Carbon Direct

Integrating Superpollutant Mitigation into Corporate Climate Action

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Acronyms and abbreviations

ACR: American Carbon Registry
AWD: alternative wetting and drying
BVCM: Beyond Value Chain Mitigation (Science Based Targets initiative)
CAR: Climate Action Reserve
CCP: Core Carbon Principles
CDR: carbon dioxide removal
CF_4: tetrafluoromethane
CH_4: methane
CO_2: carbon dioxide
EU: European Union
ETS: Emissions Trading System
FaIR: Finite Amplitude Impulse Response
F-gases: fluorinated greenhouse gas
GHG: greenhouse gas
Gt: gigatonne (billion metric tonnes)
GWP: global warming potential
GWP20: global warming potential on a 20-year time horizon
GWP100: global warming potential on a 100-year time horizon
HFC: hydrofluorocarbon
HFO: hydrofluoroolefin
ICVCM: Integrity Council for the Voluntary Carbon Market
IPCC: Intergovernmental Panel on Climate Change
kt: kilotonne
MMRV: measurement, monitoring, reporting and verification
Mt: million metric tonnes
NF_3: nitrogen trifluoride
N_2O: nitrous oxide
ODS: ozone-depleting substances
PFC: perfluorinated compound
SBTi: Science Based Targets initiative
SF_6: sulphur hexafluoride
SLCP: short-lived climate pollutant
tCO_2e: tonnes of carbon dioxide equivalent
VCM: voluntary carbon market

Executive summary

The world faces an urgent climate challenge requiring immediate and sustained action to reduce and remove greenhouse gas (GHG) emissions. While reductions and removals of carbon dioxide (CO_2) remain crucial for ensuring long-term climate stabilization, mitigating superpollutants (potent, climate-warming molecules other than CO_2) offers a critical opportunity to reduce warming over the next few decades and could help delay or prevent the adverse effects of climate change. For corporate buyers, pairing durable carbon dioxide removal (CDR) purchases with superpollutant mitigation creates a powerful, complementary climate strategy.

Some superpollutants that are currently emitted, such as methane and certain hydrofluorocarbons (HFCs), cause very large warming impacts over the near term. Therefore, reducing emissions of these superpollutants today can significantly slow the rate of warming by mid-century. There are many existing and emerging opportunities for mitigating superpollutant emissions, including a wide range of established methodologies and a growing set of novel ones that reflect recent science and technology innovation. While the voluntary carbon market (VCM) currently offers buyers opportunities to support credible superpollutant projects across multiple categories, there is enormous headroom for additional near-term climate impact from increased investment.

However, because superpollutants break down in the atmosphere at different rates than CO_2, emissions accounting methods must reliably track these varied lifetimes, and corporate claims should ultimately evolve to reflect this. For example, reducing short-lived superpollutants like methane provides outsized climate benefits in the near term (over roughly one to three decades) but the impacts are minimal after that. The current method of assessing superpollutants' global warming potential over a 100-year horizon (GWP100) and converting this into an equivalent impact in tonnes of CO_2 emissions (tCO_2e) obscures an important temporal difference with CO_2 mitigation, which delivers smaller near-term cooling impacts but sustains moderate climate benefits for well over a century. To address this, corporate buyers should consider additionally assessing the actual climate impact (avoided warming) of their superpollutant mitigation projects on an annual basis, as part of developing a broader climate strategy.

One specific opportunity is to pair short-lived superpollutant mitigation with durable CDR. When combined appropriately, the timescales over which both interventions deliver benefits complement one another: superpollutant reductions provide immediate cooling while CDR addresses longer-term effects. This combined impact can be robustly demonstrated using an accounting approach known as annual warming matching, enabling motivated stakeholders to make highly defensible claims about their climate commitments, achieving both accelerated and durable climate benefits.

Key takeaways

- **Near-term, large-scale impact:** Superpollutants are responsible for roughly 35–50% of today's warming, and their potency combined with short atmospheric lifetimes (for a subset of superpollutants) means abatement yields immediate climate benefits.
- **Complementary action:** Acting on superpollutants is complementary to, but not a substitute for, CO_2 emissions mitigation. Durable CDR and reduction of CO_2 emissions remain essential for long-term climate stabilization.
- **Market credibility:** The VCM already supports a range of credible superpollutant abatement projects, such as landfill methane capture, HFC replacement, and nitrous oxide (N_2O) destruction. These projects are often rated highly for quality. However, there is enormous headroom for additional action.
- **Scientific rigor:** Annual warming matching is an accounting framework that is more scientifically robust than using global warming potential (GWP) metrics alone to achieve a consistently planet-cooling outcome over future years.

Recommendations for buyers

- **Continue superpollutant mitigation:** Regardless of existing CDR investments, companies should consider incorporating or expanding high-quality superpollutant credit purchases into their decarbonization strategies to deliver accelerated climate benefits.
- **Assess annual warming impacts:** To achieve the most rigorous measurement of planet cooling across multiple timescales, corporate buyers should consider assessing the annual warming impact of their climate mitigation instead of exclusively following a GWP100 accounting approach.
- **Pair superpollutant abatement with durable CDR projects:** Pairing near-term, short-lived superpollutant mitigation with long-term, durable CDR, known as CDR pairing, can ensure a consistently negative warming profile in future years that drives sustained climate impact.
- **Communicate impact transparently:** Companies should ground their claims in the overall atmospheric impact of interventions, now and in the future. This is particularly true for compensation claims, but is also relevant for contribution claims.

An opportunity for expanded climate change mitigation

Superpollutant mitigation offers a major opportunity for greater action on climate change mitigation. Historic and ongoing anthropogenic GHG emissions mean that we live in a world with a rapidly changing climate. While CO_2 is responsible for the largest share of warming to date, methane, N_2O and other non-CO_2 greenhouse gases, known collectively as superpollutants, are responsible for 35–50% of observed warming (**figure 1**).[1]

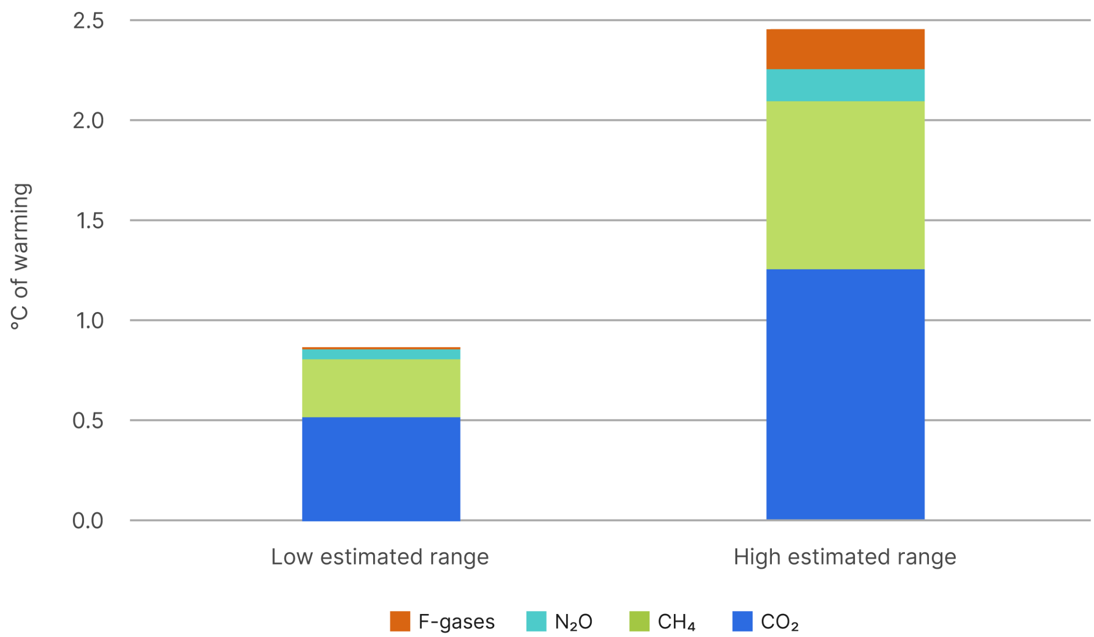

Figure 1. Contribution to current warming from carbon dioxide (CO_2) and non-CO_2 greenhouse gases, based on emissions from human activities from 1850–2019, in degrees Celsius (°C).[2] Note: Carbon Direct calculated the observed warming range using the Intergovernmental Panel on Climate Change's radiative forcing studies, which evaluated emissions' contribution to warming from 2010–2019 relative to 1850–1900. The ranges are broken down by individual gases. Ranges used (all rounded to two decimal points) are: 0.52–1.25°C for CO_2, 0.29–0.84°C for methane (CH_4), 0.05–0.16°C for nitrous oxide (N_2O), and 0.01–0.20°C for F-gases. We combined the high and low ranges for each gas to calculate the percent contribution of non-CO_2 gases to observed warming. Source: Carbon Direct.

1. Intergovernmental Panel on Climate Change. 2023. Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Lee H, Romero J, editors. Geneva (Switzerland): IPCC; [accessed 2025 Oct 30]. https://www.ipcc.ch/report/ar6/syr/downloads/report/IPCC_AR6_SYR_FullVolume.pdf.

2. Intergovernmental Panel on Climate Change. 2021. Summary for Policymakers. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge (UK): Cambridge University Press; pp. 3–32. [accessed 2025 Dec 8]. https://doi.org/10.1017/9781009157896.001

Superpollutants have high near-term warming potential, which can be hundreds or even thousands of times greater than CO_2 per unit of mass in the first few years after they are emitted. Some superpollutants have brief atmospheric lifetimes of only a few years. These are known as short-lived climate pollutants (SLCPs). Others remain in the atmosphere for much longer, sometimes centuries or more (**table 1**). By contrast, a substantial portion of emitted CO_2 remains in the atmosphere over extremely long timescales, making it effectively permanent unless actively removed through durable CDR.

Table 1. Greenhouse gas (GHG) lifetimes, global warming potentials (GWPs), and major sources

GHG	Atmospheric lifetime (years)	Relative lifetime	GWP100 (tCO_2e)	GWP20 (tCO_2e)	Major sources
HFC-32 (CH_2F_2)	5.4		771	2,690	Refrigerant leakage
Methane (CH_4)	11.8	Short-lived	27.9	81.2	Oil and gas production, livestock and agricultural management, waste disposal
HFC-134a (CH_2FCHF_3)	14		1,530	4,140	Refrigerant leakage
Nitrous oxide (N_2O)	109		273	273	Industrial processes, livestock, and agricultural management
Nitrogen trifluoride (NF_3)	569		17,400	13,400	Industrial production of semiconductors
Sulphur hexafluoride (SF_6)	1,000	Long-lived	24,300	18,200	Electrical transmission and distribution
Tetrafluoromethane (CF_4)	50,000		7,380	5,300	Aluminum, rare metal production, and industrial production of semiconductors
Carbon dioxide (CO_2)	No single lifetime* (50-200)**		1	1	Fossil fuel combustion

Note: Lifetimes and GWPs sourced from Intergovernmental Panel on Climate Change (2021),[3] while major sources of pollutants pulled from a variety of registries and methodologies. GHGs are ordered by atmospheric lifetime. tCO_2e = tonnes of CO_2 emissions. HFC = hydrofluorocarbon.

* No single lifetime can be defined for CO_2 due to different removal rates by different processes. Approximately 50% is removed within 30 years, an additional 30% within a few centuries, and the remaining 20% persists for thousands of years.[4]

** Equilibration timescale range. CO_2 has no single lifetime due to multiple removal processes operating on different timescales.[5]

3. Smith C, et al. 2021. The Earth's energy budget, climate feedbacks, and climate sensitivity supplementary material. In: Masson-Delmotte V, et al., editors. Climate change 2021: the physical science basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPPC). IPCC; [accessed 2025 Oct 28]. https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Chapter07_SM.pdf

4. Solomon S, et al. 2007. Climate change 2007: the physical science basis. Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL, editors. Technical Summary. p. 24-25. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPPC). [accessed 2026 Jan 20]. https://www.ipcc.ch/site/assets/uploads/2018/02/ar4-wg1-ts-1.pdf

5. Intergovernmental Panel on Climate Change. 2001. Climate change 2001: the scientific basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Houghton JT, Ding Y, Griggs DJ, Noguer M, van der Linden PJ, Dai X, Maskell K, Johnson CA, editors. Technical Summary. p. 38. [accessed 2026 Jan 20]. https://www.ipcc.ch/site/assets/uploads/2018/07/WG1_TAR_TS.pdf

Reducing ongoing GHG emissions and removing GHGs that are already in the atmosphere due to historical emissions are both crucial to limit climate damage. Regrettably, the world is not reducing GHG emissions fast enough to meet global targets and avoid the worst effects of climate change. These impacts are already manifesting in communities worldwide, from intensifying extreme weather events to disrupted agricultural systems. Without dramatic acceleration in emissions reductions, these impacts will grow ever more severe. Superpollutant mitigation can play a key role in making that acceleration possible.[6, 7]

The different atmospheric lifetimes of superpollutants and CO_2 can lead to confusion about evaluating the relative impacts of taking action to address them. Evaluating tradeoffs between near-term and longer-term climate benefits and damages is complex, and is influenced by both scientific reasoning and societal value judgements. This means that science alone cannot determine the optimal balance between CO_2 mitigation and action on SLCPs—both matter for climate outcomes over different time horizons. Analyses from the Intergovernmental Panel on Climate Change (IPCC) estimate the need for multiple gigatonnes (Gt) of CDR before the end of this century in order to meet climate targets for 2100.[8] Early efforts have begun to expand CDR, but we remain orders of magnitude behind the scale needed now and in the future.[9]

Meanwhile, the Earth's climate system may be approaching tipping points which would represent irreversible changes well before that date. Examples include melting of the Greenland ice sheet, permafrost thaw, and Amazon rainforest dieback.[10] While there is substantial scientific uncertainty around the timeframes or temperatures that would trigger these changes, evidence suggests that current climate policies risk triggering them, resulting in irreversible harm to parts of our climate system.[11] The risk of triggering these events increases the value of keeping mean global surface temperatures below certain thresholds over the near- to medium-term, and sustaining that temperature limit over time.

Taking action on superpollutants now has a range of important co-benefits. Beyond climate benefits, reducing superpollutant emissions improves public health through improving air quality and could lead to

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6. Veerabhadran Ramanathan, from the Scripps Institution of Oceanography, was one of the first scientists to identify the warming potential of non-CO_2 greenhouse gases and the short-term climate benefits from their reduction. His pioneering work on non-CO_2 GHG pollutants and aerosols provided much of the foundation for the scholarship of this report.

7. Scripps Institution of Oceanography. 2026. Ramanathan, Ram. [accessed 2026 Feb 10]. https://scripps.ucsd.edu/profiles/vramanathan

8. Intergovernmental Panel on Climate Change. 2023. Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Lee H, Romero J, editors. Geneva (Switzerland): IPCC; [accessed 2025 Dec 10]. 184 p. https://www.ipcc.ch/report/ar6/syr/downloads/report/IPCC_AR6_SYR_FullVolume.pdf.

9. Carbon Direct. 2026. 2026 State of the Voluntary Carbon Market. [accessed 2025 Dec 1]. https://www.carbon-direct.com/voluntary-carbon-market/2026

10. Hoegh-Guldberg O, et al. 2018. Impacts of 1.5°C global warming on natural and human systems. In: Masson-Delmotte V, et al., editors. Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. Cambridge University Press; p. 175–312. https://www.cambridge.org/core/books/global-warming-of-15c/impacts-of-15c-global-warming-on-natural-and-human-systems/DB3792F393E5009842EE23B9532B4654

11. Deutloff J, Held H, Lenton TM. 2025. High probability of triggering climate tipping points under current policies modestly amplified by Amazon dieback and permafrost thaw. Earth System Dynamics. 16(2):565–583. https://doi.org/10.5194/esd-16-565-2025

greater food security.[12] Some forms of superpollutant mitigation are also highly cost-effective, with benefits that include substantial reductions in future climate-related economic damages.[13] These co-benefits can have both an immediate and sustained impact on human well-being, reducing levels of respiratory and cardiovascular disease, preventing premature mortalities from air pollution, and mitigating the disruption and impact natural disasters have on crop yields.[14]

In this report, we outline how companies can start accomplishing enhanced climate impact by measuring the full climate impact of their GHG emissions, pairing superpollutant purchases with durable CDR, and communicating the impact of these purchases in a clear and transparent manner.

All corporate action advancing credible superpollutant abatement is essential and must be continued. Existing superpollutant projects already deliver significant climate benefits, and this current momentum must be acknowledged and encouraged. This report promotes the adoption of a scientifically rigorous approach for achieving climate change mitigation impact in both the near- and long-term by pairing action on superpollutants with durable CDR. Regardless, all companies advancing their climate strategies should consider incorporating or expanding superpollutant purchases into their decarbonization strategies, whether by integrating them with existing carbon portfolios, continuing to procure credits from superpollutant projects on the VCM, or advancing Beyond Value Chain Mitigation (BVCM)[15] efforts.

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12. World Resources Institute. 2023. 3 reasons why countries must take faster action to reduce short-lived climate pollutants. Washington (DC): World Resources Institute; [accessed 2025 Oct 30]. https://www.wri.org/insights/short-lived-climate-pollutant-reductions

13. Stoerk T, Rising J, Shindell D, Dietz S. 2025. Global methane action pays for itself at least six times over. Science. 390(6772):eadu7392 [accessed 2026 Feb 11]. https://www.science.org/doi/10.1126/science.adu7392

14. Climate & Clean Air Coalition. 2025. Short-lived climate pollutants and food security. [accessed 2025 Nov 13]. https://www.ccacoalition.org/content/short-lived-climate-pollutants-and-food-security

15. Science Based Targets Initiative. 2024. Above And Beyond: An SBTi Report On The Design And Implementation Of Beyond Value Chain Mitigation (BVCM). [accessed 2026 Feb 6]. https://files.sciencebasedtargets.org/production/files/Above-and-Beyond-Report-on-BVCM.pdf

Integrating super-pollutants into corporate climate strategy

When thoughtfully integrated, superpollutant action can complement, rather than compete with, voluntary corporate action on essential longer-term decarbonization measures. Voluntary climate action is needed to fill the gaps left by insufficient regulation, enforcement, funding, and global policies to address superpollutants at the speed and scale required. Corporate commitments can help drive meaningful near-term climate benefits while complementing policy efforts. The VCM is an important mechanism that provides a pathway for companies to support innovation and direct private capital toward solutions that would otherwise lack adequate funding. Voluntary action sends crucial demand signals that unlock project finance, helping to scale emerging technologies and build the infrastructure needed for gigatonne-scale climate solutions.

Corporate action on superpollutants can advance alongside the long-term goal of CO_2 mitigation, with both efforts strengthening decarbonization efforts. Taking action on both superpollutant emissions reductions and CDR can be highly complementary.

Corporations that pair superpollutant action with longer-term decarbonization efforts, such as durable CDR, can sustain the climate change impact achieved by superpollutant mitigation beyond the near term and help fill the gap between CDR deployment and its realized climate benefits.

Corporate engagement in the VCM has increased for both CO_2 and non-CO_2 credits. Non-CO_2 credit retirements have grown substantially, from only 400 tCO_2e retired in 2004 to over 27 million tCO_2e in 2024.[16] This expansion, while promising, is still far lower than what is needed. For instance, methane mitigation on the VCM over the last five years represented less than 1% of total methane emissions over the same time frame.[17] As companies advance their climate strategies, expanding the focus on superpollutants offers important opportunities to deliver accelerated climate benefits. In particular, pairing superpollutant and durable CDR credits provides a compelling and complementary approach.

16. Retirement quantities are based on Carbon Direct analysis using data on issuance and retirements from five registries (Climate Action Reserve, American Carbon Registry, Gold Standard, Verra, and ART-TREES).

17. This percentage is based on Carbon Direct analysis using data on retirements from five registries (Climate Action Reserve, American Carbon Registry, Gold Standard, Verra, and ART-TREES) and data on methane emissions from Global Methane Budget (2024) and Integrated Carbon Observation System (2024).

Methane represents a disproportionate share of superpollutant emissions, making it a massive and obvious opportunity for abatement.[18] Total methane emissions, including both anthropogenic and natural sources, amount to around 689 million tonnes (Mt) per year.[19, 20] Similar patterns hold for N_2O, although it accounts for a smaller share of emissions than methane. According to the Global N_2O Budget, total N_2O emissions amounted to about 28 Mt/year in 2020.[21, 22]

F-gases also represent an important opportunity for mitigation, but their diversity of types, sources, lifetimes, and radiative forcing make them more challenging to assess uniformly. The Kyoto Protocol lists HFCs, perfluorinated compounds (PFCs), and sulphur hexafluoride (SF_6) as the F-gas GHGs in Annex A,[23] with nitrogen trifluoride (NF_3) added by the Doha Amendment.[24] Because HFCs and PFCs are categories, rather than individual GHG species, they include a large number of specific compounds.

For example, the European Union's F-gas Regulation lists 19 different HFC compounds and nine PFC compounds under Annex 1, with additional compounds listed under Annex 2 and 3 (see *Appendix A* for a more extensive listing).[25] As a result, the opportunities for F-gas mitigation are highly diverse.

Corporate buyers should understand rebound risk when selecting short-lived superpollutant projects. While methane and other short-lived superpollutant mitigation delivers substantial near-term cooling, the short atmospheric lifetimes of these gases means benefits fade after a limited period of time. If emissions resume, whether due to climate payments ending or finite project lifetimes, temperatures can "rebound" (see *Appendix C*). Buyers should therefore emphasize projects designed for permanent emissions reductions through physical infrastructure changes, economically sustainable operational shifts, or system-wide transitions.

18. This assumes that all sources are accessible and that it is feasible to destroy them. It also assumes that unhindered demand would remain consistent enough over time to enable permanent displacement of superpollutant sources, especially those that may require continuous procurement and deployment, such as feed additives for cattle.

19. Global Carbon Project. 2024. Global Methane Budget 2000–2020. [accessed 2025 Dec 8]. https://doi.org/10.5194/essd-2024-115

20. Most interventions to reduce methane emissions are focused on anthropogenic sources, such as landfills or oil and gas production. However, some interventions, like wetland restoration, target natural sources of methane emissions that have been released due to disturbance.

21. Global Carbon Project. 2024. Global N_2O Budget. [accessed 2025 Dec 5]. https://www.globalcarbonproject.org/nitrousoxidebudget/

22. This number is based on top-down averages for 2020. Conversion factor Mt N_2O = (44/28) * TgN. Note: Tg = teragram, or one million metric tonnes. Global N_2O Budget data is denominated in TgN but their visuals show N_2O.

23. United Nations Framework Convention on Climate Change. 1997. Kyoto Protocol. [accessed 2026 Feb 6]. https://unfccc.int/sites/default/files/resource/docs/cop3/l07a01.pdf

24. United Nations Framework Convention on Climate Change. 2012. Doha Amendment to the Kyoto Protocol. [accessed 2026 Feb 6]. https://unfccc.int/files/kyoto_protocol/application/pdf/kp_doha_amendment_english.pdf

25. European Union. 2024. Consolidated text: Regulation (EU) 2024/573 of the European Parliament and of the Council of 7 February 2024 on fluorinated greenhouse gases, amending Directive (EU) 2019/1937 and repealing Regulation (EU) No 517/2014. [accessed 2026 Feb 6]. https://eur-lex.europa.eu/eli/reg/2024/573#anx_I

Challenges and opportunities for improving superpollutant impact accounting

Improved accuracy in measuring the climate impacts of superpollutant mitigation projects would help address the gap in voluntary action on superpollutants. The current system uses the concept of GWP to convert an amount (in tonnes) of non-CO_2 gas into an equivalent amount of CO_2 climate impact (expressed as tCO_2e, see **table 1**). While this approach is highly convenient because of its simplicity, it obscures the different timescales over which superpollutants affect the climate. An alternative approach, involving separate accounting, tracks each GHG individually without conversion factors, ensuring that superpollutant mitigation remains distinct from CO_2 mitigation. While this framework eliminates concerns about substituting gases with fundamentally different atmospheric lifetimes, it requires significant changes to existing GHG accounting systems and could make it more challenging to assess holistic climate action across an organization's portfolio. The limitation of the GWP approach becomes clear when we examine the annual warming (radiative forcing) differences of various GHGs (**figure 2**). For example, a tonne of methane prevented from entering the atmosphere delivers immediate, near-term climate mitigation, but that benefit diminishes quickly over time. Meanwhile, permanently removing a tonne of CO_2 prevents warming that would otherwise persist for hundreds of years or longer, but provides a smaller amount of mitigation in the near term. The standard GWP100 accounting method attempts to capture both effects in a single number, but obscures the temporal dynamics that matter for achieving both near-term and long-term cooling of the planet.

The use of the GWP method, therefore, unavoidably embeds a policy or value judgement about the importance of future climate damages. Some alternatives like GWP20 (which compares the warming of a superpollutant to CO_2 over a 20-year timeframe) can be used, but simply reflect a nearer-term focus rather than a more accurate and complete picture of climate impact. The arbitrariness of the GWP approach, and the fact that it obscures these different timescales of impact, can undermine optimal decision-making around corporate climate strategy.

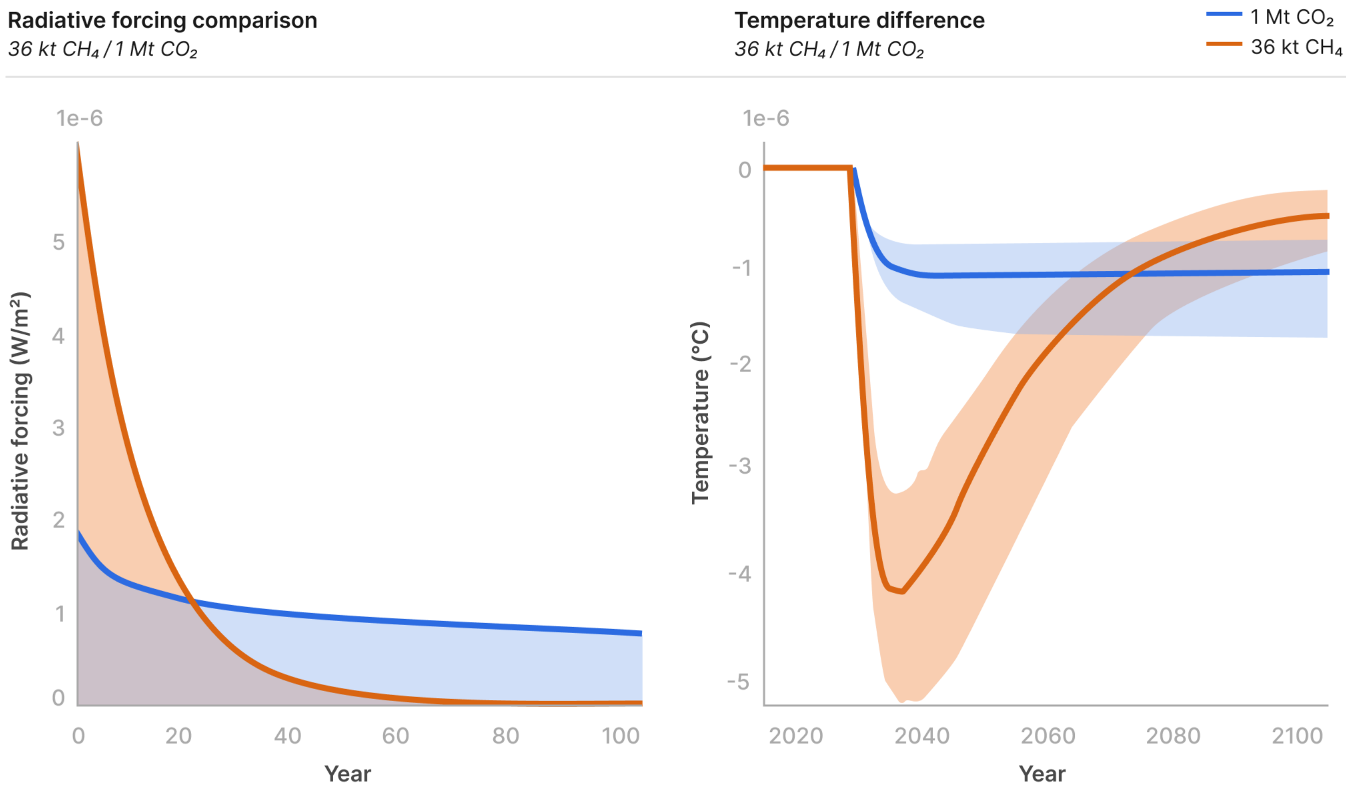

Figure 2. Comparing future warming that results from equivalent amounts of carbon dioxide (CO_2) and methane (CH_4) emissions using a GWP100 conversion factor, with radiative forcing expressed as watts per square meter (W/m²), temperature difference from a baseline scenario in degrees Celsius (°C), CO_2 shown in megatonnes (Mt) and CH_4 shown in kilotonnes (kt). Left: The radiative forcing (rate of warming) from CH_4 emissions in year zero is far higher than CO_2 in the near term (over one to three decades) but drops rapidly after that. The rate of warming from CO_2 continues to be significant for over a century. Right: The impacts of this difference can be seen in the avoided temperature rise compared to a baseline scenario (SSP2-4.5).[26] Avoiding 36 kt of CH_4 emissions in 2030 leads to lower temperatures over several decades than avoiding 1 Mt of CO_2 emissions. However, avoiding CO_2 emissions leads to lower temperatures in the second half of the century. This illustrates how the use of GWP conversion factors can obscure the timing of climate impacts. Notes: 1e-6 = 0.000001 (one millionth). The shaded area in the right plot reflects 5th/95th percentile ranges across an ensemble of model configurations using the Finite Amplitude Impulse Response (FaIR) climate emulator (see *Appendix C*). Source: Carbon Direct.

Annual warming matching approaches provide a more accurate representation of the actual climate impact of voluntary corporate mitigation actions over time. Rather than collapsing complex atmospheric dynamics into a single conversion factor (via GWP), annual warming matching tracks the future warming impact of mitigation activities to provide an accurate view of climate impacts on the atmosphere. This approach captures the magnitude of near-term warming as well as the fading impacts of SLCPs as they decompose in the atmosphere through various mechanisms. Annual warming matching is an accounting framework that can be applied to any combination of GHG mitigation activities.

26. National Oceanic and Atmospheric Administration. Climate Model—Surface Temperature Change: SSP2 (Middle of the Road)—2015–2100. Science On a Sphere. [accessed 2025 Dec 8]. https://sos.noaa.gov/catalog/datasets/climate-model-surface-temperature-change-ssp2-middle-road-2015-2100/

One particularly powerful application is CDR pairing, which uses this framework to combine short-lived superpollutant (SLCP) mitigation with durable CDR, ensuring consistently negative warming over time. While this method requires more sophisticated modeling and communication, adding cost and complexity beyond the current capabilities of many organizations, it gives a comprehensive temporal profile of climate benefits, making it particularly valuable for evaluating superpollutant mitigation. Rapid changes in this space, including the development of accessible toolsets to operationalize these models, may increase rigor and expand opportunities for their application, though a detailed exploration of such tools is beyond the scope of this paper.

"Pairing" short-lived superpollutant mitigation and durable CDR illustrates how annual warming matching can work in practice. One of the most important opportunities for companies to integrate superpollutant mitigation into their climate strategy is to pair it with purchases of CDR. The near-term climate benefits of short-lived superpollutant mitigation can synergistically complement the long-term benefits of CDR, providing a balanced overall impact. Using the annual warming matching approach to pairing can ensure a consistently negative warming profile that drives sustained planetary cooling.

In the first example (**figure 3**), the baseline scenario is the purchase and delivery of 1 Mt of CDR in 2030. An alternative, paired scenario begins with the purchase and delivery of 0.036 Mt (36 kilotonnes [kt]) of methane abatement in 2030 (chosen because it represents 1 $MtCO_2e$ using GWP100), paired with the delivery of 1 Mt of CDR in a future year. As shown, the initial methane mitigation purchase avoids substantial warming in the near term, achieving maximum cooling impact within the first 10-15 years. However, because methane has a relatively short atmospheric lifetime, the avoided warming diminishes after that, falling below the baseline scenario after 20 years. The timing of the future-year CDR delivery is chosen to occur in the year when the avoided warming from the methane purchase falls below the avoided warming from the baseline scenario, which is 2050 (20 years later) in this case.

Note that a smaller initial purchase of methane mitigation would make this cross-over point occur even earlier, as shown in the second example (**figure 4**). In this case, the methane abatement in the starting year (2030) is only 0.018 Mt (18 kt, or 0.5 $MtCO_2e$ using GWP100), and the cross-over point occurs 12 years later, requiring delivery of 1 Mt of CDR in 2042.[27] This pairing approach generates a combined avoided warming that remains consistently equal to or more than the baseline scenario throughout the entire time horizon, avoiding the situation in which early climate benefits from methane mitigation eventually fall below the baseline as methane's effects dissipate.

27. Regardless of the amount of methane mitigation initially purchased, the amount of CDR delivered in a future year in the paired scenario must be the same as the baseline scenario (1 Mt in these examples) for long-term avoided warming to be equivalent.

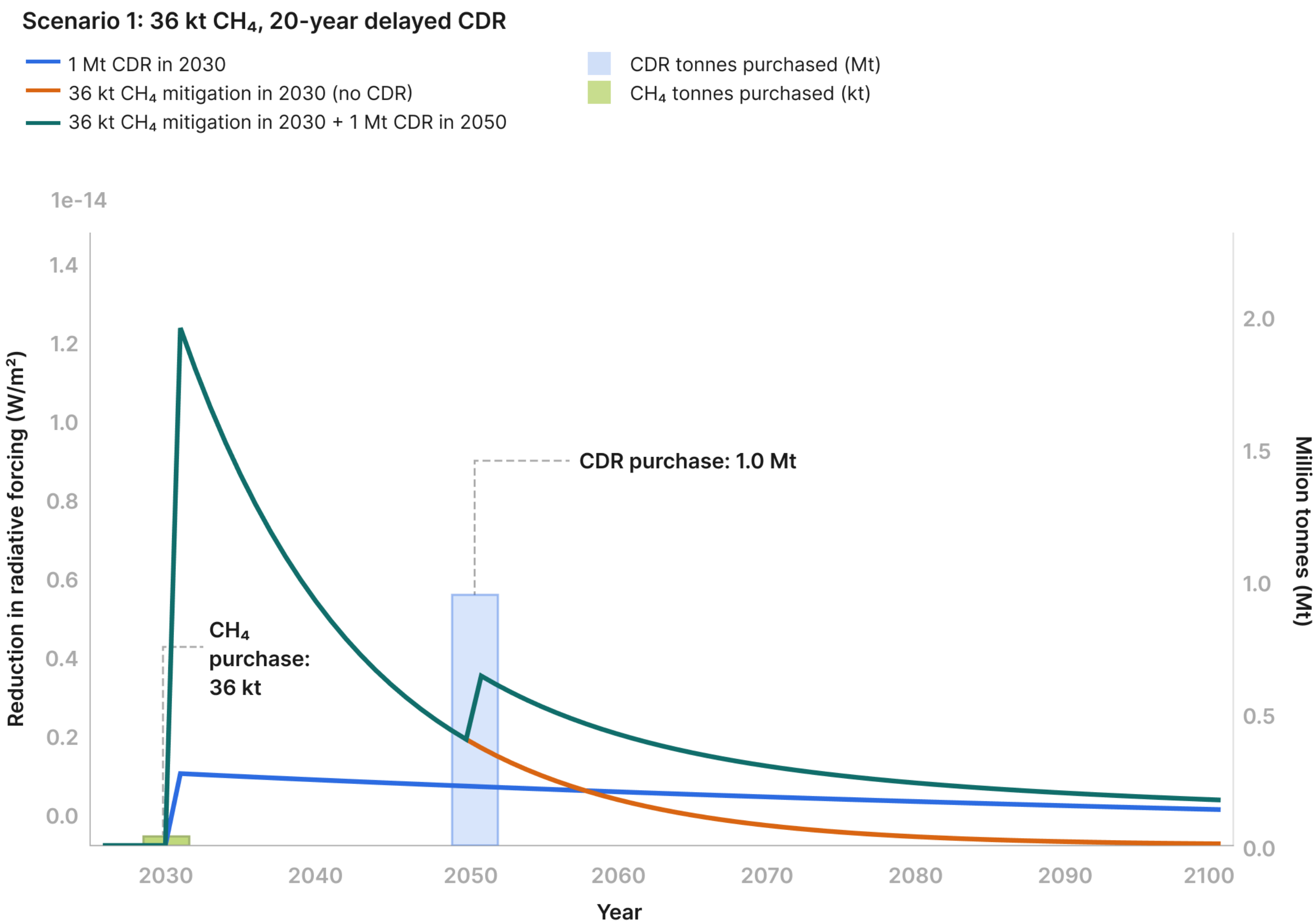

Figure 3: Avoided warming impact of different credit purchasing scenarios, with radiative forcing expressed as watts per square meter (W/m^2). The figure compares the future avoided radiative forcing from a one-time baseline purchase of 1 million tonnes (Mt) of carbon dioxide removal (CDR), represented by the blue line, with that of a paired one-time purchase of 0.036 Mt (or 36 kilotonnes [kt]) of methane (CH_4) mitigation plus a one-time purchase of 1 Mt of CDR, delayed by 20 years, represented by the green line. The red line represents the reduction in radiative forcing resulting from the purchase of 0.036 Mt of CH_4 without the additional CDR purchase 20 years later, when avoided warming falls below the baseline by 2050. Note: 1e-14 = 0.00000000000001 (one hundred-trillionth). Source: Carbon Direct.

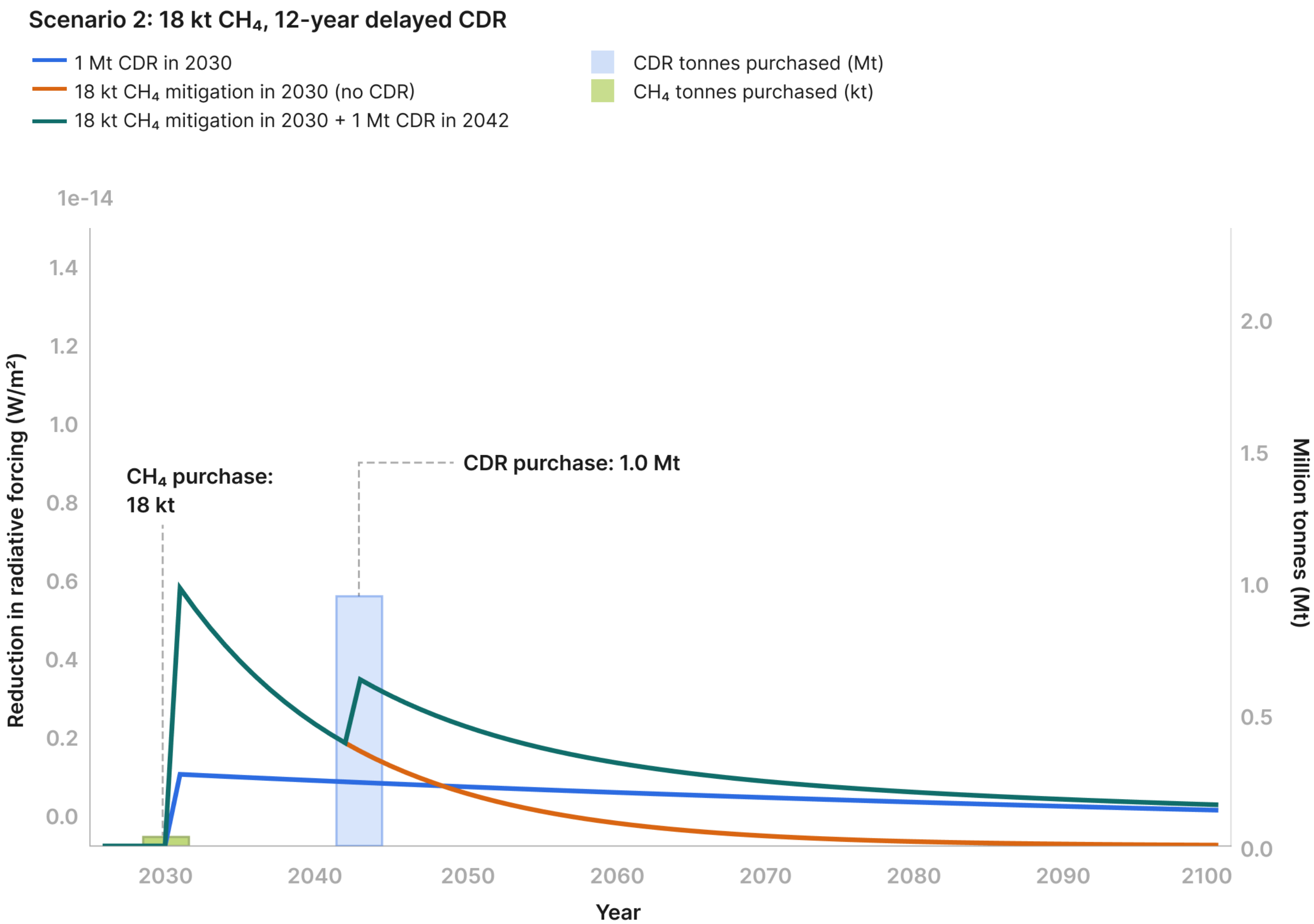

Figure 4: Avoided warming impact of different credit purchasing scenarios, with radiative forcing expressed as watts per square meter (W/m²). The figure compares the future avoided radiative forcing from a one-time baseline purchase of 1 million tonnes (Mt) of carbon dioxide removal (CDR), represented by the blue line, with that of a paired one-time purchase of 0.018 Mt (18 kilotonnes [kt]) of methane mitigation (CH_4) plus a one-time purchase of 1 Mt of CDR delayed by 12 years, represented by the green line. The red line represents the reduction in radiative forcing resulting from the purchase of 0.018 Mt of CH_4 without the additional CDR purchase 12 years later, when avoided warming falls below the baseline by 2042. Note: 1e-14 = 0.00000000000001 (one hundred-trillionth). Source: Carbon Direct.

Annual warming matching is particularly relevant for some types of CDR projects that experience a lag in their net removal.[28] These include CDR pathways that take place in open systems like surficial enhanced rock weathering on agricultural fields[29] and marine CDR,[30] both of which are subject to environmental factors that may cause delayed drawdown. Minor delays may also occur due to front-loaded emissions, such as in direct air capture with carbon storage projects where the embodied emissions of capital equipment are incurred before the project begins operation. Finally, biomass-based carbon removal and storage projects using waste biomass may also experience counterfactual delays, where atmospheric drawdown is only realized as the carbon in biomass would have otherwise been released through decay—a lag that can span decades depending on the feedstock and environmental conditions.[31] This lag period between a CDR intervention's development and its net realized atmospheric drawdown can be addressed by pairing these projects with short-lived superpollutant mitigation, using annual warming matching to support transparent claims about impacts across all timescales.

Assessing the temperature impacts of CDR pairing is possible, but introduces substantial additional uncertainty. Using modern climate emulator tools (see *Appendix C*) it is possible to translate a CDR pairing approach into the projected impact of credit purchasing on temperature rise. However, given the range of possible future climate scenarios, the results include significant uncertainty and outputs should be treated conservatively. To illustrate this, **figure 5** shows the projected temperature difference between the baseline and paired scenarios discussed above and illustrated in **figures 3 and 4**. Both paired scenarios result in lower temperatures (less warming) than the baseline scenario for the median (50th percentile) modeling result.

Effective CDR pairing requires thoughtful procurement strategies that have contractual and capital guardrails to ensure that both the superpollutant mitigation and CDR take place. Companies must establish robust, credible mechanisms to ensure CDR purchases proceed as planned when pairing with superpollutant mitigation. One credible approach is for companies to sign contracts for both short-lived superpollutant mitigation and durable CDR in reasonable proximity to each other, and before the claim year, to ensure delivery of CDR. While immediate, simultaneous contracting of both may not be feasible, timeframes beyond months will delay the availability of present-day capital commitments to support scaling the CDR market, and may call claims into question.[32] This does require the availability of funding for both

28. Cabiyo B, et al. 2026. Consistent temporal accounting supports credible CDR use [preprint]. [accessed 2026 Feb 2]. CDRxiv. https://cdrxiv.org/preprint/302?version=1.

29. Carbon Direct. 2024. A Buyer's Guide to Enhanced Rock Weathering in Croplands. [accessed 2025 Dec 8]. https://www.carbon-direct.com/research-and-reports/enhanced-rock-weathering-in-croplands

30. Carbon Direct. 2025 Mar 31. Marine carbon dioxide removal: what it is and how it works. [accessed 2025 Dec 8]. https://www.carbon-direct.com/insights/marine-carbon-dioxide-removal-what-it-is-and-how-it-works

31. Cabiyo B, et al. 2026. Consistent temporal accounting supports credible CDR use [preprint]. [accessed 2026 Feb 2]. CDRxiv. https://cdrxiv.org/preprint/302?version=1.

32. When accounting for CDR pairing under a compensation (or "tonne-for-tonne") claim, the reporting under GWP100 should not exceed one tCO_2e for the given CDR credit (even if paired with a superpollutant purchase). This is because it is an upfront purchase to ensure the continuity of future climate impact over time, not an additional claim.

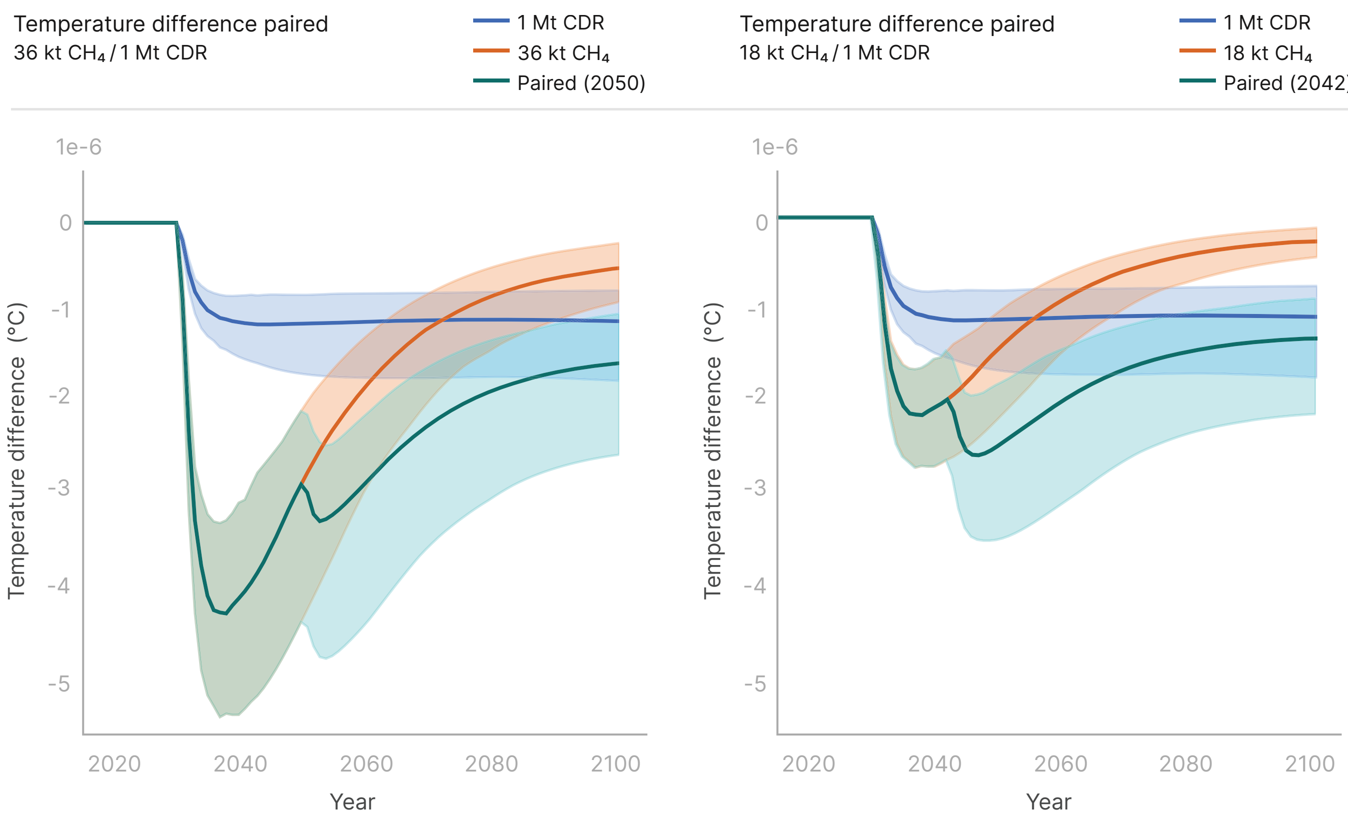

Figure 5: Future temperature impacts of the two different credit purchasing scenarios, as shown in figures 3 and 4 and described in the text, with temperature difference from a baseline scenario in degrees Celsius (°C). This figure compares the future temperature difference (cooling) that results from a one-time baseline purchase of 1 million tonnes (Mt) of carbon dioxide removal (CDR) in 2030, represented by the blue line, with that of a paired one-time purchase of 36 kilotonnes (kt) of methane (CH_4) mitigation in 2030 plus a one-time purchase of 1 Mt of CDR delayed by 20 years (left) or a one-time purchase of 18 kt CH_4 mitigation in 2030 plus a one-time purchase of 1 Mt of CDR delayed by 12 years (right), represented by the green line. Notes: 1e-6 = 0.000001 (one millionth). The red lines represent the temperature difference resulting from the purchase of CH_4 mitigation without the additional, paired CDR purchase to prevent the avoided warming from falling below the baseline in subsequent years. The shaded areas reflect 5th/95th percentile ranges across an ensemble of model configurations using the Finite Amplitude Impulse Response (FaIR) climate emulator (see Appendix C). Source: Carbon Direct.

intervention types, but provides clarity and simplified accounting.[33] One rigorous way to ensure sufficient guardrails for these CDR commitments is through a bankable, forward-offtake agreement between buyers and CDR suppliers, specifying the volume or cost of CDR to be procured over a given timeline, with limited and clearly specified termination rights. For companies already funding durable CDR, the incremental cost of adding superpollutant mitigation is likely to be small, given the large near-time climate impact of SLCPs (particularly methane).

There are other financing approaches that could be considered, such as escrow or pension funds. These offer increased flexibility, but less near-term certainty for suppliers in the CDR market to continue scaling. Escrow funds or similar mechanisms that commit capital to purchase durable CDR at a future date offer less specificity than binding

33. Funding does not need to be transferred immediately, with payment on delivery as common practice for CDR purchases. However, CDR developers need contractual commitments to secure bank financing and debt.

offtake agreements but can play a highly valuable role in future market development, particularly in supporting early-stage companies that can use the committed funding to attract additional investment. For technologies that lack mid- or later-stage providers this could provide vital support to catalyze the emergence of a range of innovative, early-stage firms that can begin the process of growth toward at-scale CDR project delivery.

Scaling commercial deployment of proven CDR technologies requires bankable forward-offtake commitments to enable access to debt and equity financing from capital markets. Binding offtake agreements therefore drive scaling and deployment, while escrow funds and other commitments can catalyze innovation and help new technologies progress toward commercial readiness. Though the use of annual warming matching and CDR pairing demands greater strategic investment, early adopters can establish themselves as leaders in comprehensive climate action, paving the way for broader adoption as best practices evolve (**box 1**). For companies pursuing superpollutant mitigation alone, CDR pairing would represent a significant upgrade and is encouraged.

Box 1: Carbon dioxide removal (CDR) pairing

Pairing short-lived superpollutant mitigation credit purchases with durable CDR helps address temporal differences between different greenhouse gases (i.e., different atmospheric lifetimes and the time delay between CDR project initiation and net carbon dioxide drawdown). It enables mitigation of both near- and long-term warming through achieving consistently negative warming.

Benefits of CDR pairing

- Addresses the differences in atmospheric lifetime between short-lived superpollutants and carbon dioxide mitigation efforts, ensuring both near- and long-term climate change mitigation goals are achieved
- Enables corporates to achieve a consistently negative warming impact, mitigating the impact of lag for some types of CDR purchases

Challenges with CDR pairing

- Not currently standard practice, requiring corporate buy-in and behavioral change, which could cause increased resource requirements (both time and cost)
- Currently best suited to market pioneers, who can build analysis tools to help other stakeholders begin adoption

Considerations for corporate action on superpollutants

Corporations have wide-ranging motivations for engaging in voluntary action on superpollutant mitigation, such as direct liability for their emissions inventory, mitigating unintended near-term emissions releases from deploying CDR projects, getting ahead of future regulatory requirements, and many others. There is no one-size-fits-all approach to engagement. However, the choice of accounting method is critical to assessing the climate impacts of superpollutants and forms the foundation of any superpollutant-related claims. Corporations can remain accountable through transparent, external-facing claims, but these claims must accurately represent the company's actions. Clear communication and framing are essential for companies to maintain market integrity and credibly represent the climate benefits of their superpollutant mitigation projects. The following section outlines different approaches for how corporations can communicate the climate impact of these investments.

Compensation claims

Compensation claims involve a direct link between superpollutant mitigation and corporate emissions. Under these claims, companies assert that the climate impact of their superpollutant mitigation activities directly counterbalances the same volumes of unabated emissions in their emissions inventory; this is commonly referred to as a "tonne-for-tonne" approach.

Companies can pursue compensation claims through three distinct approaches:

- **Annual warming matching:** Companies pair near-term superpollutant mitigation with durable CDR to address both immediate and long-term warming. This combined climate intervention enables highly credible claims to compensate for different GHG emissions over the near and long term by delivering equivalent cooling across relevant timescales. By addressing the distinct temporal profiles of different GHGs, this approach allows companies to maintain unified emissions reduction targets while acknowledging scientific differences between pollutants.
- **Like-for-like approach:** Companies match their direct or indirect emissions from superpollutants with credits from a project that mitigates the same GHG. For example, companies with significant methane emissions can fund methane destruction projects that match their annual methane emissions. This matching acknowledges the distinct differences of GHGs while maintaining the principle of compensation. However, this makes it impossible to set a unified emission-reduction target across all GHGs, and currently the Greenhouse Gas Protocol does not include guidance on

how compensation claims for superpollutant mitigation credits should count toward corporate targets in its inventory standards.

- **Conventional GWP approach with caveats:** Companies continue to use the GWP100 conversion approach but clearly disclose its limitations and acknowledge the different timescales over which their actions will and will not have climate impact. This approach maintains compatibility with existing reporting frameworks but requires explicit acknowledgment that superpollutant mitigation delivers near-term cooling benefits not fully captured by long-term metrics. Transparency is essential to maintaining credibility and clarity with this approach.

Companies with material superpollutant emissions in their corporate inventories might consider a compensation claim to ensure they take full accountability for their direct emissions before pursuing contribution-style commitments, such as mitigating emissions beyond their value chain. However, the Greenhouse Gas Protocol's inventory standards do not currently provide guidance on using superpollutant mitigation credits as compensation claims toward corporate targets. Additionally, companies selecting any compensation approach must address the critical issue of emissions fungibility (**box 2**).

Box 2: Emissions fungibility

Greenhouse gas (GHG) emissions are considered fungible when one unit of GHG (e.g., carbon dioxide) is treated as being equivalent to and interchangeable with one unit of a different GHG (e.g., methane). The typical accounting approach for fungibility is to convert all GHGs to tonnes of carbon dioxide equivalent (tCO_2e) using their global warming potential (GWP) over a 100-year horizon (GWP100), or (in rare cases) a 20-year horizon (GWP20).

Benefits of emissions fungibility

- Simple conversion process makes it the most widely used approach to date
- Easy comparison across GHGs and overall emissions helps support corporate climate action

Challenges with emissions fungibility

- Different GHGs have different atmospheric lifetimes and potencies
- Masks temporal climate impacts, resulting in different levels of cooling over different timescales

Contribution claims

Companies can also fund high-impact superpollutant mitigation beyond their value chain, without claiming an offset against their own corporate emissions. Unlike the compensation approaches described above, these contribution claims do not assert a direct link between superpollutant mitigation and corporate emissions. While these credits are not counted toward specific emissions reduction targets within a company's value chain, they represent a company's voluntary contribution to broader global climate mitigation efforts and recognize the destruction of superpollutants as valuable climate action beyond a company's emission reduction obligations.[34] Companies that either do not have material superpollutant emissions in their footprint or are already engaging in contribution-style commitments, such as through the Science Based Targets initiative's (SBTi's) BVCM framework, might consider this approach.[35, 36]

While SBTi's BVCM framework includes mitigation of all GHGs and provides examples of companies' BVCM commitments that include superpollutant mitigation (methane destruction), it does not provide dedicated guidance on how superpollutants should be treated when making corporate claims.[37]

Regardless of which approach companies adopt, transparency remains the most important factor in making claims. Clear communication about purchases, climate impact across different timescales, and how interventions relate to corporate emissions allows stakeholders to evaluate the credibility and ambition of corporate strategies. The framework we recommend provides companies with tools to deepen the scientific rigor of their engagement with superpollutant mitigation. This rigor should extend to corporate communications and disclosures about the impacts of corporate climate action.

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34. Voluntary Carbon Markets Integrity Initiative. 2023. Claims code of practice. London: Voluntary Carbon Markets Integrity Initiative; [accessed 2025 Nov 12]. https://vcmintegrity.org/wp-content/uploads/2023/06/VCMI-Claims-Code-of-Practice.pdf

35. The BVCM, while still a viable framework, is being integrated into a broader framework of the SBTi's on-going emissions responsibility framework.

36. Science Based Targets initiative. 2025. Ongoing emissions responsibility: A framework for credible and competitive climate action. [accessed 2025 Nov 14]. https://files.sciencebasedtargets.org/production/files/Ongoing-emissions-responsibility-A-framework-for-credible-and-competitive-climate-action.pdf)

37. Science Based Targets Initiative. 2024. Above And Beyond: An SBTi Report On The Design And Implementation Of Beyond Value Chain Mitigation (BVCM). [accessed 2026 Feb 6]. https://files.sciencebasedtargets.org/production/files/Above-and-Beyond-Report-on-BVCM.pdf

Existing and promising opportunities for superpollutant mitigation

The VCM currently offers buyers a broad range of established and growing opportunities for superpollutant mitigation. Many existing, high-quality superpollutant projects represent low-hanging fruit in the suite of climate mitigation solutions, delivering impact at relatively low cost through established, scalable interventions. High-quality superpollutant projects across methane, F-gases, and N_2O are well represented on the VCM, and have been for over a decade. There are also many opportunities for corporations to support high-potential projects that have yet to be tested at scale. To date, while showing growth, superpollutant credit issuances on the VCM remain much lower than the current opportunity for mitigation. Both issuances and retirements of credits from superpollutant projects have increased substantially, with the volume of issuances nearly tripling between 2020 and 2025, resulting in large availability of credits on the market today.[38]

In 2025, issuances were concentrated in three categories: HFC replacement in foam production (~18%), landfill methane (~17%), and gas system leak detection and repair (~12%), creating opportunities for buyers to scale as standards continue to develop.[39] Further promising opportunities exist where sectors are scaling rapidly. For example, SF_6-free electrical switchgear and tetrafluoromethane (CF_4) mitigation in semiconductor manufacturing present opportunities as data center and chip production expand due to the rapid growth in electricity demand for artificial intelligence. As these proven and emerging mitigation opportunities continue to expand, technologies such as remote sensing offer promising improvements to measurement, monitoring, reporting, and verification (MMRV) challenges faced by some categories (see *Appendix A* for more details on challenges and opportunities).

38. Carbon Direct. 2026. 2026 State of the Voluntary Carbon Market. [accessed 2025 Dec 1]. https://www.carbon-direct.com/voluntary-carbon-market/2026

39. Carbon Direct. 2026. 2026 State of the Voluntary Carbon Market. [accessed 2025 Dec 1]. https://www.carbon-direct.com/voluntary-carbon-market/2026

Companies such as Google,[40] Netflix,[41] Salesforce,[42] and Workday[43] demonstrate the emerging opportunity for corporations to integrate superpollutant mitigation into their climate strategies, despite superpollutants representing a small fraction of their own emissions. These early movers signal a promising path forward for other companies seeking to maximize climate impact through their voluntary purchases. Netflix and Salesforce, among other commitments, have both announced procurement of landfill gas management credits, and Workday announced a partnership with Tradewater to plug orphaned wells, which are another source of methane emissions.

Google has announced partnerships with Recoolit for F-gas destruction and with Cool Effect for landfill methane mitigation. These projects aim to eliminate more than 25,000 tonnes of superpollutants by 2030, through F-gas destruction in residential and commercial cooling systems in Indonesia and methane destruction from landfills in Brazil.

These commitments are both forward offtakes, consequently Google has not yet made compensation claims from these purchases. However, Google has clearly outlined that, if they do, they will either match these tonnes against SLCP emissions in their own footprint (i.e., using separate accounting for a compensation claim) or replace the superpollutant credits with longer-lived credits (i.e., CDR pairing).[44, 45, 46]

While the superpollutant buyer landscape is less concentrated than in the CDR market, a large proportion of retirements (33% in 2024) are still being made by the top 10 buyers. Some of these buyers have material volumes of superpollutants directly in their emissions inventory (e.g., Shell), while others have identified superpollutant credits as a readily available, reliable, low-cost alternative on the VCM.

40. Spock R. 2025 May 8. We're announcing two new partnerships to eliminate superpollutants and help the atmosphere. Google; [accessed 2025 Dec 8]. https://blog.google/outreach-initiatives/sustainability/google-eliminating-superpollutants-to-help-atmosphere/

41. Netflix, Inc. 2024. 2023 Environmental, Social & Governance Report. Netflix, Inc.; [accessed 2025 Nov 13]. https://s22.q4cdn.com/959853165/files/doc_downloads/2024/6/2023-Netflix-Environmental-Social-Governance-Report.pdf

42. Salesforce, Inc. 2025. FY25 Salesforce Carbon Credit Portfolio. Salesforce; [accessed 2025 Nov 14]. https://www.salesforce.com/en-us/wp-content/uploads/sites/4/documents/legal/compliance%20documents/salesforce-carbon-credit-portfolio.pdf

43. Workday, Inc. 2025. Lighting the Path Forward: 2025 Global Impact Report. Workday, Inc.; [accessed 2025 Nov 13]. https://www.workday.com/content/dam/web/en-us/documents/other/workday-global-impact-report.pdf?tlaAppCB

44. Spock R. 2025 May 8. We're announcing two new partnerships to eliminate superpollutants and help the atmosphere. Google; [accessed 2025 Dec 8]. https://blog.google/outreach-initiatives/sustainability/google-eliminating-superpollutants-to-help-atmosphere

45. Recoolit. 2023. Our Work. [accessed 2025 Dec 8]. https://www.recoolit.com/our-work

46. Cool Effect. 2024. About us. Cool Effect; [accessed 2025 Nov 12]. https://www.cooleffect.org/about-us

Conclusion

Urgent action on superpollutants offers a significant opportunity for corporate buyers to mitigate near-term warming. Many existing, high-quality superpollutant projects represent low-hanging fruit in the suite of climate mitigation solutions, delivering impact at relatively low cost through established, scalable interventions. However, superpollutant mitigation is not a substitute for long-term CO_2 drawdown, which remains essential. Companies and governments should increase action on both superpollutants and CO_2, not one or the other.

Pairing superpollutant mitigation and durable CDR ensures reduced climate warming is achieved consistently over time. It extends climate benefits beyond those achievable with superpollutant action alone. Action on superpollutants today provides an important short-term bridge in climate mitigation while CDR projects get up to scale and before CDR starts to provide cooling benefits. Together, superpollutant mitigation and CDR can ensure that reduced warming is achieved immediately and sustained over the coming decades, an essential approach for minimizing the negative impacts of climate change.

Corporate buyers should continue to support the high-quality superpollutant mitigation projects that are available today on the VCM. Highly motivated companies could transition from a GWP100 accounting approach to an annual warming matching approach. This would enable a more scientifically rigorous pathway to achieving sustained climate cooling, over the near term and the long term.

Early movers making paired purchases of superpollutant mitigation credits and high-quality CDR can motivate and engage other companies and policymakers. Corporate buyers have the opportunity to signal demand for rapidly scaling superpollutant mitigation technologies globally, delivering immediate benefits to the climate and communities worldwide.

Appendix A: Promising mitigation opportunities on the VCM

There is a broad range of superpollutant project categories on the VCM but certain project types dominate. The three largest categories in 2025 by issuances were: HFC replacement in foam production (~18%), landfill methane (~17%), and leak detection and repair in gas systems (~12%) (**figure A1**). This presents clear opportunities for corporates to engage with tried and tested solutions currently available on the market and scale them further. Promising opportunities, such as SF_6 replacement in electrical switchgear and CF_4 destruction in semiconductor fabrication, are expected to become more relevant as they are tied to the rapid growth in electricity demand for data centers and semiconductor production, driven by artificial intelligence research and deployment.

The improved ability to monitor methane emissions at high temporal and spatial resolution through remote sensing may also enable credible MMRV for other forms of interventions (e.g., alternative wetting and drying [AWD] for rice production) and unlock potential scaling. Registries are responding quickly to the need to improve and build on methodologies to better support current project categories (**box 3**). However, the market still lacks clear and transparent quality criteria for superpollutant mitigation projects that address their unique challenges, which is needed in order to drive forward both the development of these projects and buyer confidence at scale.

Rice paddies in Kumano, Japan. Source: Sean Pavone Photo, Adobe Stock.

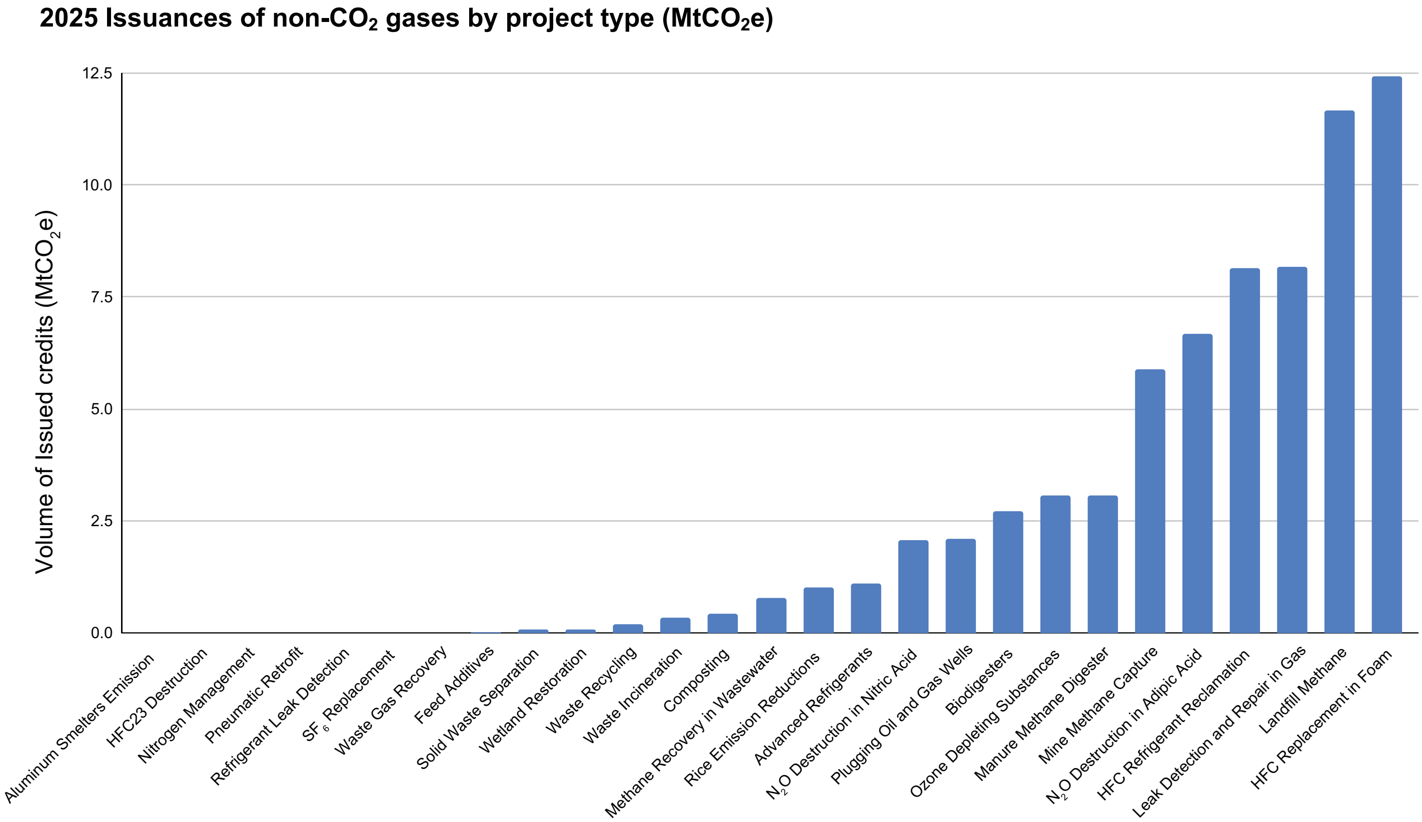

Figure A1: Issuances of superpollutant credits by project type in 2025. Some of these project types mitigate both non-CO_2 and CO_2 emissions. Data on the gases being claimed is not currently available on registries. Consequently, an assumption is made to include project categories that are considered to have material non-CO_2 emissions credits. Note: HFC = hydrofluorocarbon, $MtCO_2e$ = million tonnes of carbon dioxide equivalent, N_2O = nitrous oxide, SF_6 = sulphur hexafluoride. Source: Carbon Direct, based on data extracted from five major registries: Carbon Action Reserve, American Carbon Registry, Gold Standard, Verra, and ART-TREES.

Box 3. Existing methodology considerations and challenges

While superpollutant credits have been available on the voluntary carbon market (VCM) for decades, the increased attention they have recently received highlights existing challenges and inconsistencies with methodologies. Registries are quickly responding to these gaps. For example, Isometric announced in October of 2025 that two new methodologies are currently under development for landfill methane and hydrofluorocarbon (HFC) projects.[47] In the meantime, corporations should be cognizant of existing methodology limitations when selecting projects. Key challenges are seen across two particular areas: project additionality and the feasibility of measurement, monitoring, reporting and verification (MMRV) requirements.

Additionality: Currently, most methodologies define superpollutant projects as additional if the activity would not have occurred without the existence of the voluntary credit mechanism (i.e., there is no regulatory requirement for the activity, it is not common practice, and there is not sufficient financial incentive for the activity to occur without additional funding from VCM revenue). One of the real-world challenges with this definition is that, while regulatory mandates for emissions controls may exist, they may not be adequately enforced. This can lead to an underestimation of a project's regulatory additionality. This can happen for a range of reasons, such as a lack of clarity on ownership of the infrastructure that is producing the emissions. This is particularly true for methane abatement projects involving abandoned wells. While a government body may provide financing to plug abandoned wells, there is evidence that these projects are not receiving sufficient funding and are reliant on VCM revenues to operate.[48] While progress is being made for certain methodologies, significant gaps still exist. Currently, a broad range of factors determines a project's additionality. Some methodologies use simple "positive technology" lists to determine additionality, while others include legal and financial requirement tests. With emerging and proposed regulations and government-driven initiatives that may lack regulatory mandate or sufficient funding for enforcement, methodologies must outline the bounds of regulatory additionality in more detail, to ensure that projects go above and beyond what is required by regulation. Credit buyers should ensure that thorough due diligence is conducted to stress-test projects for additionality, including both underestimation of regulatory additionality and overestimation of financial additionality.

MMRV: Certain categories of superpollutant projects face MMRV challenges; for example, complexities arise when attempting to track methane leakage emissions from natural gas transportation or when assessing superpollutant emissions from refrigerant leakage. Leakage emissions tracking is typically based on assumptions about leakage rates, leading to uncertainty. However, recent developments and investment in satellite monitoring of superpollutant emissions have improved our ability to measure methane and other emissions.[49, 50]

47. Jubbawy E. 2025 Oct 20. Isometric expands into superpollutants. isometric.com; [accessed 2025 Dec 8]. https://isometric.com/writing-articles/isometric-expands-into-superpollutants

48. Dogniaux M, et al. 2025. Global satellite survey reveals uncertainty in landfill methane emissions. Nature. 647(8089):397–402. https://doi.org/10.1038/s41586-025-09683-8

49. Global Methane Tracker 2023: The case for methane policy and regulation. International Energy Agency; [accessed 2025 Dec 8]. https://www.iea.org/reports/global-methane-tracker-2023/the-case-for-methane-policy-and-regulation

50. Dogniaux M et al. 2025. Global satellite survey reveals uncertainty in landfill methane emissions. Nature. 647(8089):397–402. https://doi.org/10.1038/s41586-025-09683-8

HFC replacement in foam production

As HFCs are entirely human-made, there is significant potential to reduce their use and production that is directly in our control; this mitigates the emissions generated from their end-of-life fate or through accidental leakage into the atmosphere.[51]

HFCs are commonly used in foam production for insulation. One approach is to replace HFCs in foam blowing agents with alternatives that have a lower GWP, such as pentane and polyurethane.[52, 53] However, given the salience of reducing these emissions and the ease of controlling whether the product is created, there have been recent regulatory developments phasing out the use of HFCs. This has caused some registries, such as the American Carbon Registry (ACR), to inactivate their foam replacement methodologies due to concerns about regulatory additionality.[54] Reclaiming blowing agents from end-of-life appliances or other installed banks is addressed under certain methodologies.[55]

Landfill methane

Landfill methane contributes to about 10% of total anthropogenic methane emissions (**figure A2**). Consequently, there is a large scope for reducing methane emissions associated with organic waste decomposition in landfills.[56, 57] To mitigate this methane release, projects install vertical wells that are spaced 100–200 feet apart and extend down through waste mass, extracting methane for flaring or energy generation. Other strategies include bioremediation or covering, which is particularly useful in open dump sites,[58] although methodologies for these approaches are largely absent from the VCM.[59]

51. Climate & Clean Air Coalition. n.d. Hydrofluorocarbons (HFCs). [accessed 2025 Dec 8]. https://www.ccacoalition.org/short-lived-climate-pollutants/hydrofluorocarbons-hfcs

52. American Carbon Registry. 2023. Foam blowing agents primer. American Carbon Registry; [accessed 2025 Nov 12]. https://acrcarbon.org/wp-content/uploads/2023/03/Foam-Blowing-Agents-Primer.pdf

53. United Nations Framework Convention on Climate Change. 2010. Avoidance of HFC emissions in rigid Poly Urethane Foam (PUF) manufacturing. Bonn (Germany): United Nations Framework Convention on Climate Change; [accessed 2025 Nov 12]. https://cdm.unfccc.int/UserManagement/FileStorage/BN2QD6HAJ901E4XSCG8IR53FPWVLUZ

54. American Carbon Registry. 2022. INACTIVE: Transition to Advanced Formulation Blowing Agents in Foam Manufacturing and Use. [accessed 2025 Dec 8]. https://acrcarbon.org/methodology/transition-to-advanced-formulation-blowing-agents-in-foam-manufacturing-and-use/

55. Yale Carbon Containment Lab. 2023. Primer on Carbon Credits from Fluorocarbon Emissions Reductions [accessed 2025 Dec 5] https://carboncontainmentlab.org/documents/fluorocarbon-methodologies-primer.pdf

56. This is based on Carbon Direct analysis using country-level data from ClimateTRACE for solid waste.

57. Garland E, Alves O, Frankiewicz T, Ayandele E. 2023. Mitigating Landfill Methane: Key Strategies and Policy Levers to Drive Emissions Reductions. RMI; [accessed 2025 Nov 12]. https://rmi.org/wp-content/uploads/dlm_uploads/2023/06/landfill_monitoring_memo_series.pdf

58. Ayandele E, Jungclaus M, Huffman K. 2022 Sep 7. Top Strategies to Cut Dangerous Methane Emissions from Landfills. RMI; [accessed 2025 Dec 8]. https://rmi.org/top-strategies-to-cut-dangerous-methane-emissions-from-landfills/

59. Verra. 2025. Methodology For Increasing Methanotrophic Methane Oxidation of Anthropogenic Methane. [accessed 2025 Dec 8]. https://verra.org/methodologies/methodology-for-increasing-methanotrophic-methane-oxidation-of-anthropogenic-methane/

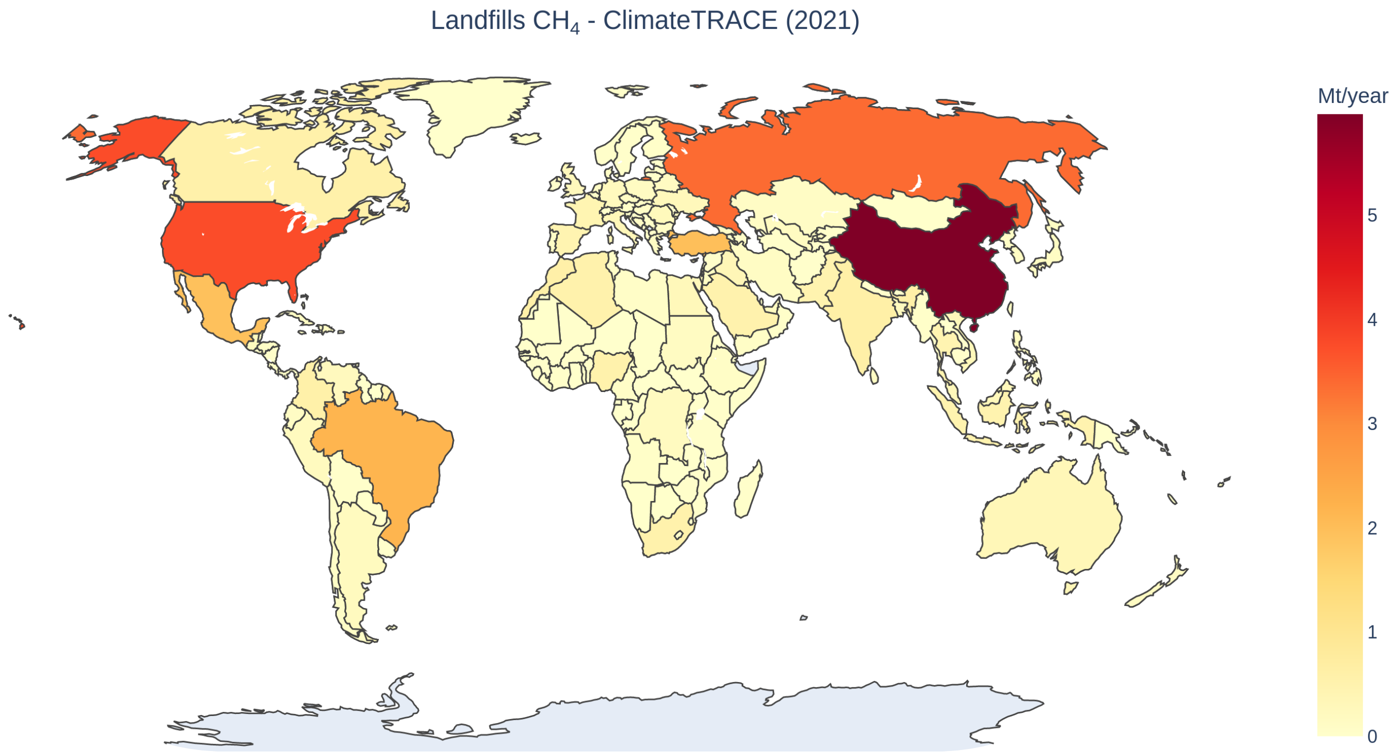

Figure A2: Landfill methane emissions by country. Note: Mt CH_4/year = million metric tonnes of methane per year. Source: ClimateTRACE country level data.[60]

As well as being the dominant project category for methane credits issued and retired on the VCM, there have been recent promising updates in the methodologies developed for landfill methane projects. This includes approval of landfill methane methodologies from the Integrity Council for the Voluntary Carbon Market (ICVCM) under their Core Carbon Principles (CCP) certification in June 2024, and the United Nation's approval of landfill methane as the first Article 6.4 methodology in November 2025.[61] Receiving CCP certification gives reassurance to buyers that these credits are determined to meet a quality standard, as set by the ICVCM.[62] Further, the approval of a landfill methane methodology under Article 6.4 means countries can now use landfill methane credits issued under this methodology to help other countries meet their climate targets as part of the Paris Agreement. For suppliers of these credits, this is a clear signal of future demand that is aligned across regulatory and voluntary sectors. It represents a large step toward standardizing methodology requirements for these credits, which enables greater buyer confidence.

Leak detection and repair in gas systems

HFCs and other high-GWP refrigerants escape through leaks in cooling and refrigeration systems during operation and maintenance. Leak detection and reduction projects implement enhanced monitoring systems, improved maintenance

60. ClimateTRACE. 2025. Comprehensive Emissions Insight. [accessed 2025 Nov 15]. https://climatetrace.org/

61. United Nations Framework Convention on Climate Change. 2025 Oct 30. UN Body agrees first methodology under Paris Agreement carbon market | UNFCCC. [accessed 2025 Dec 8]. https://unfccc.int/news/un-body-agrees-first-methodology-under-paris-agreement-carbon-market

62. Integrity Council for the Voluntary Carbon Market. 2025. The Core Carbon Principles. [accessed 2025 Dec 8]. https://icvcm.org/core-carbon-principles/

protocols, and advanced leak detection technologies to minimize fugitive emissions from existing equipment. These projects are attractive for their applicability across large installed equipment, relatively low implementation costs, and ability to deliver immediate emission reductions without a system overhaul. Current challenges include accurately quantifying baseline leak rates, ensuring long-term maintenance commitment, and demonstrating financial additionality when leak reduction aligns with cost-saving operational improvements or regulatory additionality in the face of emerging regulatory requirements. Limited methodologies are available, with Verra VM0001 as the primary methodology.[63]

Future promising mitigation opportunities

Although they are not currently dominant project categories on the VCM, there is promising potential for reducing methane emissions from rice farming with AWD projects and from livestock through enteric methane feed additives. Both of these project types have significant potential for scale, as they aim to reduce emissions from large-scale food production.

In addition, there are other promising project categories in rapidly growing industries that could offer opportunities to mitigate superpollutants.

Alternate wetting and drying

AWD projects periodically drain rice paddies to reduce the anaerobic conditions that generate methane, on average halving methane emissions and saving water consumption (by about 30%).[64] AWD projects are promising because about half of the world's population relies on rice as a primary food, and methane emissions from rice farming represent about 6–10% of total anthropogenic methane emissions today (**figure A3**); rice farming also consumes 28% of the world's freshwater resources.[65, 66, 67] Even modest AWD adoption delivers large, low-cost methane abatement with additional environmental benefits, such as reduced water consumption. To date, key challenges have been the verification of practices and quantification of emission reductions. Additionally, AWD can lead to an increase of N_2O emissions, which needs to be accounted for while estimating methane reduction credits. Future use of advanced satellite monitoring could support remote and more accurate MMRV.

63. Verra. 2024. VM0001: Refrigerant leak detection, version 1.2. [accessed 2025 Dec 8]. https://verra.org/methodologies/vm0001-refrigerant-leak-detection-v1-2/

64. Climate & Clean Air Coalition. 2016. Alternate Wetting and Drying Infographic. [accessed 2025 Dec 8]. https://www.ccacoalition.org/resources/alternate-wetting-and-drying-infographic

65. The 6% number is based on Carbon Direct analysis of ClimateTRACE data.

66. Food and Agriculture Organization of the United Nations. 2023. FAOSTAT: Crops and livestock products. [accessed 2025 Dec 8]. https://www.fao.org/faostat/en/#data/QCL

67. Climate & Clean Air Coalition. n.d. Asia - Accelerating methane reductions in rice production systems through market-based mechanisms (AMR) [AGR-22-002] [accessed 2025 Dec 8]. https://www.ccacoalition.org/projects/asia-accelerating-methane-reductions-rice-production-systems-through-market-based-mechanisms-amr-agr-22-002

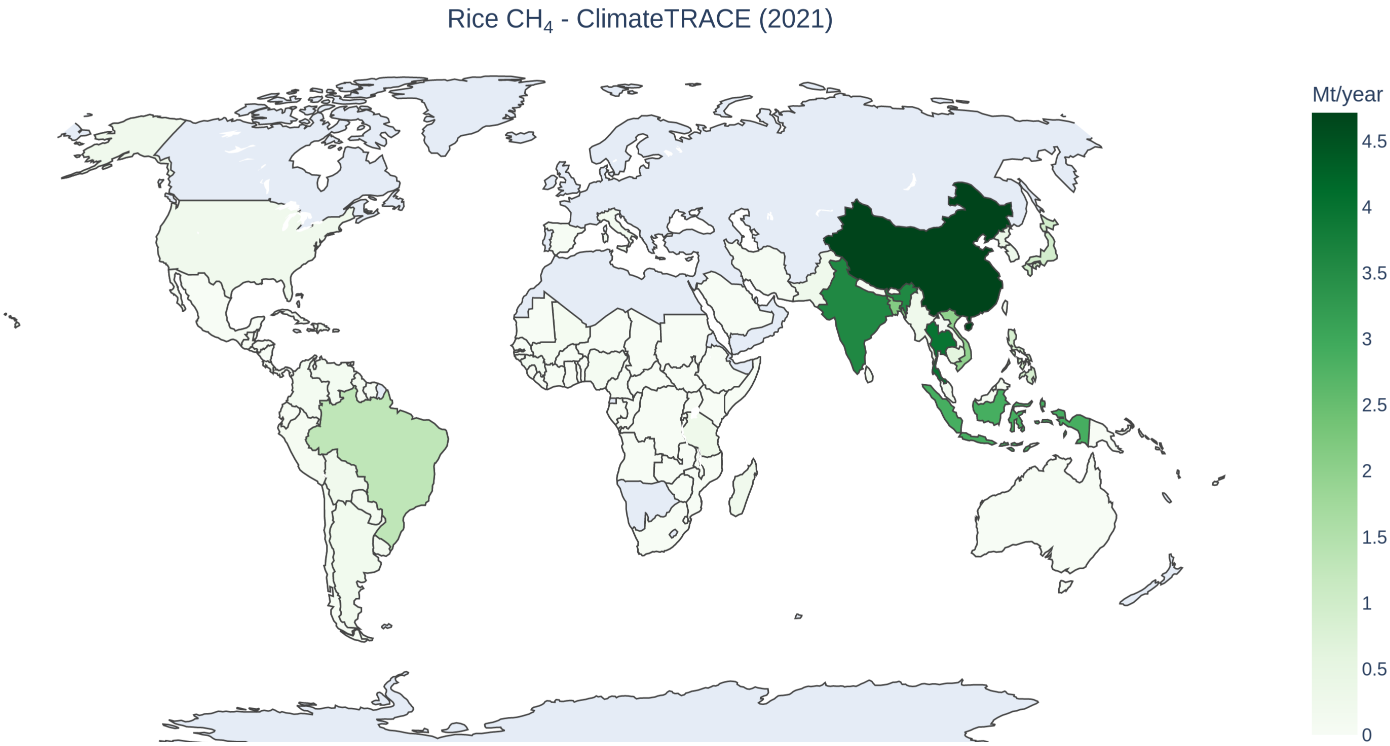

Figure A3: Rice cultivation methane emissions by country. Note: Mt CH_4/year = million metric tonnes of methane per year. Source: Carbon Direct, based on ClimateTRACE country-level data.[68]

Enteric methane feed additives

Emissions from enteric methane and manure make up about 30% of total anthropogenic methane emissions.[69] Feed additives (e.g., 3-NOP, red seaweed, probiotics, etc.)[70] inhibit methanogenesis in cattle rumen, delivering immediate methane emission reductions.[71, 72] This is attractive for its high abatement potential in cattle-heavy regions and its ability to integrate into existing feeding systems. Current challenges include ensuring consistency in funding to maintain continuous adoption, which is essential for sustained impact; variable efficacy across diets and production systems (e.g., feedlot versus pasture systems); quantification of reduction credits; and the likelihood that longer-term genetic or vaccine options, if proven effective, could offer lower-cost, more durable reductions. While longer-term options wait to be proven, action cannot be delayed as enteric fermentation and manure present the largest source of anthropogenic methane emissions (**figure B1**).

Other categories

Other categories of superpollutant mitigation not currently dominant in the VCM are promising due to their connection to growing industries, such as

68. ClimateTRACE. 2025. Comprehensive Emissions Insight. [accessed 2025 Nov 15]. https://climatetrace.org/

69. Percentage is based on Carbon Direct analysis using country-level data extracted from ClimateTRACE.

70. dsm-firmenich. 2025. Methane Inhibitors - Bovaer®. [accessed 2025 Dec 8]. https://www.dsm-firmenich.com/anh/products-and-services/products/methane-inhibitors/bovaer.html

71. Hristov AN. 2024. Invited review: Advances in nutrition and feed additives to mitigate enteric methane emissions. J Dairy Sci. 107(7):4129-4146. https://doi.org/10.3168/jds.2023-24440

72. Agriculture and Horticulture Development Board. 2025. Methane-reducing feed additives. [accessed 2025 Dec 8]. https://ahdb.org.uk/knowledge-library/methane-reducing-feed-additives

SF_6-free electrical switchgear and CF_4 destruction, or use of alternatives, in semiconductor fabrication. These solutions are particularly promising given the rapid increase in electricity demand for data centers and semiconductor production resulting from the expansion of artificial intelligence research and deployment.

SF_6-FREE ELECTRICAL SWITCHGEAR

SF_6 is commonly used as an insulating or circuit-breaking medium in electrical switchgear.[73] This superpollutant can escape to the atmosphere during maintenance and end-of-life disposal.[74] Mitigation projects look to replace SF_6 with alternative insulating gases or solid alternatives. With significant grid buildout and electrification ahead, SF_6-free designs are a timely, scalable lever that can lock in decades of avoided emissions. The main hurdle to overcome is the additional investment cost for new alternatives.[75]

CF_4 DESTRUCTION OR ALTERNATIVES IN SEMICONDUCTOR FABRICATION

CF_4 is commonly used in the plasma-based etching and cleaning process for semiconductor manufacturing.[76] One existing form of mitigation includes CF_4 destruction using a catalytic oxidation unit.[77] It is promising because semiconductor facilities are very controlled, monitored environments, enabling targeted interventions with readily measured impacts.

73. Burges K, Warncke K, Gschrey B. 2020. Briefing paper: SF6 and alternatives in electrical switchgear and related equipment. European Commission; [accessed 2025 Nov 12]. https://climate.ec.europa.eu/system/files/2020-04/2020_03_25_sf6_and_alternatives_en.pdf

74. Innovation for Cool Earth Forum. 2025. ICEF 2025 Roadmap: Sustainable Data Centers. [accessed 2025 Nov 13]. https://www.icef.go.jp/wp-content/themes/icef_new/pdf/roadmap/icef2025_roadmap.pdf

75. Burges K, Warncke K, Gschrey B. 2020. Briefing paper: SF6 and alternatives in electrical switchgear and related equipment. European Commission; [accessed 2025 Nov 12]. https://climate.ec.europa.eu/system/files/2020-04/2020_03_25_sf6_and_alternatives_en.pdf

76. Raoux S. 2023. Fluorinated greenhouse gas and net-zero emissions from the electronics industry: the proof is in the pudding. Carbon Management. 14(1): 2179941. [accessed 2025 Nov 13]. https://doi.org/10.1080/17583004.2023.2179941

77. International Carbon Registry. 2025. AM-0096 methodology. Carbonregistry.com; [accessed 2025 Dec 8]. https://www.carbonregistry.com/methodologies/am-0096?utm

Appendix B: Magnitude of the opportunity

Anthropogenic methane

The total annual methane emissions across all anthropogenic categories amount to about 366 Mt, according to Global Carbon Project's 2020 Global Methane Budget.[78] ClimateTRACE reports a slightly lower total of about 353 Mt for 2021, when measurements are aggregated to the country-level by sector, rather than aggregated by site.[79] Total methane emissions, including both anthropogenic and natural sources, amount to around 689 Mt/year.[80, 81] However, the opportunity for abatement is not evenly distributed. In terms of economic status (Global North and Global South), there is a mismatch between where many current and would-be credit buyers operate and where the greatest opportunity for effective intervention lies. A disproportionate share of both anthropogenic and natural methane emissions sources are located in the Global South, while corporate buyers of methane destruction credits are likely to be largely located in the Global North (**figure B1**).[82]

While subsectors like oil and gas show consistent results between Global Methane Budget and ClimateTRACE data, others diverge, making overall assessment more complicated. For example, ClimateTRACE reports 25 Mt more coal mine methane emissions than the Global Methane Budget does. This reflects uncertainty and the need for improved data on sources of methane emissions. However, this general bifurcation between Global North and Global South means that many buyers should consider non-local projects to maximize effective climate action.

Anthropogenic N_2O emissions

Anthropogenic N_2O emissions, which are dominated by direct N_2O emissions from agriculture in the Global South, account for about 9.3 Mt/year of total global N_2O emissions (**figure B2**).

78. Global Carbon Project. 2024. Global Methane Budget 2000–2020. [accessed 2025 Dec 8]. https://doi.org/10.5194/essd-2024-115

79. ClimateTRACE. 2025. Comprehensive Emissions Insight. [accessed 2025 Nov 15]. https://climatetrace.org/

80. Global Carbon Project. 2024. Global Methane Budget 2000–2020. [accessed 2025 Dec 8]. https://doi.org/10.5194/essd-2024-115

81. Most interventions to reduce methane emissions are focused on anthropogenic sources, such as landfills or oil and gas production. However, some interventions, like wetland restoration, target natural sources of methane emissions that have been released due to disturbance.

82. This uneven distribution of total emissions is based on data from the 2020 Global Methane Budget.

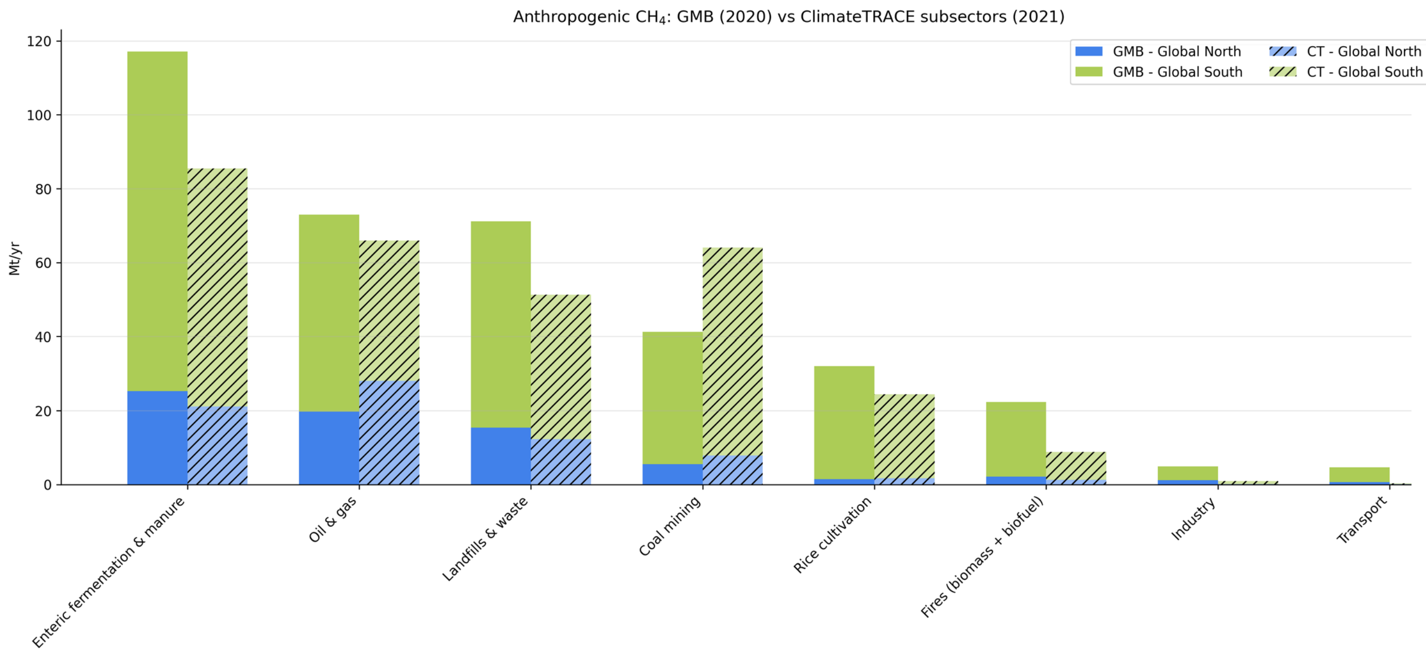

Figure B1: Anthropogenic methane (CH_4) emissions by sector. The Global North includes: USA, Canada, Europe, South Korea, Japan. The Global South includes: Central America, South America, Africa, the Middle East, China, Asia, and Russia. Note: CT = ClimateTRACE, GMB = Global Methane Budget, Mt = million metric tonnes. The Global North and South definitions use slightly different regional categories as presented in the Global Methane Budget dataset. Source: Carbon Direct, with site-level data sourced from Global Methane Budget and ClimateTRACE.[83, 84]

83. Global Carbon Project. 2024. Global Methane Budget 2000–2020. [accessed 2025 Dec 8]. https://doi.org/10.5194/essd-2024-115

84. ClimateTRACE. 2025. Comprehensive Emissions Insight. [accessed 2025 Nov 15]. https://climatetrace.org/

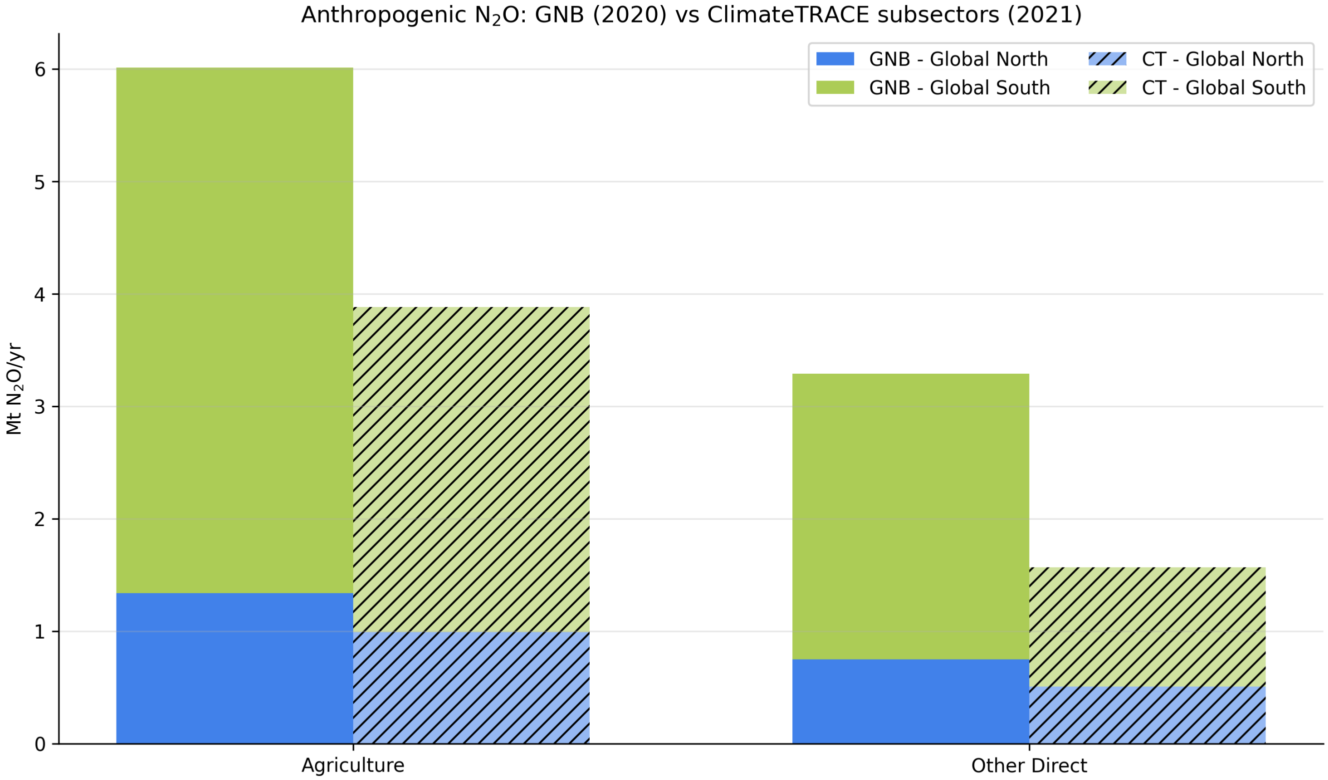

Figure B2: Anthropogenic nitrous oxide (N_2O) emissions. Note: CT = ClimateTRACE, GNB = Global N_2O Budget, Mt = million metric tonnes. Source: Carbon Direct, based on data sourced from 2020 Global N_2O Regional Budget and ClimateTRACE.[85, 86]

85. Global Carbon Project. 2024. Global N2O Budget. [accessed 2025 Dec 5]. https://www.globalcarbonproject.org/nitrousoxidebudget/

86. ClimateTRACE. 2025. Comprehensive Emissions Insight. [accessed 2025 Nov 15]. https://climatetrace.org/

Appendix C: Quantitative climate modeling assumptions

The Earth's climate is being changed by human emissions of GHGs. Quantitatively modeling these changes, and forecasting how key indicators such as global surface air temperature will continue to change in the future, is important for guiding climate policy and voluntary corporate climate strategies.[87] This involves linking four separate factors: the rate of future GHG emissions (in tonnes per year), how this affects GHG concentrations in the atmosphere (in parts per million or billion, taking into account the different lifetimes of different GHGs), how these concentrations affect radiative forcing (the rate at which GHGs trap additional heat in the Earth system), and how this heat leads to climate impacts (including temperature change, sea level rise, and storm severity). This linkage is complex, because of feedbacks and non-linear interactions in the Earth's climate system (**figure C1**).

Detailed modeling of these climate interactions relies on fundamental physics-driven global climate models and Earth systems models, which are very computationally intensive.[88] However, time and computational resource constraints limit the usefulness of global climate models and Earth systems models for broad scenario comparison, sensitivity testing, and large ensemble analyses. Instead, researchers often use reduced-complexity climate models, which abstract climate system relationships without modeling the fundamental physical phenomenon. These reduced-complexity climate models are parameterized to simulate the behavior of high-complexity models and can generate transparent, decision-relevant projections quickly across many emissions pathways and uncertainty cases, making iterative assessment feasible. To enable inter-comparison across various climate models, researchers have established standard scenarios for future emissions known as the Shared Socioeconomic Pathways (SSPs).[89] Using these SSPs, climate scientists and policymakers can assess the likely climate impacts from changes to GHG emissions relative to a baseline, helping quantify the climate outcomes that are likely to result from incremental GHG reductions and removals. However, different climate models arrive at slightly different conclusions about these outcomes even when using the same future emissions scenarios, which means that all future climate impact projections should be understood to have a range of uncertainty.

87. European Commission. 2024. Climate Indicators: Temperature. Copernicus; [accessed 2026 Feb 6]. https://climate.copernicus.eu/climate-indicators/temperature

88. United States Department of Energy. n.d. DOE Explains...Earth System and Climate Models. [accessed 2026 Feb 6]. https://www.energy.gov/science/doe-explainsearth-system-and-climate-models

89. International Institute for Applied Systems Analysis. 2026. Shared Socioeconomic Pathways Scenario Database. [accessed Jan 7 2026]. https://iiasa.ac.at/models-tools-data/ssp

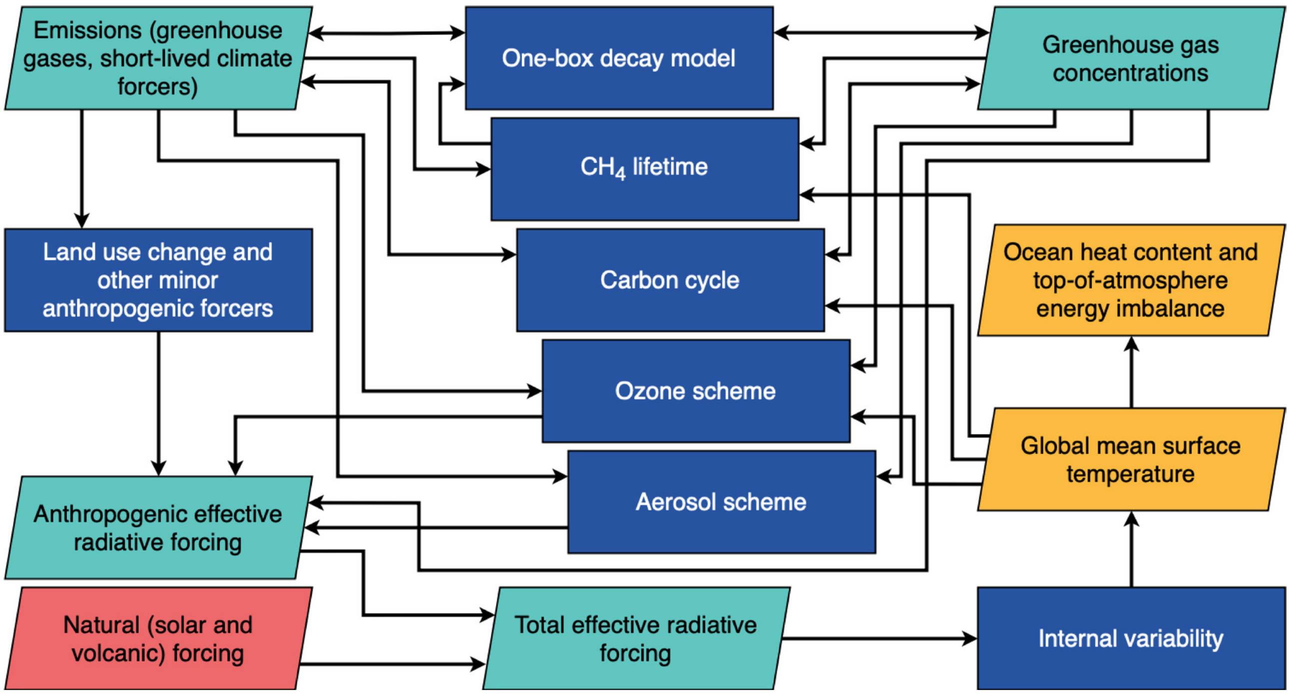

Figure C1. Simplified depiction of the climate processes modeled in the Finite Amplitude Impulse Response (FaIR) climate emulator, including GHG emissions, changes in atmospheric concentration, resulting radiative forcing, and further resulting climate indicators like global mean surface temperature. Source: FaIR documentation.[90]

We used the FaIR reduced-complexity climate model, which can emulate the results from a range of more advanced climate models, in order to explore the future climate impacts of different GHG emissions scenarios. We chose FaIR because of its low computational cost (simulations run in seconds) while maintaining relatively close alignment with the results of global climate models, e.g. CMIP6.[91, 92]

The projected changes in mean surface temperature anomaly were modeled using a methane lifetime routine that is based on coefficients from Thornhill et al. (2021),[93] and the equilibrium climate sensitivity[94] is derived from the 4xCO_2 response in each of the CMIP6 climate models as ensemble configurations. Emissions were taken from the Reduced Complexity Model Intercomparison Project (RCMIP) datasets.[95, 96]

90. FaIR Development Team. 2024. Introduction — fair 2.2.3+7.gec46fef documentation. [accessed 2026 Feb 6]. https://docs.fairmodel.net/en/latest/intro.html

91. We used FaIR version 2.2.3, and used parameter selections from the "SSP emissions runs using CMIP6 calibrations" example except where otherwise noted.

92. FaIR Development Team. 2024. SSP emissions runs using CMIP6 calibrations. [accessed 2026 Feb 6]. https://docs.fairmodel.net/en/latest/examples/cmip6_ssp_emissions_run.html

93. Thornhill GD et al. 2021. Effective radiative forcing from emissions of reactive gases and aerosols – a multi-model comparison. Atmospheric Chemistry and Physics. 21(2):853–874. [accessed 2026 Feb 6]. https://acp.copernicus.org/articles/21/853/2021/. https://doi.org/10.5194/acp-21-853-2021

94. Hausfather Z. 2018 Jun 19. Explainer: How scientists estimate climate sensitivity. Carbon Brief; [accessed 2026 Feb 6]. https://www.carbonbrief.org/explainer-how-scientists-estimate-climate-sensitivity/

95. Reduced Complexity Model Intercomparison Project. 2025. RCMIP's current status (November 2025). [accessed 2026 Feb 6]. https://www.rcmip.org/

96. The RCMIP framework utilizes a standard subset of SSP Scenarios and associated climate variables, identical to the scenarios used in the high-complexity CMIP6 model runs. These scenarios are used to ensure harmonization between the reduced-complexity climate models and global climate models.

Model configurations were taken from the three-layer model in Cummins et al. (2020).[97]

Reducing anthropogenic superpollutant emissions slows global average surface temperature rise because it reduces radiative forcing.[98] However, the size and duration of the effect varies by superpollutant. To illustrate this, we modeled an aggressive campaign to ramp down anthropogenic methane emissions by 50% (approximately 200 Mt/year) over the next two decades. This would yield approximately 0.1°C less warming by 2050, and 0.25°C less warming by 2080 (**figure C2**). However, if that ramp-down were reversed following the 20-year campaign, temperatures would return to near the projected levels by 2100 (**figure C3**).[99]

To extend the analysis to N_2O, we performed similar modeling for two different scenarios in which methane emissions are unchanged, but N_2O emissions are ramped down to half over a twenty-year period. In the first, the emissions reductions are sustained following the ramp-down period (**figure C4**), and in the second, the emissions reductions rebound to their original values (**figure C5**).

Because N_2O contributes a substantially smaller amount of warming than either CO_2 or methane, the impacts on temperature are far less pronounced, although they are sustained for a longer period of time given N_2O's longer atmospheric lifetime. The first N_2O scenario, with ramp-down sustained (**figure C4**), most likely results in a reduced temperature rise of 0.015°C in 2055 and 0.06°C in 2100, and the second N_2O scenario, with ramp-down rebounded (**figure C5**), most likely results in a reduced temperature rise of approximately 0.02°C between 2060 and 2100.

Finally, to further extend the analysis to F-gases, we performed similar modeling using a scenario in which methane and N_2O are unchanged, but all relevant F-gases are ramped down to half over a 20-year period, and sustained at those levels (**figure C6**).[100] As with N_2O, the impacts are less pronounced than with methane, although they are sustained for a longer period of time. The scenario most likely results in a reduced temperature rise of 0.01°C in 2050 and almost 0.04°C in 2100.

97. Cummins DP, Stephenson DB, Stott PA. 2020. A new energy-balance approach to linear filtering for estimating effective radiative forcing from temperature time series. Advances in Statistical Climatology, Meteorology and Oceanography. 6(2):91–102. [accessed 2026 Feb 11]. https://doi.org/10.5194/ascmo-6-91-2020

98. Radiative Forcing - an overview | ScienceDirect Topics. [accessed 2025 Dec 8]. https://www.sciencedirect.com/topics/earth-and-planetary-sciences/radiative-forcing

99. Notably, these modeling projections are based on "middle of the road" future CO_2 emissions scenarios (and baseline superpollutant emissions scenarios), as represented in the World Climate Research Programme's SSP2-4.5 scenario. The SSP2-4.5 scenario assumes that current emissions levels continue until 2050 and then decrease, but do not reach net zero by the end of the century. The impacts may be different under alternative future CO_2 emissions scenarios. Also, because many parameters of the Earth's climate response to increased GHGs in the atmosphere remain uncertain, there is significant and unavoidable uncertainty in temperature forecasts, as represented by shaded error bars in figures C2-C6. It is therefore critical to treat these temperature forecasts as ranges, rather than definitive or precise predictions of climate outcomes.

100. The individual F-gas species whose emissions are modified in this scenario are: carbon tetrafluoride (CF_4), hexafluoroethane (C_2F_6), octafluoropropane (C_3F_8), octafluorocyclobutane (c-C_4F_8), perfluorobutane (C_4F_{10}), perfluoropentane (C_5F_{12}), perfluorohexane (C_6F_{14}), perfluoroheptane (C_7F_{16}), perfluorooctane (C_8F_{18}), nitrogen trifluoride (NF_3), sulfur hexafluoride (SF_6), pentafluoroethane (HFC-125), 1,1,1,2-tetrafluoroethane (HFC-134a), 1,1,1-trifluoroethane (HFC-143a), 1,1-difluoroethane (HFC-152a), 1,1,1,2,3,3,3-heptafluoropropane (HFC-227ea), trifluoromethane (HFC-23), 1,1,1,3,3,3-Hexafluoropropane (HFC-236fa), 1,1,1,3,3-pentafluoropropane (HFC-245fa), difluoromethane (HFC-32), 1,1,1,3,3-pentafluorobutane (HFC-365mfc), and 1,1,1,2,2,3,4,5,5,5-decafluoropentane (HFC-4310mee).

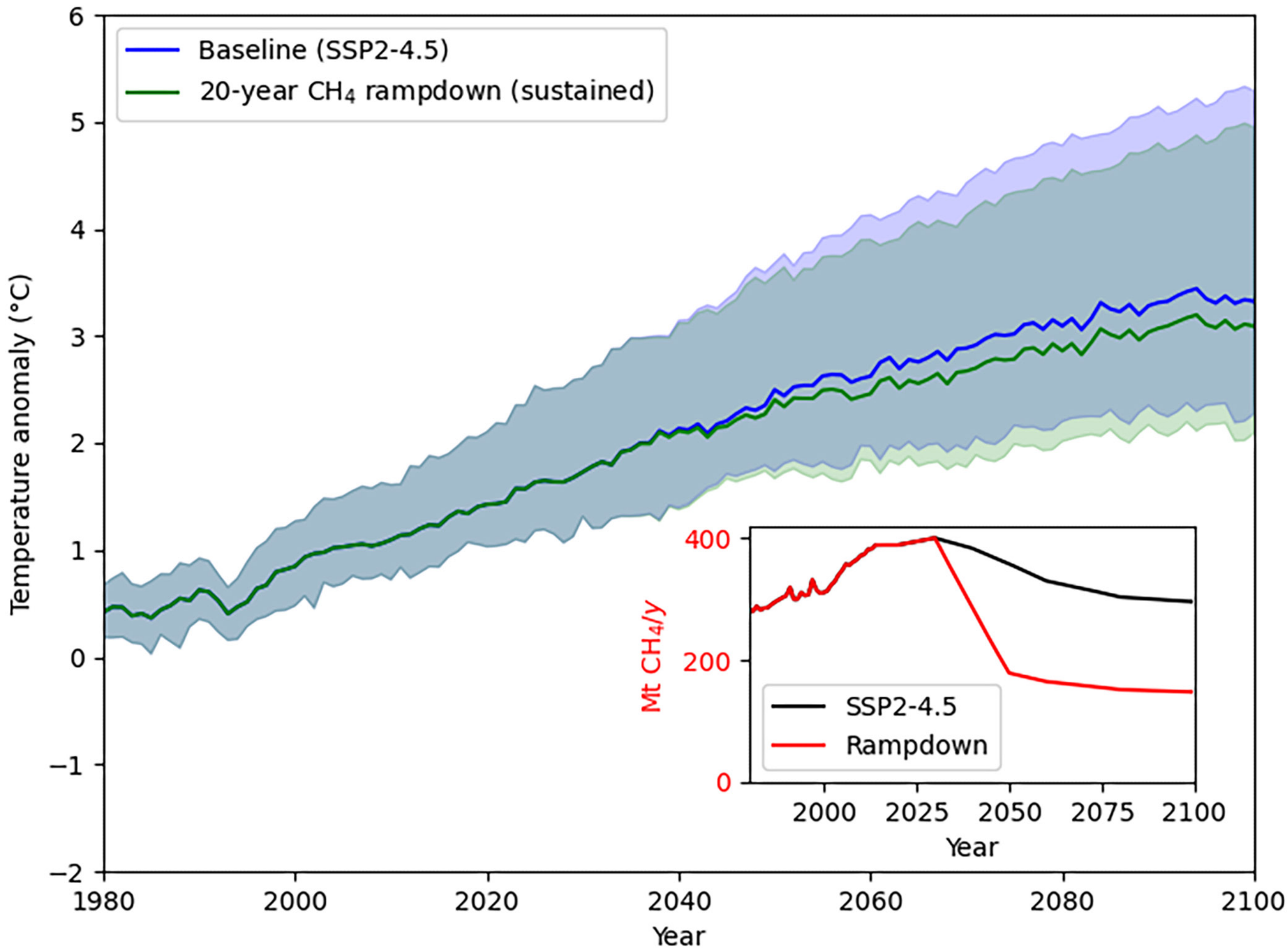

Figure C2: Average global surface temperature impact from reducing anthropogenic methane (CH_4) emissions by 50% over 2030–2050, and sustaining the reductions, with temperature shown in degrees Celsius (°C). These scenarios are modeled in the Finite Amplitude Impulse Response (FaIR) simple climate model,[101] based on SSP2-4.5, with a range of climate sensitivity parameters. The central values are the median (50th percentile) and the shaded areas represent 5th/95th percentile ranges across an ensemble of model configurations. Notes: CO_2 = carbon dioxide, Gt CO_2/y = gigatonnes of carbon dioxide per year, Mt CH_4/y = million tonnes of methane per year. Source: Carbon Direct.

101. FaIR Development Team. 2024. FaIR: Finite Amplitude Impulse Response simple climate model — fair 2.2.3 documentation. [accessed 2025 Dec 8]. https://docs.fairmodel.net/en/stable/index.html

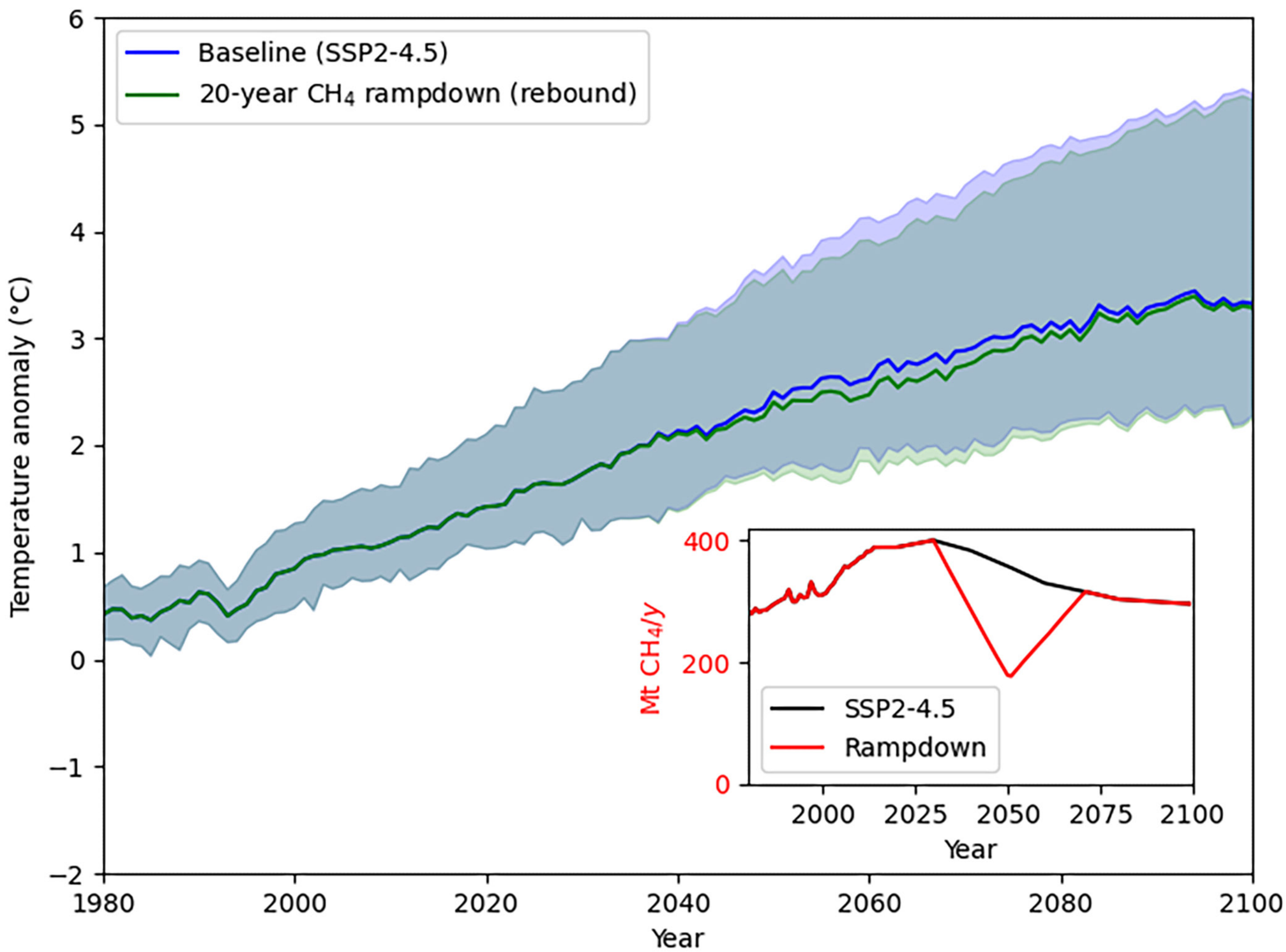

Figure C3: Average global surface temperature impact from reducing anthropogenic methane (CH_4) emissions by 50% over 2030–2050, and then allowing the emissions to return, rebounding temperatures by the end of the century, with temperature shown in degrees Celsius (°C). These scenarios are modeled in the Finite Amplitude Impulse Response (FaIR) simple climate model,[102] based on SSP2-4.5, with a range of climate sensitivity parameters. The central values are the median (50th percentile) and the shaded areas represent 5th/95th percentile ranges across an ensemble of model configurations. Notes: CO_2 = carbon dioxide, Gt CO_2/y = gigatonnes of carbon dioxide per year, Mt CH_4/y = million tonnes of methane per year. Source: Carbon Direct.

102. FaIR Development Team. 2024. FaIR: Finite Amplitude Impulse Response simple climate model — fair 2.2.3 documentation. [accessed 2025 Dec 8]. https://docs.fairmodel.net/en/stable/index.html

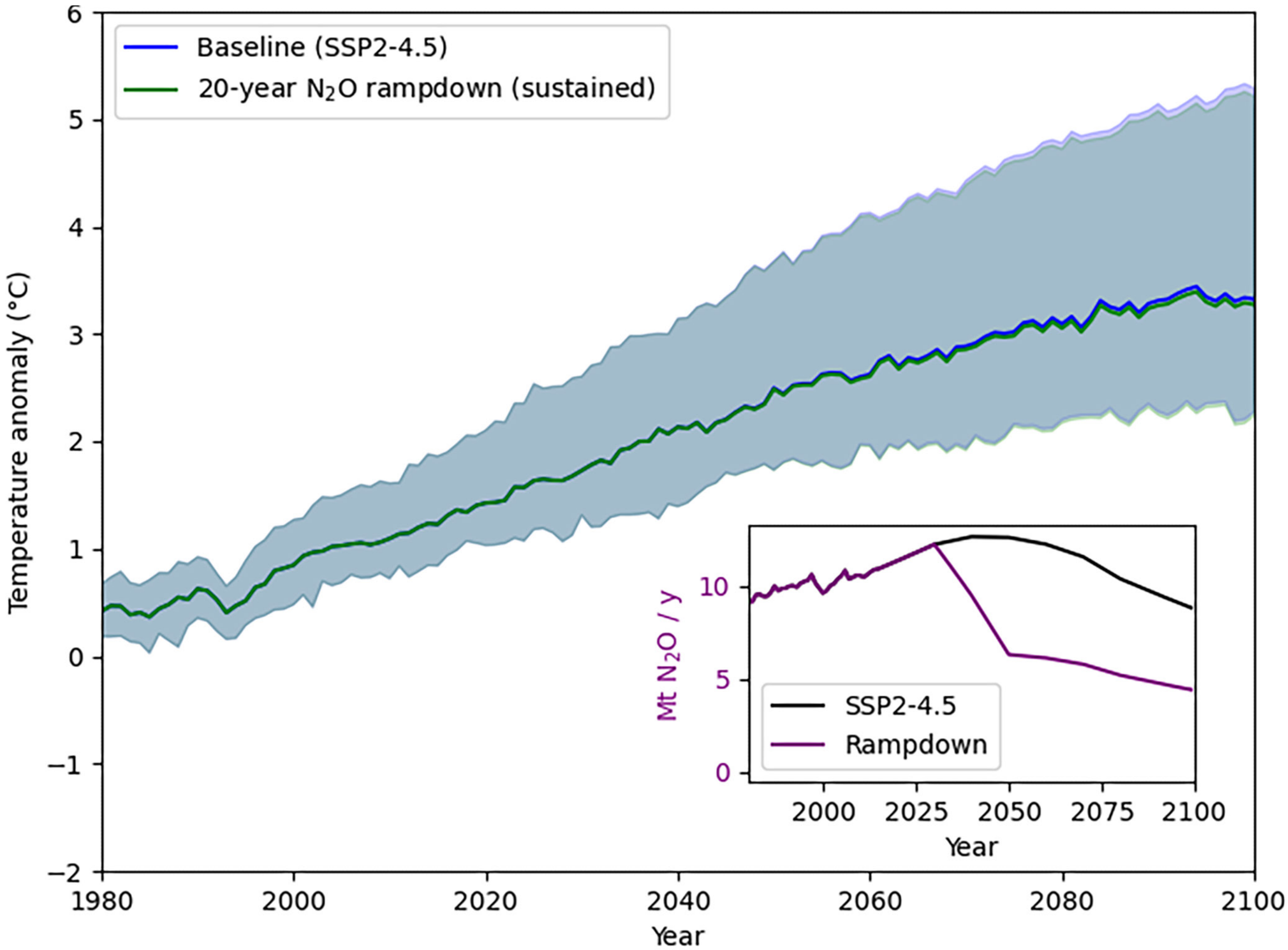

Figure C4: Average global surface temperature impact from reducing anthropogenic nitrous oxide (N_2O) emissions by 50% over 2030–2050, and sustaining the reductions, with temperature shown in degrees Celsius (°C). These scenarios are modeled in the Finite Amplitude Impulse Response (FaIR) simple climate model,[103] based on SSP2-4.5, with a range of climate sensitivity parameters. The central values are the median (50th percentile) and the shaded areas represent 5th/95th percentile ranges across an ensemble of model configurations. Notes: CO_2 = carbon dioxide, Gt CO_2/y = gigatonnes of carbon dioxide per year, Mt N_2O/y = million tonnes of nitrous oxide per year. Source: Carbon Direct.

103. FaIR Development Team. 2024. FaIR: Finite Amplitude Impulse Response simple climate model — fair 2.2.3 documentation. [accessed 2025 Dec 8]. https://docs.fairmodel.net/en/stable/index.html

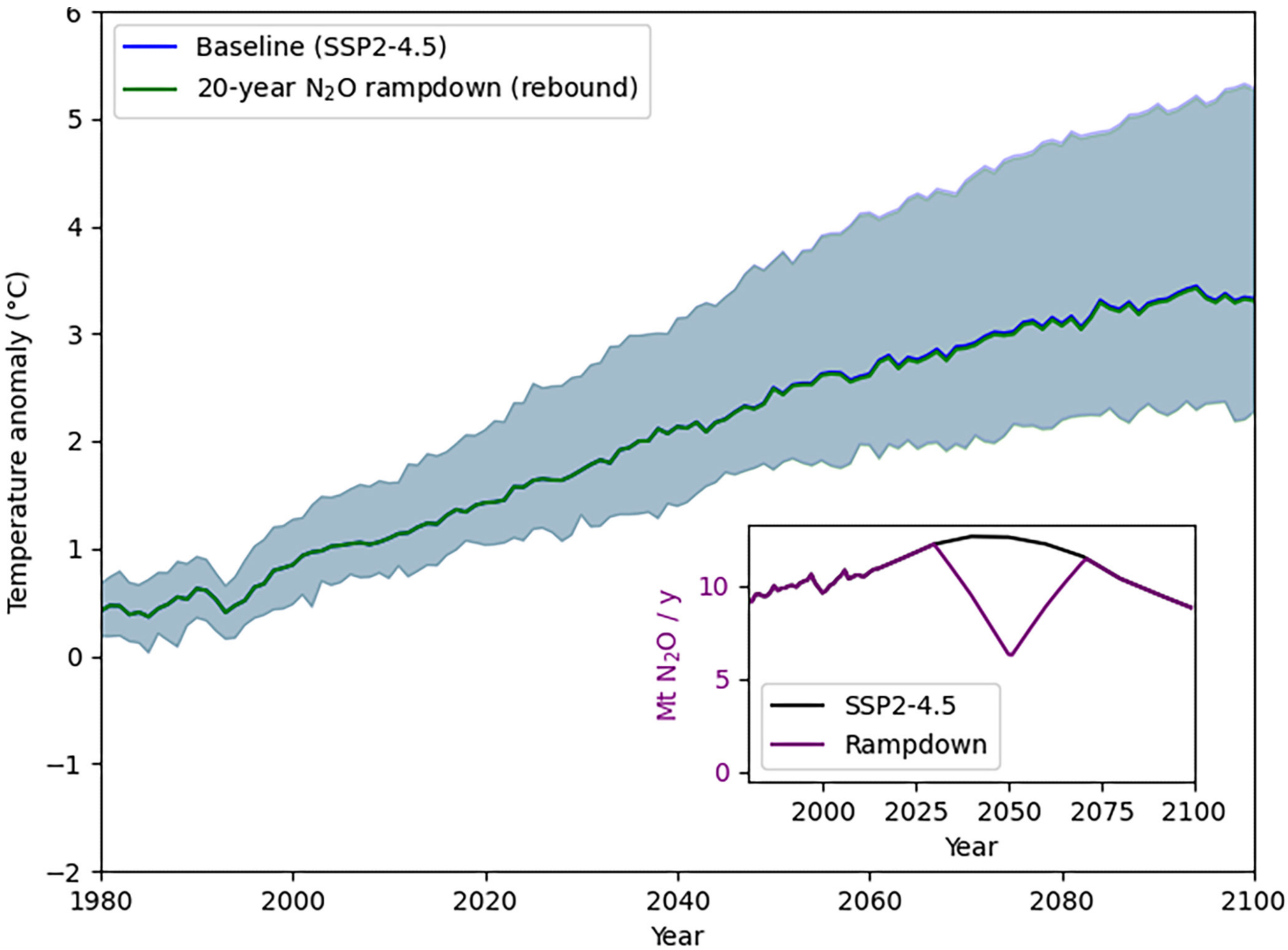

Figure C5: Average global surface temperature impact from reducing anthropogenic nitrous oxide (N_2O) emissions by 50% over 2030–2050, and then allowing the emissions to return, rebounding temperatures by the end of the century, with temperature shown in degrees Celsius (°C). These scenarios are modeled in the Finite Amplitude Impulse Response (FaIR) simple climate model,[104] based on SSP2-4.5, with a range of climate sensitivity parameters. The central values are the median (50th percentile) and the shaded areas represent 5th/95th percentile ranges across an ensemble of model configurations. Notes: CO_2 = carbon dioxide, Gt CO_2/y = gigatonnes of carbon dioxide per year, Mt N_2O/y = million tonnes of nitrous oxide per year. Source: Carbon Direct.

104. FaIR Development Team. 2024. FaIR: Finite Amplitude Impulse Response simple climate model — fair 2.2.3 documentation. [accessed 2025 Dec 8]. https://docs.fairmodel.net/en/stable/index.html

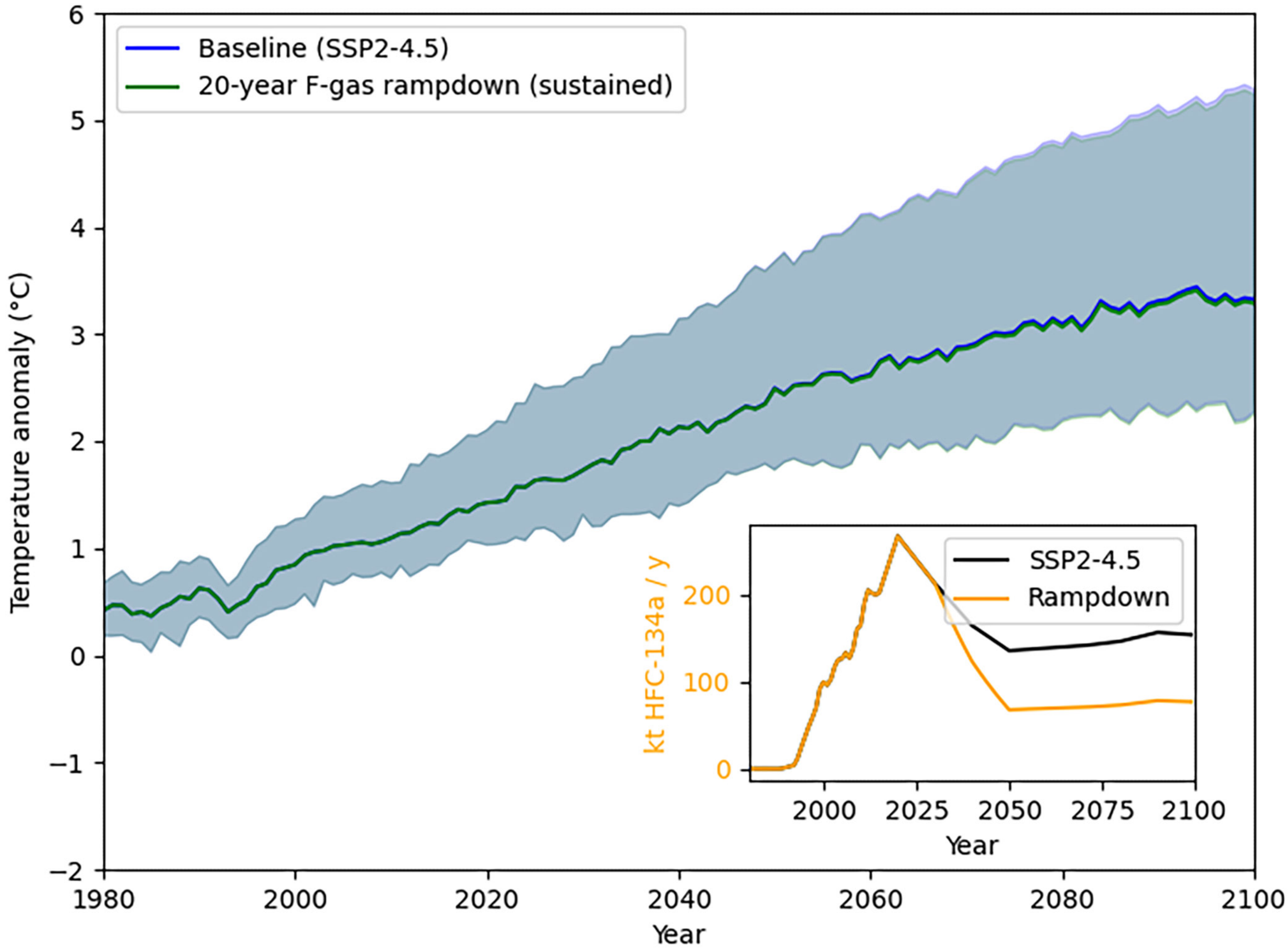

Figure C6: Average global surface temperature impact from reducing anthropogenic F-gas emissions by 50% over 2030–2050, and sustaining the reductions, with temperature shown in degrees Celsius (°C). These scenarios are modeled in the Finite Amplitude Impulse Response (FaIR) simple climate model,[105] based on SSP2-4.5, with a range of climate sensitivity parameters. The central values are the median (50th percentile) and the shaded areas represent 5th/95th percentile ranges across an ensemble of model configurations. The full list of F-gas species whose emissions are reduced is provided in the text. The emissions of 1,1,1,2-tetrafluoroethane (HFC-134a), a prominent F-gas, are shown in the inset box as a representative example. Notes: CO_2 = carbon dioxide, Gt CO_2/y = gigatonnes of carbon dioxide per year, kt HFC-134a/y = kilotonnes of HFC-134a per year. Source: Carbon Direct.

105. FaIR Development Team. 2024. FaIR: Finite Amplitude Impulse Response simple climate model — fair 2.2.3 documentation. [accessed 2025 Dec 8]. https://docs.fairmodel.net/en/stable/index.html

Appendix D: Existing project methodologies

Methane project methodologies

Livestock and manure management

BIODIGESTER SYSTEMS

Biodigester systems capture methane from manure storage facilities, converting it into energy rather than allowing it to be released into the atmosphere. This process can deliver renewable energy, reduce localized pollution, and create energy independence.[106] Current challenges include capital costs and technical expertise requirements that mean biodigesters rarely occur without carbon finance, variable baseline scenarios depending on current manure management systems, and the possibility that regulatory advancement could systematically eliminate regulatory additionality in certain jurisdictions. Comprehensive coverage exists across over 15 methodologies spanning all major registries.[107, 108, 109, 110]

GRAZING MANAGEMENT AND ENTERIC FERMENTATION

See the *Appendix A: Promising mitigation opportunities on the VCM* section for details.

Agriculture and land use

RICE CULTIVATION

See the *Appendix A: Promising mitigation opportunities on the VCM* section for details.

PEATLAND AND WETLAND RESTORATION

Drained peatlands and wetlands release substantial methane and N_2O emissions as soils decompose under aerobic conditions. Rewetting these ecosystems restores anaerobic conditions, slowing decomposition and associated emissions while rebuilding carbon stocks. These projects offer substantial climate benefits, biodiversity co-benefits, improved water quality, and flood risk reduction. Current challenges include significant capital investment, temporary methane increases during the immediate post-rewetting period, and regulatory advances that could mandate restoration

106. Integrity Council for the Voluntary Carbon Market. 2025. Biodigesters: Creating Energy - Reducing Methane. [accessed 2025 Dec 8]. https://icvcm.org/biodigesters/

107. Climate Action Reserve. 2013. U.S. livestock project protocol version 4.0. Climate Action Reserve; [accessed 2025 Dec 8]. https://climateactionreserve.org/wp-content/uploads/2023/10/US_Livestock_Protocol_Combined-1.pdf

108. Climate Action Reserve. 2010. Mexico livestock protocol version 2.0. LClimate Action Reserve; [accessed 2025 Dec 8]. https://climateactionreserve.org/wp-content/uploads/2023/10/Combined_Mexico_Livestock_Protocol_V2.0_ENG-1.pdf

109. United Nations Framework Convention on Climate Change. 2017. AMS-III.D: Methane recovery in animal manure management systems, version 21.0. [accessed 2025 Dec 8]. https://cdm.unfccc.int/sunsetcms/storage/contents/stored-file-20170728123459577/SSCWG54_EA05_AMS-III.D.pdf

110. United Nations Framework Convention on Climate Change. 2013. ACM0010: Consolidated baseline methodology for GHG emission reductions from manure management systems, version 08.0. [accessed 2025 Dec 8]. https://cdm.unfccc.int/sunsetcms/storage/contents/stored-file-20130904181124860/mp60_an08.pdf

requirements in key geographies. Despite the substantial climate opportunity, there is limited methodological coverage for these projects. While temperate and tidal wetland methodologies are active and offer immediate opportunities for engagement, tropical peatland project methodologies have received limited adoption and remain under revision.[111, 112, 113]

Waste handling and disposal

LANDFILL METHANE

See the *Appendix A: Promising mitigation opportunities on the VCM* section for details.

WASTEWATER TREATMENT

Municipal and industrial wastewater generates methane during anaerobic treatment or when discharged to anaerobic environments. Mitigation projects install aeration systems, covered anaerobic reactors with biogas capture, or aerobic treatment upgrades, reducing methane generation and release. Wastewater treatment projects are attractive for their predictable biogas yields, facility energy self-sufficiency, and the integration of co-digestion with food waste or other organic substrates for enhanced biogas production. Current challenges include capital costs and technical capacity requirements that rarely occur without carbon finance. Methodology gaps exist for decentralized wastewater systems, which are standard in informal settlements; simplified measurement approaches are needed. There is comprehensive methodological coverage of this project type, with more than 10 methodologies across all major registries.[114, 115, 116, 117]

FOOD WASTE DIVERSION

Food waste diversion prevents organic material from entering landfills, reducing methane generation from anaerobic decomposition. Projects include strategies for mitigation such as enhanced demand planning, reducing food surplus, food-sharing, and on-site processing through composting or home food recyclers. These projects are attractive for their operational flexibility across prevention, recovery, and treatment pathways and their ability to generate valuable co-products, including fertilizer and renewable energy. Current challenges include operational complexity, capital requirements, extensive exclusion lists for certain waste streams, and regulatory mandates. Comprehensive methodological coverage exists, with more than 10

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111. Verra. 2014. VM0027 Methodology for Rewetting Drained Tropical Peatlands, v1.0. [accessed 2025 Dec 8]. https://verra.org/methodologies/vm0027-methodology-for-rewetting-drained-tropical-peatlands-v1-0/

112. Verra. 2017. VM0036 Methodology for Rewetting Drained Temperate Peatlands v1.0 - Verra. [accessed 2025 Dec 8]. https://verra.org/methodologies/vm0036-methodology-for-rewetting-drained-temperate-peatlands-v1-0/

113. American Carbon Registry. 2017. Methodology for the quantification, monitoring, reporting and verification of greenhouse gas emissions reductions and removals from restoration of pocosin wetlands, Version 1.0. [accessed 2025 Dec 8]. https://acrcarbon.org/wp-content/uploads/2023/03/ACR-Pocosin-Wetlands-v1.0.pdf

114. United Nations Framework Convention on Climate Change. 2019. ACM0014: Treatment of wastewater, Version 08.0. [accessed 2025 Dec 8]. https://cdm.unfccc.int/UserManagement/FileStorage/P2IJYVHXTOEB746M3CLRK0ZG8DNA15

115. Climate Action Reserve. 2014. U.S. Organic Waste Digestion Project Protocol, Version 2.1. [accessed 2025 Dec 8]. https://climateactionreserve.org/wp-content/uploads/2023/10/Organic_Waste_Digestion_Project_Protocol_Version2.1.pdf

116. United Nations Framework Convention on Climate Change. 2019. AMS-III.H.: Methane recovery in wastewater treatment, Version 19.0. [accessed 2025 Dec 8]. https://cdm.unfccc.int/UserManagement/FileStorage/I2PQUV5XSB1O3H7EW6DJ0ANTKRYF9G

117. United Nations Framework Convention on Climate Change. 2009. AMS-III.I.: Avoidance of methane production in wastewater treatment through replacement of anaerobic systems by aerobic systems, Version 08. [accessed 2025 Dec 8]. https://cdm.unfccc.int/UserManagement/FileStorage/CROTVK6JB908P2MESAYN7ZQ53FXWGU

methodologies across major registries, spanning prevention through composting and digestion approaches.[118, 119, 120, 121]

Energy and industrial emissions

ORPHANED OIL AND GAS WELLS

Permanent well plugging (e.g., cement sealing, mechanical barriers, abandonment procedures) eliminates methane leaks from abandoned oil and gas wells where there is no responsible operator or owner, delivering immediate emission reductions. In the near term, orphaned wells lack custodians, making them clearly additional and important levers for voluntary action. However, as regulation looks to clean-up orphaned oil wells, denoting clear responsibility for them, these projects might no longer be additional. These projects are attractive for their ability to combine climate benefits with the co-benefits of groundwater protection and land restoration.[122] Current challenges include capital investment, limitations in documentation, missing historical production data for older wells, and government program expansions, which threaten regulatory additionality. If these programs are adequately funded, they could address larger fractions of the orphaned well inventory annually. There are a few methodologies active across major registries, with additional guidance under development.[123, 124, 125]

COAL MINE METHANE

Pre-drainage systems and ventilation air methane destruction (e.g., vertical wells, horizontal drilling, regenerative thermal oxidation) capture dilute and concentrated methane from active and abandoned coal operations, delivering immediate emission reductions. These projects are attractive not only because they address mine safety, but because they offer the ability to utilize captured methane for electricity generation, heat production, or pipeline injection. Current challenges include the capital-intensive nature of specialized technologies and the likelihood that regulatory expansion could mandate methane capture across more mine types. There

118. Gold Standard Foundation. 2024. Methodology - Reduction in methane emissions from landfills through decentralised organic waste processing. Version 1.0. [accessed 2025 Dec 8]. https://globalgoals.goldstandard.org/standards/441_V1.0_WMH_Reduction-in-methane-emissions-from-landfills-through-decentralised-organic-waste-processing.pdf

119. Verra. 2023. VM0046: methodology for reducing food loss and waste, version 1.0. [accessed 2025 Dec 8]. https://verra.org/methodologies/vm0046-methodology-for-reducing-food-loss-and-waste-v1-0/

120. United Nations Framework Convention on Climate Change. 2016. AMS-III.F: Avoidance of methane emissions through composting, version 12.0. [accessed 2025 Dec 8]. https://cdm.unfccc.int/UserManagement/FileStorage/V5BK1NFHM6ORYGI324CD78L0ZA9UJQ

121. United Nations Framework Convention on Climate Change. 2014. AMS-III.E: avoidance of methane production from decay of biomass through controlled combustion, gasification or mechanical/thermal treatment, version 17.0. [accessed 2025 Dec 8]. https://cdm.unfccc.int/UserManagement/FileStorage/YUCF7O03GWKZEQBRXVTA5H4DJLMI9S

122. Crompton J, Handler B, Bhalala V. 2024. Carbon credits for mitigating orphan & idle oil well methane emissions. Payne Institute Commentary Series. Golden (CO): Payne Institute for Public Policy, Colorado School of Mines; [accessed 2025 Nov 13]. https://payneinstitute.mines.edu/carbon-credits-for-mitigating-orphan-idle-oil-well-methane-emissions/

123. American Carbon Registry. 2025. INACTIVE: Plugging Orphaned Oil and Gas Wells. [accessed 2025 Dec 8]. https://acrcarbon.org/methodology/plugging-orphaned-oil-and-gas-wells/

124. CarbonPath. 2025. Methodology for methane emission removal via permanent decommissioning of orphaned and abandoned oil and natural gas wellbores. Version 1.4. [accessed 2025 Dec 8]. https://carbon-path-production.s3.amazonaws.com/resources/methodology/CarbonPath_Orphaned_and_Abandoned_Well_Carbon_Credit_Methodology_v_punfZDz.pdf

125. BCarbon. 2025. BCarbon methane emissions elimination through well plugging (MEEWP) protocol. Version 2.0. [accessed 2025 Dec 8]. https://static1.squarespace.com/static/611691387b74c566a67f385d/t/67ffc8bc7e717a49ae1d73f0/1744816318068/Methane+Protocol+-+V2.0+-+Clean.pdf

are many methodologies available across most registries.[126, 127, 128, 129]

F-gas project methodologies

Leak detection and reduction

See the *Appendix A: Promising mitigation opportunities on the VCM* section for details.

Substitutes and replacements

REFRIGERANT SUBSTITUTION

Refrigerant substitution projects replace HFCs that have high-GWP with alternatives that have lower GWPs. These alternatives include natural refrigerants such as isobutane (R-600a) and propane (R-290) or hydrofluoroolefins (HFOs) like HFO-1234ze(E) and HFO-1234yf. Substitution in commercial and industrial cooling systems delivers immediate climate benefits through GWP reductions of 90% or more.[130] These projects are attractive for their use of proven technology, clear baseline measurement, and alignment with existing regulatory phase-down schedules under the Kigali Amendment.

Current challenges include higher upfront costs for equipment retrofit or replacement, technical barriers in specific applications (particularly high-temperature or large-scale systems), and questions around regulatory additionality as mandates increasingly drive HFC phase-out independent of carbon finance. There are a few methodologies available across major registries, with the ACR as the most prominent, that are specifically designed for refrigeration and air conditioning applications.[131, 132]

FOAM BLOWING AGENTS

See the *Appendix A: Promising mitigation opportunities on the VCM* section for details.

Recovery and destruction

OZONE DEPLETING SUBSTANCES FROM END-OF-LIFE EQUIPMENT

Ozone-depleting substances (ODS) such as chlorofluorocarbons and hydrochlorofluorocarbons remain trapped in refrigeration, air conditioning, and foam insulation equipment at end-of-life. Without proper recovery, these substances are released during equipment disposal. ODS

126. Climate Action Reserve. 2012. Coal mine methane project protocol. Version 1.1. [accessed 2025 Nov 13]. https://climateactionreserve.org/wp-content/uploads/2023/10/Coal_Mine_Methane_Project_Protocol_V1.1.pdf

127. American Carbon Registry. 2022. Methodology for the quantification, monitoring, reporting and verification of greenhouse gas emissions reductions and removals from capturing and destroying methane from U.S. coal and trona mines. Version 1.1. [accessed 2025 Dec 8]. https://acrcarbon.org/wp-content/uploads/2025/03/ACR-MMC-v1.1.pdf

128. United Nations Framework Convention on Climate Change. 2014. ACM0008: Abatement of methane from coal mines. Version 08.0. [accessed 2025 Dec 8]. https://cdm.unfccc.int/methodologies/DB/YSD3FQ5WR3VPC9Q64CDTLXHLFVKKKU

129. United Nations Framework Convention on Climate Change. 2010. Consolidated methodology for coal bed methane, coal mine methane and ventilation air methane capture and use for power (electrical or motive) and heat and/or destruction through flaring or flameless oxidation. ACM0008, Version 07. [accessed 2025 Dec 8]. https://cdm.unfccc.int/methodologies/DB/7LSHSGVFVCNG9L1S7BV0P536BZAPML/view.html.

130. United States Environmental Protection Agency. 2016. Transitioning to low-GWP alternatives in commercial refrigeration. Report No.: EPA-430-F-16-073. [accessed 2025 Dec 8]. https://www.epa.gov/sites/default/files/2016-12/documents/international_transitioning_to_low-gwp_alternatives_in_commercial_refrigeration.pdf

131. American Carbon Registry. 2024. Advanced Refrigeration Systems, Version 3.0. [accessed 2025 Dec 8]. https://acrcarbon.org/methodology/advanced-refrigeration-systems/

132. United Nations Framework Convention on Climate Change. 2022. AM0071: Manufacturing and servicing of domestic and/or small commercial refrigeration appliances using a low GWP refrigerant, version 03.0. [accessed 2025 Dec 8]. https://cdm.unfccc.int/UserManagement/FileStorage/KES3M524QDYUOL1VWBTZ0XGP8FJNAH

destruction projects capture and thermally destroy these substances before they are released into the atmosphere, delivering permanent emission reductions. These projects are attractive because they address legacy emissions from the existing stock of retired equipment, provide high GWP mitigation, and demonstrate clear additionality in regions lacking mandatory ODS recovery regulations. Current challenges include establishing collection infrastructure and reverse logistics systems, demonstrating that destruction would not have occurred under baseline regulatory requirements, and accounting for declining ODS equipment stocks as older systems age out. Several methodologies are available across major registries, including Verra, ACR, and CAR.[133, 134, 135, 136, 137]

HFC RECOVERY AND RECLAMATION

Recovery and reclamation systems extract high-GWP refrigerants from end-of-life equipment and restore them to market-ready purity, avoiding atmospheric release. These projects are attractive due to the immediate emission avoidance they provide, compared to gradual-release scenarios, and for their ability to return valuable refrigerants to productive use rather than destruction. Current challenges include rigorous chain-of-custody requirements from recovery through reclamation, documentation requirements, carbon financing, and expanding regulatory mandates. Emerging coverage exists with limited active methodologies, primarily ACR's Certified Reclaimed HFC Refrigerants v2.0.[138]

N_2O project methodologies

Livestock and manure management

MANURE N_2O REDUCTION

Livestock manure management generates N_2O through nitrification and denitrification processes in nitrogen-rich organic matter. Solid-liquid separation, controlled composting systems, and storage modifications reduce the formation and release of N_2O. These projects are attractive for their ability to combine N_2O reduction with methane mitigation through integrated manure management systems and their potential to match nitrogen availability with crop uptake through optimized application timing. Current challenges include capital costs and technical requirements for separation and composting infrastructure, technically challenging monitoring, and potential indirect regulatory drivers that complicate the assessment of regulatory

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133. Climate Action Reserve. 2021. Mexico Halocarbon Protocol Version 1.0. [accessed 2025 Dec 8]. https://climateactionreserve.org/wp-content/uploads/2021/06/Mexico_Halocarbon_Protocol_V1.0_English.pdf

134. Climate Action Reserve. 2012. U.S. Ozone Depleting Substances Project Protocol Version 2.0. [accessed 2025 Dec 8]. https://climateactionreserve.org/wp-content/uploads/2024/06/U.S._ODS_Project_Protocol_V2.0.pdf

135. Verra. 2017. Recovery and Destruction of Ozone-Depleting Substances (VM0016) Version 1.1. [accessed 2025 Dec 8]. https://verra.org/methodologies/vm0016-recovery-and-destruction-of-ozone-depleting-substances-ods-from-products-v1-1/

136. American Carbon Registry. 2022. Methodology for the quantification, monitoring, reporting, and verification of greenhouse gas emissions reductions and removals from certified reclaimed HFC refrigerants, propellants, and fire suppressants. Version 2.0. [accessed 2025 Dec 8]. https://acrcarbon.org/wp-content/uploads/2023/09/ACR-Certified-Reclaimed-HFC_V2.0-FINAL.pdf

137. Carbon Containment Lab. 2024. Draft methodology for recovery and destruction of hydrofluorocarbons in Article 5 countries, version 2.1. [accessed 2025 Nov 12]. https://carboncontainmentlab.org/publications/hfc-methodology.

138. American Carbon Registry. 2022. Certified Reclaimed HFC Refrigerants, Propellants, and Fire Suppressants, Version 2.0. [accessed 2025 Dec 8]. https://acrcarbon.org/methodology/certified-reclaimed-hfc-refrigerants-propellants-and-fire-suppressants/

additionality. Limited methodology coverage exists through ACR.[139]

Agriculture and land use

SYNTHETIC FERTILIZER N_2O REDUCTION

Precision agriculture enables variable-rate fertilizer application matched to field-specific requirements, reducing the potential for over application that results in excess N_2O emissions. Enhanced efficiency fertilizers incorporating nitrification inhibitors or controlled-release coatings reduce fertilizer losses while maintaining yields. These projects are attractive for their ability to combine emission reductions with economic benefits from reducing spending on fertilizer and improving nitrogen-use efficiency. Current challenges include cost premiums, variable efficacy across soil types and climate conditions, and the need for robust field-level monitoring. Comprehensive methodologies addressing agricultural N_2O mitigation exist across major registries.[140, 141, 142]

Chemical and manufacturing industries

NITRIC ACID PRODUCTION

Catalytic and thermal destruction systems (e.g., secondary catalytic reduction, thermal decomposition units, non-selective catalytic reduction) eliminate N_2O generated during ammonia oxidation. These projects are attractive for their massive abatement potential from single facilities and the ability to retrofit existing plants without major production disruptions. Current challenges include historical perverse incentives that led to Clean Development Mechanism HFC-23 and N_2O integrity scandals, the fact that some jurisdictions lack N_2O control regulations (raising questions about regulatory additionality as policies evolve), and regulatory expansion that could mandate destruction systems beyond current requirements. Limited active methodologies are available.[143, 144, 145]

ADIPIC ACID PRODUCTION

See the *Appendix A: Promising mitigation opportunities on the VCM* section for details.

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139. American Carbon Registry. n.d. Grazing land and livestock management greenhouse gas mitigation methodology:. [accessed 2025 Dec 8]. https://acrcarbon.org/wp-content/uploads/2023/03/A-BIOTIC_pc.pdf

140. Verra. 2025. VM0042 Improved Agricultural Land Management, Version 2.2. [accessed 2025 Dec 8]. https://verra.org/methodologies/vm0042-improved-agricultural-land-management-v2-2/

141. Climate Action Reserve. 2021. Nitrogen Management Protocol Version 2.1. [accessed 2025 Dec 8]. https://climateactionreserve.org/wp-content/uploads/2023/06/Nitrogen-Management-Project-Protocol_Version-2.1_FINAL_.pdf

142. United Nations Framework Convention on Climate Change. 2014. AMS-III.A: Offsetting of synthetic nitrogen fertilizers by inoculant application in legumes-grass rotations on acidic soils on existing cropland. Version 03.0. [accessed 2025 Dec 8]. https://cdm.unfccc.int/sunsetcms/storage/contents/stored-file-20140908165555033/SSCWG45_annex11_AMS-III.A_cer03.0_fin.ask_.pdf

143. United Nations Framework Convention on Climate Change. 2018. ACM0019: N_2O abatement from nitric acid production, Version 04.0. [accessed 2025 Dec 8]. https://cdm.unfccc.int/UserManagement/FileStorage/RDX2Q6IWUVC8Y3H4MFLT7OJ1G05PEA

144. Climate Action Reserve. 2025. U.S. nitric acid production protocol. Version 3.0. [accessed 2025 Dec 8]. https://climateactionreserve.org/wp-content/uploads/2025/08/US-Nitric-Acid-Production-Protocol-V3.0.pdf

145. Environmental Investigation Agency. 2010. Ethically bankrupt: World Bank defense of the HFC-23 scandal. [accessed 2025 Dec 10]. https://static.us.eia.org/pdfs/Ethically_Bankrupt.pdf

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