, respectively) to avoid anchoring too much on anomalous sectoral contributions[33,34]. This probabilistic selection produces reference periods of different lengths with different sectoral contributions and relative emission factors.

GFED emissions For biomass burning emissions from GFED, the reference period ($\tau_{\mathrm{ref,bb}}$) always includes 2022 (the last year of the dataset used), with earlier years back to 2003 added with declining probability (0.9^n). No COVID adjustment is applied to biomass burning data, as we expect that fire emissions were less systematically affected by the restriction during the COVID-19 pandemic.

S.2 Supplementary Figures



Supplementary Figure 1: Shape of the $R_{CO_2}^{net \rightarrow gross}$ informed by the AR6 scenario database[5]. In our infilling model, the relationship is specified by the gross fossil CO_2 emissions at net zero CO_2 emissions.

S.3 Supplementary Tables

Supplementary Table 1: Assignment of CEDS sectors to sectoral categories.

Sectoral category	**Included sectors**
Energy production	1A1a_Electricity-autoproducer, 1A1a_Electricity-public, 1A1a_Heat-production, 1A1bc_Other-transformation, 1B1_Fugitive-solid-fuels, 1B2_Fugitive-petr, 1B2b_Fugitive-NG-distr, 1B2b_Fugitive-NG-prod, 1B2d_Fugitive-other-energy, 7A_Fossil-fuel-fires
Industry	1A2a_Ind-Comb-Iron-steel, 1A2b_Ind-Comb-Non-ferrous-metals, 1A2c_Ind-Comb-Chemicals, 1A2d_Ind-Comb-Pulp-paper, 1A2e_Ind-Comb-Food-tobacco, 1A2f_Ind-Comb-Non-metalic-minerals, 1A2g_Ind-Comb-Construction, 1A2g_Ind-Comb-machinery, 1A2g_Ind-Comb-mining-quarying, 1A2g_Ind-Comb-other, A2g_Ind-Comb-textile-leather, 1A2g_Ind-Comb-transpequip, 1A2g_Ind-Comb-wood-products, 1A5_Other-unspecified, 2A1_Cement-production, 2A2_Lime-production, 2Ax_Other-minerals, 2B2_Chemicals-Nitric-acid, 2B3_Chemicals-Adipic-acid, 2B_Chemical-industry, 2C1_Iron-steel-alloy-prod, 2C3_Aluminum-production, 2C4_Non-Ferrous-other-metals, 2H_Pulp-and-paper-food-beverage-wood, 2L_Other-process-emissions, 6A_Other-in-total, 6B_Other-not-in-total
Transportation	1A3b_Road, 1A3c_Rail, 1A3dii_Domestic-navigation, 1A3eii_Other-transp
Residential	1A4b_Residential, 1A4a_Commercial-institutional, 1A4c_Agriculture-forestry-fishing
Solvents	2D_Chemical-products-manufacture-processing, 2D_Degreasing-Cleaning, 2D_Other-product-use, 2D_Paint-application
Agriculture	3B_Manure-management, 3D_Rice-Cultivation, 3D_Soil-emissions, 3E_Enteric-fermentation, 3I_Agriculture-other
Waste	5A_Solid-waste-disposal, 5C_Waste-combustion, 5D_Wastewater-handling, 5E_Other-waste-handling
Shipping	1A3di_International-shipping, 1A3di_Oil_Tanker_Loading
Aviation	1A3ai_International-aviation, 1A3aii_Domestic-aviation
Indirect non-agricultural N_2O	7BC_Indirect-N2O-non-agricultural-N

Supplementary Table 2: Harmonization method for infilled F-gases

Linear interpolation until 2030	Scaling future emission levels
CFC-11, CFC-12, CFC-113, CFC-114, CFC-115,, HCFC-22, HCFC-141b, HCFC-142b, CCl_4, $CHCl_3$, CH_3Cl, CH_3CCl_3, CH_3Br, SF_6, HFC-125, HFC-152a, HFC-236fa, HFC-245fa, HFC-365mfc, HFC-4310mee	CH_2Cl_2, Halon-1211, Halon-1301, Halon-2402, CF_4, C_2F_6, C_3F_8, c-C_4F_8, C_4F_{10}, C_5F_{12}, C_6F_{14}, C_7F_{16}, C_8F_{18}, NF_3, SO_2F_2, HFC-134a, HFC-143a, HFC-227ea, HFC-23, HFC-32

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