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Superpollutant Roadmap for Corporate Action

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Acknowledgments

Carbon Containment Lab:

Authors: Anastasia O’Rourke, John Nixon, Öznur Öztürk, Sinéad Crotty, Drew Pomerantz, Jack Lowenthal, and Dean Takahashi.

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LEFF Scott Leff, Clairissa Myatt, Katie Parry, Laura Brown

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Executive Summary

Superpollutants—methane, fluorinated gases (F-gases), nitrous oxide, tropospheric ozone, and black carbon—are responsible for roughly half of today’s gross warming,¹ and cutting them is the fastest and lowest-cost way to slow warming this coming decade.

Superpollutant mitigation is no longer optional, but necessary. The IPCC’s 2°C scenario assumes global superpollutant emissions fall by nearly 50 percent by 2050, representing about 142 Gt CO₂e in cumulative avoided emissions, yet current trajectories keep these emissions essentially flat. That gap—between what targets call for and what is actually happening—is the opportunity. Closing it is the focus of this roadmap.

Corporations are positioned to close this gap as few other actors can. They are the largest source of catalytic private climate finance, hold procurement leverage over the supply chains where many of these emissions concentrate, and can make superpollutant action a market expectation rather than an exception or a coming policy driver.



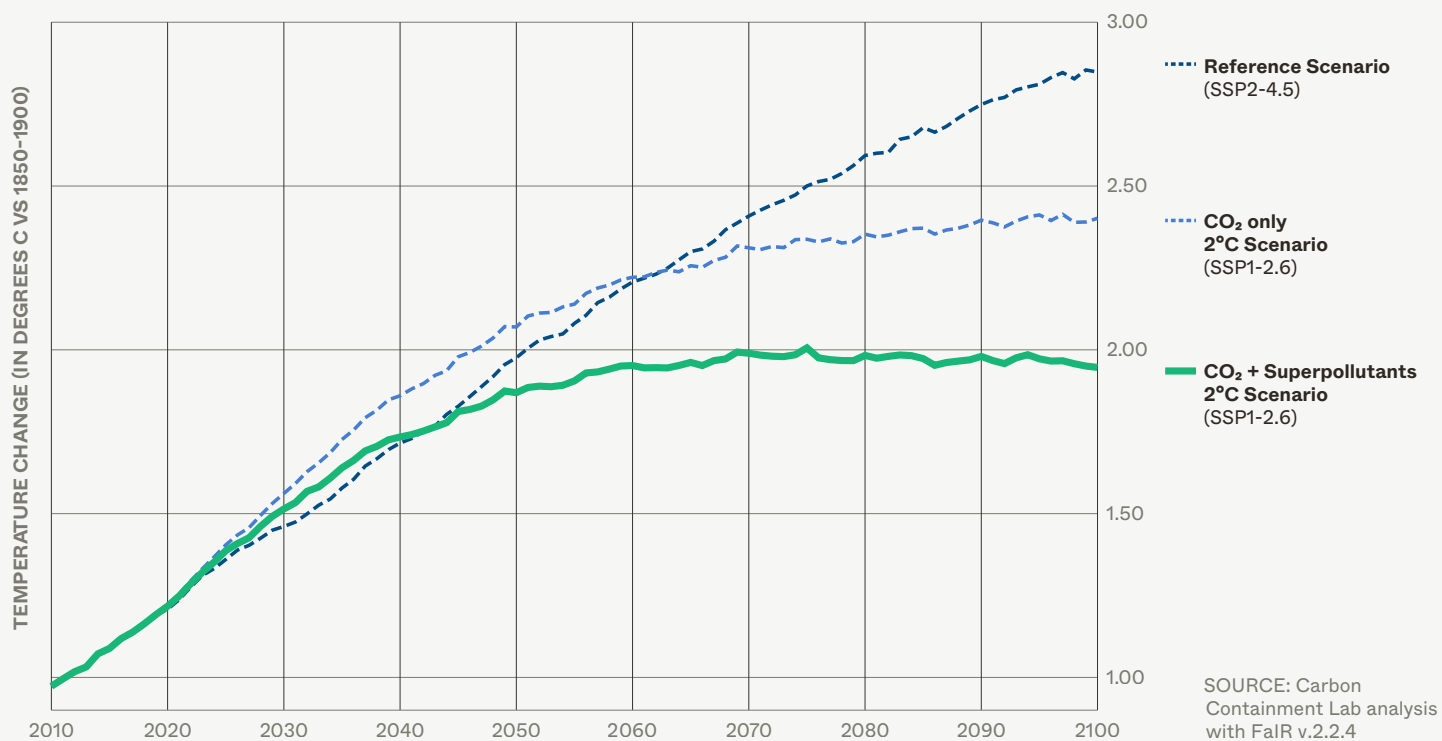
Superpollutant action can help stabilize the climate and avoid tipping points. Superpollutants are on par with carbon dioxide in that both are responsible for a nearly equal share of the warming reduction required to hold the planet below 2°C. Figure E1 presents projected global temperature outcomes through 2100 under the IPCC's 2°C scenario. It compares the contribution of CO₂ mitigation alone versus combined CO₂ and superpollutant mitigation. Of the 0.9°C of warming separating the 2°C scenario from the business-as-usual case (reference case), approximately half is attributable to CO₂ reductions, with the remaining half attributable to superpollutant reductions.

Cutting superpollutant emissions delivers rapid, near-term relief because most are short-lived in the atmosphere. A single ton of methane abated today has largely left the climate system within two decades—making it a uniquely fast acting lever.

Superpollutant action is a kickstart, not a substitute. Superpollutant action is an important complement to CO₂ action that is essential for limiting the extent of warming. Burning fossil fuel emits reflective sulfate particles that act to cool the planet. The reduction in reflective particles resulting from lower fossil fuel use, an effect known as “unmasking,” is the reason the “CO₂ only” curve in Figure E1 stays above the dark blue dashed line until 2060. Pairing superpollutant mitigation with decarbonization dampens this effect because most measures reduce warming without removing aerosol cooling.

This pairing creates an important sequencing opportunity. Rapid superpollutant abatement, achievable in low-cost, quick-turnaround interventions like leak repair and refrigerant management, will extend the scaling time needed for slower, capital-intensive CO₂ reductions in heavy industry and infrastructure.

FIGURE E1: PROJECTED TEMPERATURE CHANGES THROUGH 2100 RESULTING FROM REFERENCE SCENARIO, 2 DEGREES C SCENARIO WITH MITIGATION OF CO₂-ONLY, AND 2 DEGREES C SCENARIO WITH MITIGATION OF BOTH CO₂ AND SUPERPOLLUTANTS



Companies can—and must—be an important part of addressing these potent warmers worldwide.

Companies with substantial superpollutant footprints must take responsibility and reduce them as quickly as possible. But even companies without large amounts of superpollutants in their value chains have opportunities to finance superpollutant elimination projects worldwide through the voluntary carbon market, investing in new facilities, R&D, and sharing best practices. It is vital that all companies take decisive action given the slow pace of government action and the prospect of reaching critical tipping points soon.

Companies are aware of these gases, yet few have committed to reducing them. A decade of corporate climate action has produced more than 10,000 science-based targets, 1,900 net-zero commitments—and very few superpollutant strategies. A review of 40 large companies in exposed sectors revealed a large majority mention superpollutants by name in their sustainability reporting, but just a small percentage follow through by setting targets. The story is similar across the corporate sector—a nearly exclusive focus on CO₂ in most net zero portfolios has resulted in insufficient support and attention to superpollutant mitigation projects.

The accounting conventions that allowed this gap are closing. Superpollutants sit almost entirely in Scope 1—fugitive methane, refrigerant leakage, industrial F-gases, and nitrous oxide from chemical production—and Scope 3—agricultural, supplier, and waste emissions. This distinction is relevant because mitigation measures have stalled in Scopes 1 and 3, precisely where superpollutants tend to concentrate. Meanwhile, the latest Science Based Targets initiative (SBTi) Corporate Net-Zero Standard requires near-term Scope 1 targets to cover 100 percent of Scope 1 emissions, with no materiality carve-out and no more combining it with Scope 2. By early 2028, every large company with fugitive methane, refrigerant leakage,

or industrial F-gas emissions will hold a stand-alone, fully covered Scope 1 target. The only question is how fast companies can move on superpollutants before that deadline arrives.

Superpollutant abatement is unusually cheap and remarkably reachable. A significant share of superpollutant abatement carries negative or low net cost, because the abated substance has commercial value or the intervention is a maintenance practice rather than a capital project.² For example, about 39 percent of oil and gas methane abatement pays for itself outright and nearly all of the remainder is cost-effective below \$20 per metric ton of CO₂e.³ It is even cheaper per ton if you calculate it using GWP-20. Superpollutant emissions also tend to concentrate in identifiable point sources and equipment classes, such as wells and compressor stations, refrigeration and cooling systems, landfills, and nitric and adipic acid plants, rather than diffusing across every combustion process in an economy like for CO₂. Sources that cannot be reached from inside a company's value chain can be reached via voluntary carbon markets where prices are also low relative to other project types and can still be high quality.

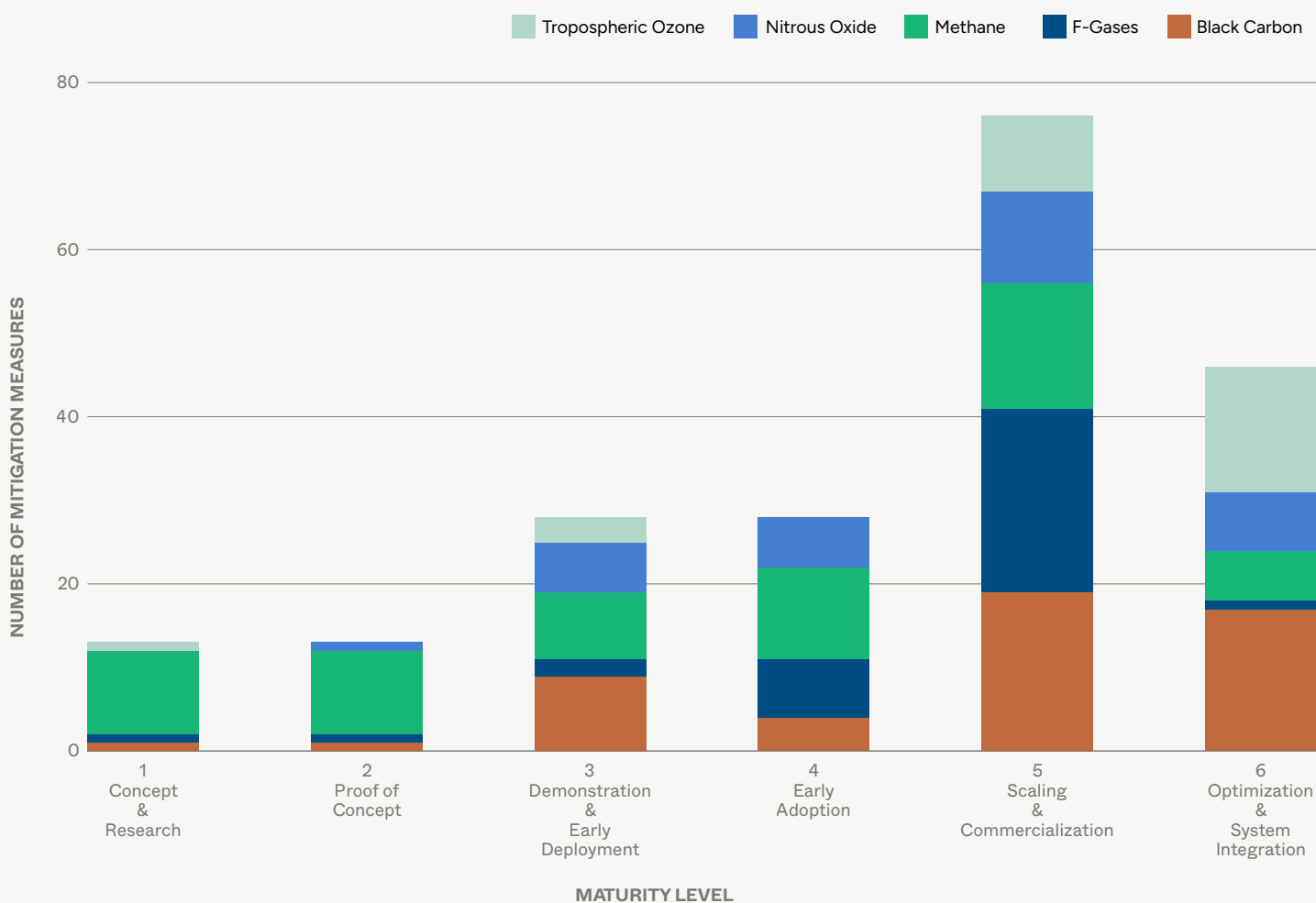
Companies should act decisively, treating superpollutants not as a footnote to their climate strategy but as its fastest-moving front.

Companies can pursue numerous opportunities and many proven pathways to make a difference.

As part of this research, the Carbon Containment Lab cataloged 204 mitigation measures—and the list is growing. Many actions mitigate more than one superpollutant and some also abate CO₂. 60 percent of these measures are mature and ready to scale up, some at a cost of less than \$1 per ton or even provide net savings. Others requiring more investment are

a natural fit for voluntary carbon markets meeting financial additionality requirements. Not every mitigation measure is equally ready; some require work on standards, methodologies or measurement. The most immediate and scalable opportunities lie where the sources are concentrated, the technology is proven, the cost is low, and additional finance can help scale up operations in the next five years.

FIGURE E2: 204 IDENTIFIED SUPERPOLLUTANT MITIGATION MEASURES BY PRIMARY GAS MITIGATED AND MEASURE MATURITY LEVEL



SOURCE: Carbon Containment Lab, 2026

Companies are finding ways to finance a range of mitigation measures—mechanisms include the use of market-based instruments such as insetting, environmental attribute certificates, or carbon credits. Companies are also claiming the emission reductions against their target or as part of a broader contribution or compensation claim.

Table E1 highlights a few select mitigation measures that are uniquely suited for near-term corporate action with high scalability potential.

In addition, superpollutant co-benefits are already found in decarbonization strategies familiar to companies. Sustainable aviation fuel, greener cement and concrete, and transitioning fleets to battery electric vehicles all have notable superpollutant co-benefits, such as reducing black carbon, nitrous oxide, and tropospheric ozone precursors like volatile organic compounds (VOCs).

TABLE E1: PRIORITY SUPERPOLLUTANT PROJECT TYPES AND THE MECHANISMS TO SUPPORT THEM

Project Type	Superpollutants Mitigated	Mechanism	Status
Biomethane from Manure Lagoons/ Anaerobic Digesters	Methane, Nitrous Oxide	Renewable Natural Gas (RNG) certificates; Spot or Forward purchase of carbon credits	Ready for expansion
Landfill Gas Capture & Destruction	Methane	Spot or Forward purchase of carbon credits	Ready for expansion
Lifecycle Refrigerant Management	F-Gases (various)	Spot or Forward purchase of reclaimed gas; and/or carbon credits supporting leak detection & repair or destruction.	Ready for expansion
Rice Methane Mitigation	Methane	Spot or Forward purchase of carbon credits/Environmental Attribute Certificate (EAC)	Gain more MRV experience with deployments
Plugging Orphaned Oil & Gas Wells	Methane	Spot or Forward purchase of carbon credits	Resolve key measurement and methodology issues
Industrial N ₂ O	Nitrous Oxide	Spot or Forward purchase of carbon credits	Resolve key methodology additionality issues

Three levers, one strategy. This roadmap organizes corporate action into three reinforcing levers:

- **Lever 1: Value Chain Intervention.** Reducing superpollutant emissions within a company's own operations and value chain.
- **Lever 2: Voluntary Carbon Markets.** Financing verified superpollutant mitigation beyond the value chain through high-integrity carbon credits.
- **Lever 3: Policy Engagement.** Supporting the policies and regulatory frameworks that make value chain and market action durable and widespread.

The three form one integrated strategy and reinforce the broader climate commitments companies have already made.

Early movers show action is a matter of choice, not capability. They help write the standards and lock in the lowest-cost abatement; those who wait inherit rules written by others and pay more to meet them. In every sector we reviewed, a small group of companies has taken serious action. Danone has committed to cut methane from its fresh-milk supply chain by 30 percent by 2030.⁴ ALDI is converting its

U.S. store network to natural refrigerants.⁵ Apple has secured commitments from semiconductor suppliers to abate at least 90 percent of F-gas emissions by 2030.⁶ Workday has signed a four-year offtake agreement to plug orphaned oil and gas wells.⁷ In March 2026, seven companies with the Beyond Alliance—Amazon, Autodesk, Figma, Google, JPMorgan Chase, Salesforce, and Workday—launched the Superpollutant Action Initiative, committing \$100 million through 2030 to projects that would not otherwise be financed.⁸ More announcements are made every day, and the category is growing quickly.

The window is now. Actions to mitigate superpollutants are a powerful confluence of urgent, immediately available, cost-effective, and fast-acting. The technologies, methods, and markets exist today; what they need is capital and corporate demand at scale. Superpollutant Roadmap for Corporate Action highlights existing abatement opportunities, their cost, and how companies can pursue them through each of the three levers.

The Carbon Containment Lab invites companies to act decisively and treat superpollutants not as a footnote to their climate strategy but as its fastest-moving front.

Foreword

Around the world, 2026 has brought record-breaking temperatures and an unrelenting run of extreme weather. North America, Africa, and Asia each recorded their warmest July on record in 2026, while Western Europe endured its hottest June–July period ever measured, fueling major wildfires across the Mediterranean. In August, a Himalayan glacier collapse in Nepal sent a wall of ice, rock, and debris across the Nepal–China border, upending lives and destroying infrastructure across local communities.

Climate change is no longer knocking on our doorstep. It is here.

Addressing superpollutants such as methane, HFCs, nitrous oxide, and black carbon offers the single greatest opportunity to bend the curve of warming in the near term. Reducing these emissions can slow the rate of warming immediately, while delivering substantial benefits for people, economies, and the environment.

Companies are beginning to take notice. Through the Superpollutant Action Initiative, leading companies have committed to mobilizing \$100 million by 2030 to accelerate action on superpollutants. This commitment is a significant first step, and we hope many more companies will join them.

But ambition needs a clear path to action. Companies have told us they want to understand where their efforts can have the greatest impact, what interventions are available, and how ambition can translate into reductions that actually move the curve. They also need a solid scientific foundation for making those decisions.

That is why we partnered with the Carbon Containment Lab to develop this roadmap. Drawing on a roster of world-renowned experts, this report synthesizes the latest science and identifies the key levers available to companies to drive action on superpollutants.

The takeaway is clear: companies cannot credibly address climate change without addressing superpollutants. Action on methane, HFCs, and other superpollutants can deliver roughly half of the mitigation needed by mid-century to limit warming to 2°C. No amount of progress on carbon dioxide alone will change what the next two decades look like; superpollutants are the only lever that acts fast enough. Because these pollutants have such a powerful near-term impact on warming, action taken today will make a meaningful difference in the trajectory of climate change.

As this report details, the opportunity is enormous, the tools to act are largely within reach today, and the solutions are cost-effective.

We hope this roadmap helps companies move from understanding the challenge to taking action, and that the \$100 million commitment of the Superpollutant Action Initiative is only the beginning.

Luke Pritchard
Director, *Beyond Alliance*

Introduction

Superpollutants are responsible for roughly half of today's gross warming,⁹ yet they remain almost entirely absent from corporate climate targets. Closing the gap between climate science and corporate practice is the fastest and most cost-effective way for companies to slow warming this decade. To date, companies have left this approach largely unused while the window to act narrows, and climate and clean air regulation tightens around it. This roadmap seeks to address the gap through three levers that companies can pull today:

- **Lever 1: Value Chain Intervention.** Reducing superpollutant emissions within a company's own operations and value chain.
- **Lever 2: Voluntary Carbon Markets.** Financing verified superpollutant mitigation beyond the value chain through high-integrity carbon credits.
- **Lever 3: Policy Engagement.** Supporting the policies and regulatory frameworks that make value-chain and market action durable and widespread.

The three form one complete strategy and reinforce the broader climate commitments companies have already made.

The urgency is tangible. Superpollutants trap far more heat than carbon dioxide, but many of them leave the atmosphere within years or decades rather

than centuries. As a result, reducing superpollutants can slow warming within this decade, a timescale no amount of carbon dioxide reduction and removal can match. Superpollutant action complements decarbonization rather than competing with it and it pays a second dividend in cleaner air, healthier ecosystems, and stronger economic resilience. The Carbon Containment Lab's modeling, presented in this roadmap, finds that meeting a 2°C temperature goal relies on superpollutant mitigation at large scale and soon. Indeed, the 2°C goal assumed by the Paris Climate Accord and standards like SBTi already assume that approximately half of the warming will be prevented by superpollutants. But action has yet to truly ramp up to meet this ambition.

Corporations are positioned to close this gap as few other actors can. They are the largest source of catalytic private climate finance, hold procurement leverage over the supply chains where these emissions concentrate, and can make superpollutant action a market expectation rather than an exception. Early movers help write the standards and lock in the lowest-cost abatement. Those who wait inherit rules written by others and pay more to meet them.

This roadmap focuses on the "how." It catalogs the numerous available and emerging mitigation measures, prioritizes solutions that are deployment-ready and can scale within five years, and discusses what is not yet ready but which has great potential.

How to use this roadmap. The chapters build in sequence but stand alone. Readers who need the case for internal use will find it in *What Are Superpollutants?*, *The State of Corporate Superpollutant Action*, and *The Climate Case for Superpollutant Action*. Readers ready to act can go directly to the lever most suited to their exposure: *Value Chain Intervention* for companies whose superpollutant sources sit inside their own operations and supply chains, *Voluntary Carbon Markets* for those seeking to finance mitigation at scale beyond their footprint, and *Policy Engagement* for those positioned to shape the rules that govern both. Each lever chapter closes with a checklist of priority actions for the next 12 to 24 months and through 2030.

The nonprofit Carbon Containment Lab developed this roadmap drawing on review from a wide range of high-profile experts, and with sponsorship from the Beyond Alliance. It grounds its recommendations in current science and real corporate practice. Over time, the Carbon Containment Lab will expand this work with additional project examples, emerging best practices, and quantified impact data. Find the latest at www.superpollutantroadmap.org

With immediate and decisive corporate action, significant reductions are within reach by 2030. Superpollutant mitigation actions are among the fastest available to drive a critical transition and slow the rate of climate change.



01

What Are Superpollutants?



Superpollutants are a group of potent climate pollutants—including methane, nitrous oxide, ozone-depleting substances and fluorinated gases (F-gases), black carbon, and tropospheric ozone—that have a disproportionately large impact on near-term warming.

These five pollutant groups are considered “super” because they trap far more energy per molecule in the atmosphere than carbon dioxide does.* In other words, superpollutants have high *radiative efficiencies*. As a result, small quantities of superpollutant emissions do disproportionate damage. While superpollutants make up only a few percent of annual anthropogenic emissions by mass, they are responsible for approximately half of the warming observed to date.¹⁰

Global warming potential (GWP) is the metric conventionally used to compare these pollutants to carbon dioxide. It combines radiative efficiency with atmospheric lifetime to express warming integrated over a chosen period, which is why the same gas carries different values on different timescales (see box “What is the Global Warming Potential (GWP) and Why Does it Matter for Superpollutants?” and Appendix A).¹¹ For example, methane is approximately 80 times as potent as carbon dioxide over 20 years and roughly 28 times over 100 years. Meanwhile, some F-gases exceed carbon dioxide by tens of thousands of times on both.

Many (though not all) superpollutants are short-lived in the atmosphere. This, combined with their high potency, means that cutting superpollutant emissions now can deliver immediate, measurable temperature benefits within years to decades.

* Black carbon is the exception to this description. It is a particle rather than a gas, and it warms mainly by absorbing incoming solar radiation and by darkening snow and ice, rather than by absorbing outgoing infrared radiation.

A second dynamic compounds the urgency. Fossil fuel combustion often emits sulfur dioxide alongside carbon dioxide, and the resulting sulfate aerosols cool the climate.¹² This cooling has offset a substantial share of the warming that accumulated greenhouse gases would otherwise have produced. Historically, air quality regulation has resulted in large sulfate reductions across North America, Europe, and increasingly China. Going forward, the transition away from burning sulfur-containing fossil fuels will further reduce the amount of sulfate aerosol cooling. As a result of the declining sulfate cooling, we will see more of the warming due to the build-up of greenhouse gases in the atmosphere that had been masked.¹³ Superpollutant mitigation is the main lever available to counteract this unmasked warming because most superpollutant measures reduce warming without removing aerosol cooling alongside.[†]

While mechanisms exist for companies seeking to act on all five superpollutant groupings, most market-based action to date has concentrated on methane, industrial nitrous oxide, and ozone-depleting substances, where measurement and verification science is most settled and where policy and regulation have yet to fully cover those emissions. Market-based actions for credible F-gas abatement are rapidly emerging, while agricultural nitrous oxide abatement pathways are at an earlier stage of development, and benefit from oftentimes addressing methane and black carbon at the same time. Black carbon and tropospheric ozone precursor gases (such as carbon monoxide and volatile organic compounds) are being addressed more selectively by both markets and policy, as later chapters detail.

† Black carbon is the main exception: measures targeting it typically also reduce co-emitted organic carbon and sulfate, which cool, so the net forcing reduction is often smaller than the black carbon figure alone implies. Agricultural nitrous oxide measures may similarly reduce ammonia and associated nitrate aerosol, though this effect is small relative to sulfate.

TABLE 1: GLOBAL WARMING POTENTIALS OF COMMON SUPERPOLLUTANTS

GHG or Class of GHG	Radiative Forcing (W/m ²)	Types/Examples	GWP-20	GWP-100
Carbon Dioxide (CO ₂)	2.3330		1	1
Methane (CH ₄)	0.5670	Fossil	82.5	29.8
		Non-fossil	79.7	27.0
Nitrous Oxide (N ₂ O)	0.2260		273	273
Chlorofluorocarbons (CFCs)	0.2980	CFC-12	12700	12500
Hydrochlorofluorocarbons (HCFCs)	0.0600	HCFC-22	5690	1960
		HCFC-141b	2710	860
		HCFC-142b	5510	2300
Hydrofluorocarbons (HFCs)	0.0480	HFC-32	2690	771
		HFC-134a	4140	1530
Hydrofluoroolefins (HFOs)	Negligible	HFO-1234yf	1.81	0.50
Perfluorocarbons (PFCs)	In AR6 halog. total*	PFC-14	5300	7380
		PFC-116	8940	12400
Sulfur Hexafluoride (SF ₆)	~0.007		18200	24300
Nitrogen Trifluoride (NF ₃)	Negligible		13400	17400
Black Carbon (BC)	0.3000		n/a	n/a
Tropospheric Ozone (TO)	0.4000		n/a	n/a

* PFCs fall within the IPCC AR6 aggregate for all halogenated gases (0.41 W/m², 1750-2019); the PFC share is small.

What is the Global Warming Potential (GWP) and Why Does it Matter for Superpollutants?

Superpollutants affect the climate in different ways than carbon dioxide: they trap much more energy per molecule than carbon dioxide when in the atmosphere, but many superpollutants are naturally removed from the atmosphere at much faster rates, and are thus described as “short-lived climate pollutants” (SLCPs). These magnified effects at different timescales make it complicated to compare superpollutants to carbon dioxide and to one another.

Global Warming Potential (GWP) is the metric most commonly used to make this comparison. The IPCC introduced the GWP concept in its 1990 First Assessment Report, where its authors described it as a simplified approach meant to illustrate the difficulty of the underlying comparison rather than a scientifically settled answer.¹⁴

GWP is a ratio that expresses how much a given mass of a superpollutant warms the climate over a chosen number of years, relative to the same mass of carbon dioxide. The time period convention used by most policy and standards is 100 years. Multiplying

an emission by its GWP produces a carbon dioxide equivalent (CO₂e), the common currency used to aggregate emissions of different gases. The IPCC updates these emissions factors based on the latest science, and these metrics are widely used in nearly all climate policy, accounting, reporting and target-setting. Appendix A explains emission metrics in more detail and provides a table with the different factors over 20-year and 100-year timescales.

The metrics we use implicitly require a choice of which timescale matters more—next decades or end of century. The choice to use GWP-100 undervalues the near-term climate impact of most superpollutants. It also contributes to undervaluing the opportunity to mitigate them at reasonable cost and with immediate effect.

Alternative approaches are being developed but are not yet well adopted. As such, GWPs are reported throughout the roadmap in 100-year time spans, denoted as (GWP-100), or if pertinent to the discussion, over twenty years as (GWP-20).

Methane

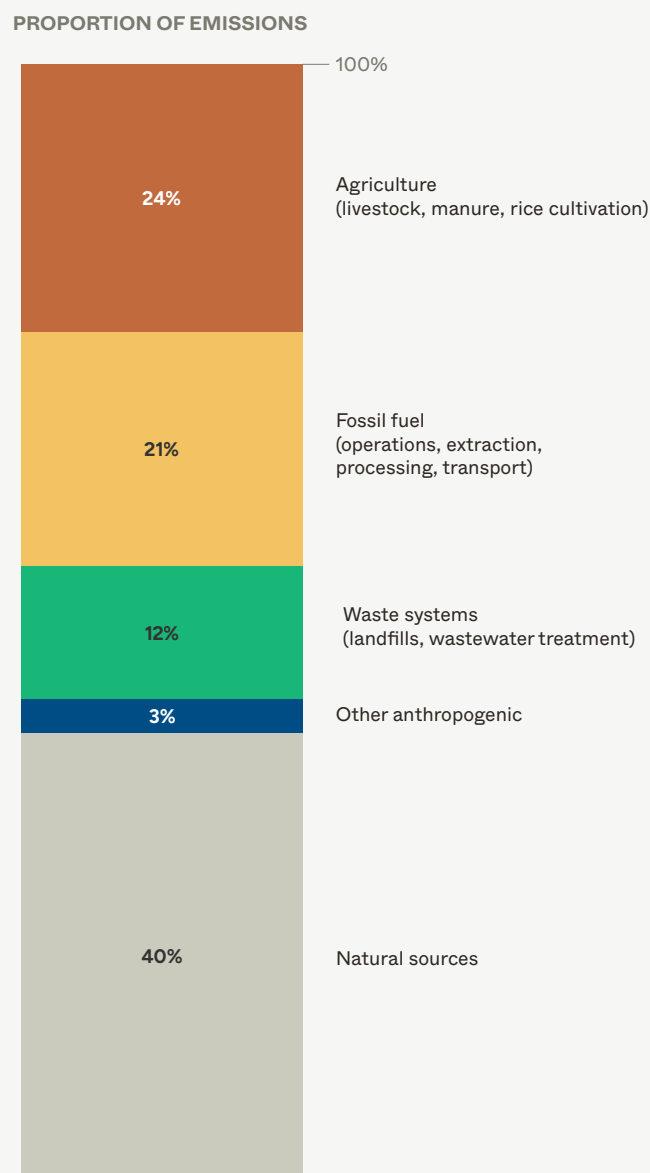
Following carbon dioxide, methane (CH₄) is the second-largest contributor to anthropogenic climate change, responsible for approximately 30 percent of gross warming since pre-industrial times.¹⁵ Front-loaded potency is its most important characteristic: over 20 years, one ton of methane traps as much heat as approximately 80 tons of carbon dioxide (GWP-20) while it is 28 tons when integrated over a century (GWP-100) as the gas naturally breaks down.¹⁶ That short-lived but intense warming means that reductions today produce discernible temperature benefits within decades. Methane is also a key precursor gas of tropospheric ozone, which is itself a superpollutant with significant negative effects on human health, agricultural yields, and ecosystems.¹⁷ Therefore, reductions in methane emissions have the added benefit of reducing ozone-related harms.¹⁸

More than 60 percent of annual methane emissions today come from human (anthropogenic) activities, with roughly 95 percent of those concentrated in three sectors.¹⁹ *Agriculture* is the largest source of anthropogenic methane, at approximately 40 percent, generated largely by livestock, manure, and rice cultivation.²⁰ *Fossil fuel operations* (extraction, processing, and transport) contribute about 35 percent through fugitive leaks, venting, and flaring.²¹ *Waste systems*, primarily landfills and wastewater treatment, add around 20 percent through organic matter decomposition in oxygen-limited environments.²² A smaller but still meaningful share of total emissions comes from *land use and land management practices*, such as creating reservoirs, draining peatlands, and altering wildfire patterns.²³

The remaining roughly 40 percent of total global methane flux comes from *natural sources*, principally wetlands, permafrost thaw, and freshwater systems. In fact, wetland emissions are themselves sensitive to warming, meaning that continued climate change

could increase natural methane output further, compounding the anthropogenic signal rather than remaining a fixed background contribution.²⁴ These natural sources are typically among the most difficult emission flows to quantify and mitigate. Atmospheric methane removal technologies that could address these sources are an emerging field of research.²⁵

FIGURE 1: SOURCES OF GLOBAL METHANE



SOURCE: Carbon Containment Lab analysis of United Nations Environment Programme and Climate and Clean Air Coalition (2021). Global Methane Assessment: Benefits and Costs of Mitigating Methane Emissions. Nairobi: United Nations Environment Programme.



Significant methane reductions are already baked into most climate models yet investments remain minimal.

The IPCC goal of limiting end-of-century peak warming to 2°C (modeled as the Shared Socioeconomic Pathway: Sustainability (SSP1-2.6)), assumes a 46 percent reduction in methane emissions by 2050. The technical means to achieve these goals are largely available and cost-effective today.²⁶ Since most anthropogenic methane emissions are concentrated in specific sectors, mitigation strategies can be highly targeted and actionable. We identified 60 different methane mitigation measures, most of which are already tested, and many of which can rapidly scale up (detailed in Appendix B). Within the fossil fuel industry, for example, standard interventions such as systematic and regular leak detection, the elimination of routine venting and flaring, and the replacement of high-bleed pneumatic equipment can abate emissions at near-zero net cost,²⁷ as the recovered natural gas retains its commercial value.²⁸ In agriculture, dietary additives have demonstrated substantial methane reductions of up to 80 percent in livestock trials, while improved manure management systems capture and treat methane before it escapes into the atmosphere.²⁹ Similarly, the waste sector can prevent emissions through landfill gas capture and utilization or the diversion of organic waste from landfills.³⁰

As methane is an important precursor gas for the formation of tropospheric ozone, mitigating it provides a combined benefit toward both superpollutants and often generates multiple localized benefits for health and safety as well.

Nitrous Oxide

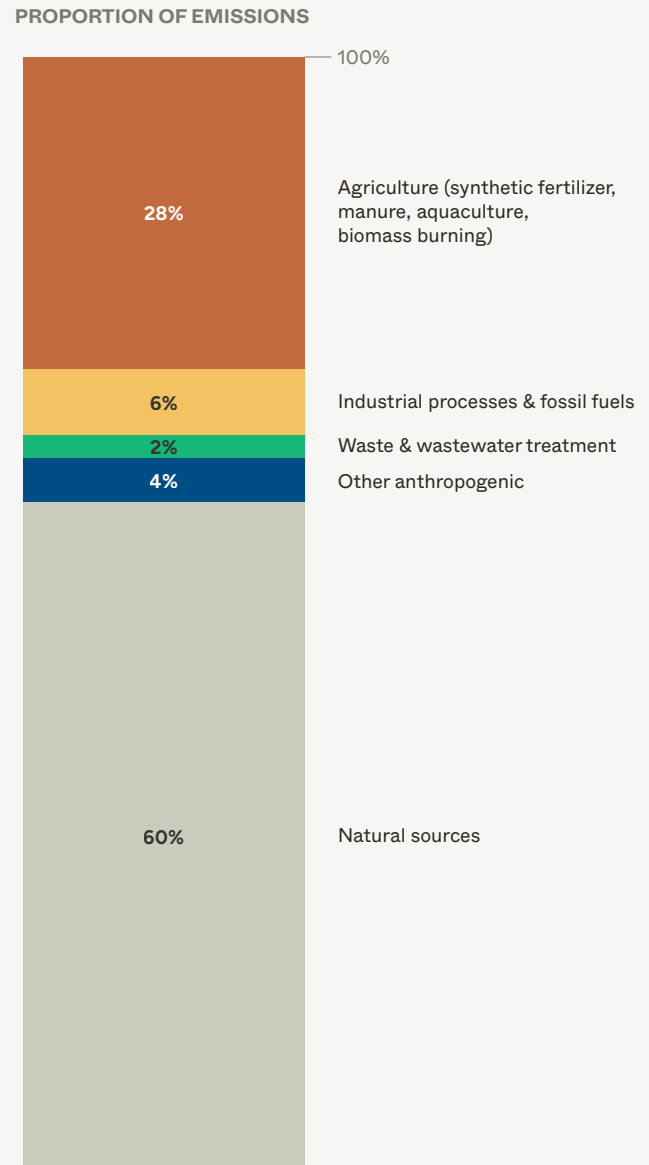
Nitrous oxide (N₂O) is responsible for approximately 10 percent of net global warming since the start of the Industrial Revolution. It has an atmospheric lifetime of 109 to 120 years, which makes it longer lived than most other superpollutants.³¹ Its GWP of 273 holds constant across both 20- and 100-year measurement horizons, a reflection of that stable, persistent warming.³² Nitrous oxide is also an ozone-depleting substance. It reacts in the stratosphere to form nitrogen oxides, which then catalyze the destruction of the ozone layer. To date, nitrous oxide is not controlled under the Montreal Protocol, the treaty framework built specifically to address ozone-depleting substances. This omission leaves its ozone impact effectively unregulated even as its atmospheric concentration continues to rise.³³

Nitrous oxide is emitted from both anthropogenic and natural sources. Roughly 40 percent of total nitrous oxide emissions are anthropogenic, equivalent to approximately 6 percent of annual global greenhouse gas emissions.³⁴ The largest source of anthropogenic nitrous oxide is agriculture, where direct soil emissions from synthetic fertilizer application, manure management, aquaculture, and biomass burning contribute more than 70 percent of net anthropogenic nitrous oxide emissions.³⁵ Industrial processes and fossil fuels (a combined 16 percent) as well as waste and wastewater treatment (about 5 percent) are the next-largest contributors to net anthropogenic nitrous oxide emissions and are typically point sources.³⁶

Nitrous oxide is also a natural product of the nitrogen cycle—its movement between the atmosphere,

plants, animals, soil, and water.³⁷ Most natural nitrous oxide emissions come from bacteria that break down nitrogen in soils and oceans.³⁸

FIGURE 2: GLOBAL NITROUS OXIDE SOURCES



SOURCE: Carbon Containment Lab analysis of United Nations Environment Programme (2024) Global Nitrous Oxide Assessment



The IPCC's modeled target of limiting end-of-century peak warming to 2°C (SSP1-2.6) assumes a one-third reduction in nitrous oxide emissions by 2050. Industrial and energy sectors hold some of the most immediate, cost-effective abatement opportunities available, particularly in industrial gas production of nitric acid, adipic acid, and caprolactam, where nitrous oxide is an unwanted by-product (as described in Appendix F: Voluntary Carbon Market Case Studies). Installing available pollution control technologies at these facilities could abate 116 million tons of carbon dioxide-equivalent (CO₂e) a year by 2030. Two-thirds of this amount is potentially achievable at \$0.50 to \$5 per ton CO₂e.³⁹ This combination of proven technology, low cost, point source, and modest current uptake makes industrial nitrous oxide abatement one of the clearest near-term priorities among the available pathways.

The agricultural sector can also drastically cut nitrous oxide emissions through targeted management. The 4R framework (right source, right rate, right time, right place) pairs reduced nitrogen application rates with enhanced efficiency fertilizers and has been shown to cut total nitrous oxide emissions by more than half without affecting yields.⁴⁰ These reductions can be achieved at low gross mitigation cost (as fertilizer savings offset a substantial portion of the implementation costs) while generating net savings of roughly \$85 per ton of CO₂e when including societal benefits.⁴¹ Underlying practices are also well-established. However, since nitrous oxide emissions also arise from dispersed, highly variable field conditions, soil type, precipitation, and fertilization patterns, conducting baseline measurement and verification is substantially harder than for industrial point sources.⁴² Many of the nitrous oxide mitigation measures also contribute to the reduction of tropospheric ozone.

Ozone-Depleting Substances and F-gases

Ozone-depleting substances (ODS) and fluorinated gases (F-gases) are related classes of synthetic, fluorine-containing compounds used primarily in air conditioning, refrigeration, insulation, electronics, and industrial manufacturing as well as the production of commodity materials such as aluminum. Both classes share an extraordinary chemical stability and potent heat-trapping ability, making them industrially valuable but climatically hazardous.⁴³ The rest of this report refers to this group of gases broadly as “F-gases.”

Chlorofluorocarbons (CFCs) and **hydrochlorofluorocarbons (HCFCs)** were developed during the 20th century for use as refrigerants in air conditioning and refrigeration, aerosol propellants, and blowing agents in foam manufacturing. Due to their chemical stability, they persist in the atmosphere long enough to migrate to the stratosphere, where they catalyze ozone destruction, thinning the ozone layer.⁴⁴ They are also extraordinarily effective at trapping heat: common CFCs carry a GWP-20 of 8,320 (CFC-11), 12,700 (CFC-12), and 6,860 (CFC-113), respectively.⁴⁵ CFC production has been fully phased out under the Montreal Protocol. Meanwhile, HCFCs are in the final stages of phaseout, with developed countries targeting full elimination by 2030 and developing countries by 2040.⁴⁶ Nonetheless, 3.8 million tons of ODS (about 6.8 billion tons of CO₂e)⁴⁷ are estimated to be sitting in old equipment and stockpiles and will reach the atmosphere unless recovered and destroyed.

Hydrofluorocarbons (HFCs) were developed to replace ozone-depleting substances. HFCs do not deplete the ozone layer, but they remain extremely potent greenhouse gases and today represent approximately 90 percent of F-gas by volume and emissions. There are hundreds of different HFCs and HFC blends developed for different applications. Common HFCs are highly potent and have a wide range of atmospheric lifetimes (Appendix A). For example, HFC-32 (prevalent in residential air-conditioning systems) has a GWP-20 of 2,690, HFC-134a (used in automotive air conditioning) has a GWP-20 of 4,140 and HFC-143a (prevalent in commercial refrigeration) has a GWP-20 of 7,840.⁴⁸ The Kigali Amendment restricts the production of high GWP HFCs. It is expected to limit projected HFC-induced warming in 2100 by around 90 percent compared to a no HFC policy case.⁴⁹ However, as with ODS, the bank of HFC emissions sitting in equipment and stockpiles continues to grow rapidly and will eventually be released into the atmosphere absent intervention. Other macro factors related to growing demand and economic development are expected to cause the cooling sector to account for more than 10 percent of total global emissions in 2050.⁵⁰

ODS and F-gases share an extraordinary chemical stability and potent heat-trapping ability, making them industrially valuable but climatically hazardous.

Hydrofluoroolefins (HFOs) represent a newly developed subclass of HFCs that break down in the atmosphere within days, resulting in ultra-low GWP.⁵¹ For example, the widely adopted HFO-1234yf (used in automotive air conditioning) carries a GWP-20 of 1.81, and HFO-1234ze(E) (used as a foam blowing agent and aerosol propellant) has a GWP-20 of 4.94.⁵² HFOs do not deplete the ozone layer, though they typically exhibit mild flammability, requiring safety features in system design.⁵³ Also, HFOs belong to the broader class of per- and polyfluoroalkyl substances (PFAS), and their atmospheric degradation produces trifluoroacetic acid (TFA), a persistent environmental contaminant that accumulates in water systems and soils.⁵⁴ The growing evidence of its impact on the environment and human health has prompted scientific and regulatory scrutiny, including restrictions under the emerging European Union's PFAS rules.⁵⁵

Perfluorocarbons (PFCs) are fully fluorinated compounds with extraordinary atmospheric longevity, making their cumulative warming impact disproportionate to their emission volume.⁵⁶ The main sources are from primary aluminum and semiconductors production.⁵⁷ PFCs carry high 20-year and 100-year GWPs. For example, CF₄ (PFC-14)

has a GWP-20 of 5,300 and a GWP-100 of 7,380. Abatement efforts in the aluminum industry have sharply reduced PFC emission intensity since the 1990s. However, total global PFC emissions have continued to grow in recent years, primarily due to rising aluminum production in China.⁵⁸

Sulfur hexafluoride (SF₆) is the most potent greenhouse gas currently known, carrying a GWP-20 of 18,200, a GWP-100 of 24,300,⁵⁹ and an atmospheric lifetime of up to 3,200 years.⁶⁰ It is used primarily as an electrical insulator in high-voltage switchgear and transmission equipment as well as in magnesium foundries and semiconductor manufacturing. Gases can escape through aging seals, small pipeline leaks, routine maintenance, refilling processes, or catastrophic equipment failure.⁶¹ Global SF₆ use has been rising as power grids expand to support both economic growth and renewable energy deployment, particularly in emerging economies, where new wind and solar installations require substantial new high-voltage switchgear.⁶² SF₆ represents a small share of total F-gas emissions by volume, but its extreme potency means that mitigation efforts such as promoting substitutes or stopping leaks should be a priority.



Lifecycle refrigerant management is estimated to potentially avoid an additional 39 billion tons of CO₂e from 2025 to 2050.

Nitrogen trifluoride (NF₃) is another highly potent gas which is used in the semiconductor industry as a plasma etchant and chamber cleaning agent, with a GWP-20 of 13,400 and a GWP-100 of 17,400.⁶³ Its atmospheric lifetime is approximately 569 years and it has been mandated for inclusion in national greenhouse gas inventories under the UNFCCC since 2013.⁶⁴ NF₃ represents the smallest of the F-gas classes by total emissions volume, but its use has grown alongside the expansion of global semiconductor manufacturing capacity.⁶⁵

Unlike methane and nitrous oxide, ozone-depleting substances and F-gases are entirely synthetic, meaning every molecule in the atmosphere originates from human production rather than natural background sources. This quality gives policymakers and companies a more direct lever over both ends of the life cycle. In other words, production can be capped or banned outright, controls implemented to stop leaks and fugitive emissions, and existing banks can be actively recovered and recycled or destroyed. Reflecting this greater degree of control, SSP1-2.6, the IPCC scenario consistent with limiting end-of-century warming to below 2°C, assumes a more than 87 percent reduction in F-gas emissions by 2050.

The main mitigation measures for ODS and F-gases fall into three interconnected areas: reducing cooling demand, transitioning to low- or zero-GWP gases and equipment, and managing the gases across their full life cycle.⁶⁶ All of these complement the production phase downs in place under international policy. Passive measures, such as better insulation and shading, optimized temperature settings, and better system controls, can reduce the amount of cooling and therefore volume of gases required in the first place. Transitioning technologies from high-GWP refrigerants and equipment to low- and zero-GWP alternatives while maintaining energy efficiency can prevent both direct and indirect energy-related emissions. Lifecycle refrigerant management (LRM) is essential for addressing the large quantity of ODS and F-gases already in equipment and stockpiles. Leak prevention and good servicing practices can reduce emissions during operation.⁶⁷ Recovery, recycling, and reclamation reduce demand for virgin refrigerant while equipment still has a useful life, and environmentally sound destruction can remove high GWP and ODS gases from circulation to ensure they are never released into the atmosphere. LRM is estimated to potentially avoid an additional 39 billion tons of CO₂e from 2025 to 2050 beyond Kigali, making it a major untapped F-gas mitigation opportunity.⁶⁸

Tropospheric Ozone

Tropospheric or “ground level” ozone is a secondary or “indirect” pollutant—it forms in the lower atmosphere through a series of chemical reactions involving precursor gases: methane (CH₄), nitrogen oxides (NO_x), non-methane volatile organic compounds (NMVOCs), and carbon monoxide (CO). Molecular hydrogen (H₂) also plays a smaller, indirect role through its effects on atmospheric hydroxyl radical (OH) chemistry.⁶⁹ Tropospheric ozone’s location distinguishes it from stratospheric ozone, the protective layer in the upper atmosphere that absorbs ultraviolet radiation. The two are chemically identical but functionally opposite—that is, protective at altitude, harmful at ground level. Alongside carbon dioxide and methane, tropospheric ozone is among the largest contributors to anthropogenic warming.⁷⁰

Precursor emissions for tropospheric ozone span the global economy. Nitrogen oxide emissions come from both fossil fuel combustion (coal combustion, vehicle exhaust) and non-fossil sources (biomass burning, microbial nitrogen cycling in soils and animal waste).⁷¹ Industrial solvents and chemical manufacturing contribute significantly to NMVOCs, particularly in East Asia and Europe.⁷² Agricultural burning is a major source of NMVOCs and carbon monoxide across sub-Saharan Africa and Brazil.⁷³ While these non-methane precursors are vital to address, methane holds a distinct role: because its decadal atmospheric lifetime allows it to mix globally before breaking down, it generates a persistent background level of tropospheric ozone worldwide, rather than the regional, short-lived ozone spikes associated with some of the other precursor gases. This global reach is why methane mitigation is highlighted as a standout option for reducing surface ozone levels broadly, complementing the need to address regional precursor emissions.⁷⁴

Protective at altitude and harmful at ground level, ozone needs careful management to protect both climate and health.

The effects of tropospheric ozone on human populations and ecosystems extend well beyond the climate. By 2030, ozone-induced crop yield losses are projected to be 5 to 26 percent for wheat and 4 to 9 percent for maize under business-as-usual scenarios.⁷⁵ Further, prolonged tropospheric ozone exposure is associated with approximately 1.4 million deaths a year globally, an all-cause mortality estimate substantially higher than prior figures based on respiratory disease alone.⁷⁶ Short-term exposure is separately associated with an estimated 177,000 deaths a year.⁷⁷

Under the 2°C scenario, the IPCC assumes aggressive, globally coordinated air quality policy, supported by stricter pollution control legislation and expanded access to clean cooking fuels, will substantially reduce these precursor emissions. Action on precursor gases can be achieved today; a list of these can be found in Appendix B. Given the regional variation in many of the precursor emissions and their impact, localized analysis of mitigation measures is recommended. Mitigation measures include some that are already on corporate sustainability agendas such as electrifying vehicle fleets and using low-VOC materials and paints. In addition, industrial and power-sector pollution controls are available and already mandated in many countries or states.

Black Carbon

Black carbon, unlike the other pollutants in this roadmap, is not a gas. Commonly known as soot, black carbon is a fine, solid particulate produced by the incomplete combustion of carbon-based fuels, including biomass, coal, and diesel, among other sources.

Black carbon is a major contributor to poor air quality resulting in immediate and negative health impacts. Prolonged exposure to black carbon is associated with a 6.8 percent increased risk of cardiovascular disease. And ambient particulate matter in the air less than 2.5 microns (PM_{2.5}), of which black carbon is a disproportionately hazardous component, is linked to an estimated 4.7 million premature deaths globally each year.⁷⁸

Black carbon's climate effect is variable, depending on emission altitude, co-emitted pollutants, and interactions with clouds and snow or ice surfaces.⁷⁹ It has an atmospheric lifetime of only days to weeks,⁸⁰ the shortest of any major climate pollutant, which means emissions reductions today produce a

measurable atmospheric response within days rather than decades. However, the effects can be difficult to measure against a baseline given variability in conditions. See Appendix A for an explanation of black carbon and GWP metrics.

A concentrated set of sources produce anthropogenic black carbon emissions. *Residential solid fuel combustion*, practiced by nearly one-third of the global population for heating and cooking, contributes nearly half of anthropogenic black carbon emissions⁸¹ and is also the leading cause of household air pollution, responsible for an estimated 3.7 million premature deaths annually.⁸² *Transportation* is the next-largest source, accounting for roughly one-quarter of anthropogenic emissions, generated primarily by diesel combustion in road vehicles and maritime shipping.⁸³ When black carbon is directly deposited at high latitudes, it accelerates regional ice melt with consequences for security and Arctic ecosystems. *Industrial sources*, especially brick kilns and coke ovens in China and South Asia, are also significant; these industries together account for nearly 79 percent of China's total black carbon output.⁸⁴ *Unvented kerosene lamps* and *gas flaring* at oil and gas facilities are smaller but locally significant sources.



Effective black carbon interventions require a nuanced, source-specific approach. Black carbon is frequently co-emitted with organic carbon (with the ratio varying by source) which tends to reflect sunlight and cool the atmosphere rather than warm it. Climate mitigation strategies should therefore be focused on sources with the highest black-to-organic-carbon ratio.

Despite its variable effect on climate, under the 2°C scenario, the IPCC assumes black carbon emissions are reduced by more than half by 2050. Global modeling suggests that this is feasible, and specifically that fully implementing available control measures over a 20-year period could cut global black carbon emissions by as much as 80 percent, with a substantial share achievable at net cost savings.⁸⁵

Promising mitigation measures include transforming vehicles and shipping from diesel to electric and using ultra-low sulfur fuels.⁸⁶ Prioritizing retrofits on Arctic and near-Arctic shipping routes may offer a disproportionate climate return because of deposits of soot settling directly onto snow and ice, reducing reflectivity (albedo effect) and causing greater localized warming impact.⁸⁷

In the residential sector, clean cookstove programs can deliver net cost savings of approximately \$6 per

ton of CO₂e even before accounting for health benefits and directly reducing the household air pollution burden.⁸⁸ Sources with the largest health burden, regardless of their net warming effect, remain the clearest public health priority.

These five superpollutants collectively have a defining strategic property: they are responsible for a disproportionate share of near-term warming and the technology to abate them is available now, in many cases at low or negative net cost. That combination—outsized near-term climate impact paired with mature, deployable solutions—is precisely what makes superpollutants a distinct opportunity for corporate climate strategy. This potential is separate from, and complementary to, carbon dioxide reductions. The scientific and technical case established in this chapter is, on its own, not yet a strategic one. It defines superpollutants and why their physics matter; it does not yet articulate whether companies are seizing that opportunity, why they should, or how.

The following chapters take up each of those questions in turn.



02

The State of Corporate Superpollutant Action



Corporate climate action to date has focused overwhelmingly on carbon dioxide. It has also stalled in the two GHG Protocol Scopes where superpollutants are most prevalent—Scope 1 and Scope 3. A recent report shows that 58 percent of S&P 500 companies with a stand-alone Scope 1 target report flat or rising Scope 1 emissions, and 62 percent report flat or rising Scope 3 emissions.⁸⁹ Simultaneously, economic conditions are forcing greater capital discipline, and increasingly prescriptive standards have created greater transparency into results.

Superpollutants are the abatement class best matched to those emergent conditions. For companies in the sectors where superpollutants concentrate, acting on them is becoming less an opportunity than a condition of delivering the targets they have already set. And for companies without as much direct exposure, numerous opportunities exist to contribute to climate stabilization at relatively low marginal abatement costs and meaningful scale.

Companies are naming the gases without setting goals against them

A decade of corporate climate action has produced more than 10,000 science-based targets and 1,900 net-zero commitments.⁹⁰ To date, few superpollutant-specific strategies have emerged.

A Carbon Containment Lab review of public climate disclosures from 40 large companies⁹¹ in sectors with superpollutant exposure—oil and gas, retail, food and consumer products, technology and media, and finance—found the great majority of companies name these gases at least once in their sustainability reporting, most commonly as a bundled component of their emissions footprints. Eighty-eight percent of the 40 companies name methane, 75 percent name F-gases or refrigerants, and 63 percent name nitrous oxide. But few set a goal against them. Only 13 of the 40 companies presented a quantified methane target, six an F-gas target, and one a nitrous oxide target.

TABLE 2: SUPERPOLLUTANT DISCLOSURE CONVERTS INTO TARGETS AT A DECLINING RATE

Gas	Names the gas	Holds a target	Conversion rate
Methane	35/40 (88%)	13/40 (33%)	37%
Methane (excl. oil and gas)	24/29 (83%)	2/29 (7%)	8%
F-gases	30/40 (75%)	6/40 (15%)	20%
Nitrous oxide	25/40 (63%)	1/40 (3%)	4%

The conversion rate falls as the gas becomes harder to detect and control: 37 percent for methane, 20 percent for F-gases, and 4 percent for nitrous oxide. That ordering tracks the practical difficulty of each case—concentrated and increasingly regulated point sources, diffuse equipment leakage spread across owned and leased estates, and dispersed agricultural emissions sitting several tiers up a supply chain or downstream in mixed waste facilities.

The methane targets also rest almost entirely on a single sector and appear to respond to existing or pending regulation. Eleven of the 13 methane targets belong to the oil and gas companies in the scan, where the EU Methane Regulation, the Oil and Gas Decarbonization Charter, and Oil & Gas Methane Partnership 2.0 (OGMP 2.0) have made methane intensity targets close to a condition for operations.⁹² Outside oil and gas, only two of 24 companies that name methane set a target against it. Setting superpollutant targets is therefore nearly absent except where policy has already compelled it.

Interviews with corporate practitioners conducted for this roadmap describe the same gap from the inside. Sustainability teams understand that superpollutants exist across their Scope 1, 2, and 3 footprints, and many can identify the major sources. But they have yet to lean into mitigating them.

They lack the elements that enable goal setting—a credible methodology for how superpollutant reductions count toward existing climate commitments, and clarity on how to fold superpollutant action into climate plans that took years to negotiate internally.⁹³

Where companies are embracing value chain intervention, voluntary carbon markets, and policy engagement on carbon dioxide at scale, they are only beginning to do so on superpollutants.

- 
- Value Chain Intervention: Pilots rather than portfolios.** In the sectors where superpollutants concentrate—food and agriculture, refrigeration and cooling, energy, and waste—value-chain interventions are typically described in publicly available reports and press releases as pilots rather than portfolio commitments. Consistent with standard reporting guidelines, most large food companies express climate goals in aggregate carbon dioxide-equivalents and treat methane and nitrous oxide interventions as discrete projects rather than managed programs. Refrigerant transition planning exists, but adoption trails ambition. Across the largest U.S. supermarket chains, only three of 16 received passing scores on Environmental Investigation Agency’s (EIA) 2024 Climate-Friendly Supermarkets Scorecard. The sector average for annual HFC leak rate sits at roughly 25 percent, exceeding the level that EPA’s voluntary GreenChill program treats as best practice by fivefold—yet just five of the 16 companies even disclose their leak rate.⁹⁴
- 
- Voluntary Carbon Markets: Capital is not reaching superpollutants at scale.** Superpollutant credits remain a small share of issuance and retirement, and the methodologies and supply pipeline needed to change that pattern are only now being built at scale. The most frequently cited pressure on corporate climate targets is financial rather than technical. Fifty-five percent of executives polled by The Conference Board identified capital allocation, cost, or return on investment as a factor likely to prompt significant adjustment or delay, ahead of evolving regulatory requirements (45 percent) and technology readiness (37 percent).⁹⁵
- 
- Policy Engagement: Advocacy trails corporate ambition.** Oftentimes, companies hold publicly supportive climate positions while powerful trade associations engage in regressive advocacy. S&P Global’s Corporate Sustainability Assessment, which evaluated disclosures from 12,813 public companies across 62 industries in 2024, finds that 82 percent of companies have not aligned their lobbying and trade association activities with the Paris Agreement and just 2 percent have a process to address misalignments between their position and the climate change policies of trade associations.⁹⁶ This impact compounds when 65 percent of U.S.-based industry associations “are engaging highly negatively on climate policy,” as found by InfluenceMap’s analysis.⁹⁷ For example, lobbying against the EU Methane Regulation came predominantly from industry associations seeking to delay implementation, dilute leak-detection standards, and weaken coverage for imported gas.⁹⁸ When the regulation was at risk, it was a coalition of 44 institutional investors representing more than €4.85 trillion in assets that wrote publicly to defend it.⁹⁹ Another constructive exception is F-gases, where manufacturers and refrigerant producers supported the Kigali Amendment and the U.S. AIM Act because a predictable global phase-down levels the playing field and protects against high-GWP imports.¹⁰⁰

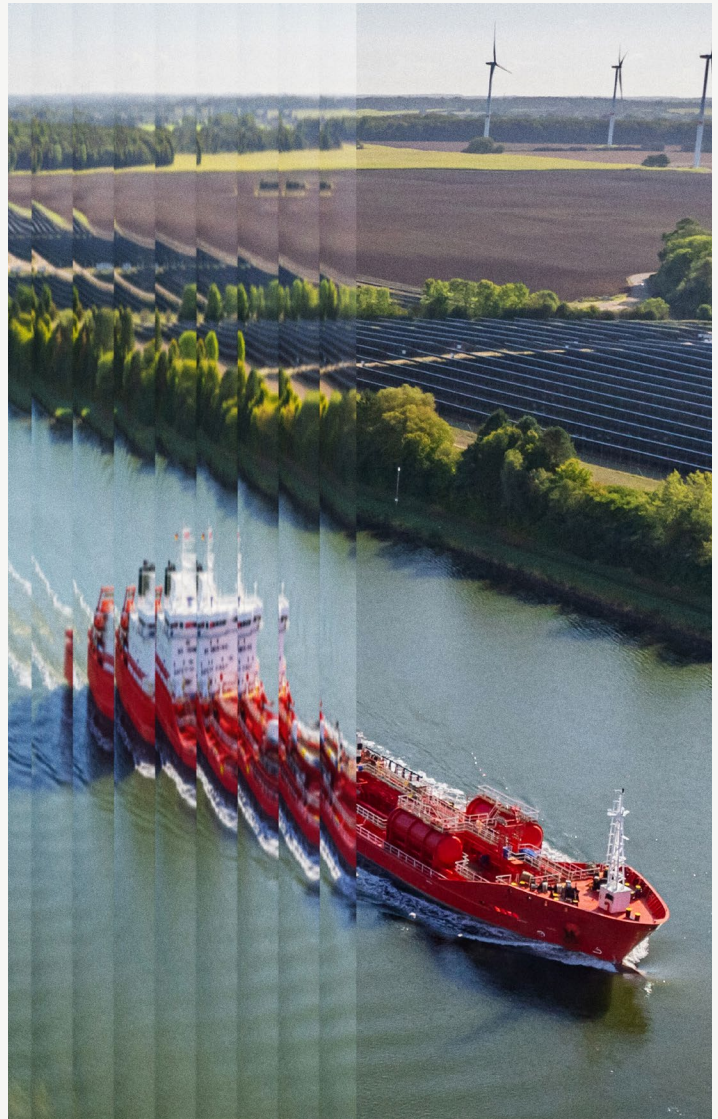
Narrowing the gap between internal ambition and external voice is, on its own, one of the largest potential opportunities. It costs little, if anything, for companies and can shift entire markets rather than individual project portfolios.

The gap persists for reasons specific to superpollutants

SBTi's Corporate Net-Zero Standard required companies to include methane, nitrous oxide, and F-gases inside their carbon dioxide equivalent targets, but it did not mandate separate targets for any individual gas.¹⁰¹ The GHG Protocol's corporate standard did not require Scope 3 disclosure and did not provide standardized, mandatory treatment of facilitated emissions.¹⁰² The major net-zero frameworks, therefore, have created uncertainty about how superpollutants fit into strategy by bundling them within "aggregate GHG" rather than as a distinct category necessitating separate action. Further, they offered little specific guidance on how to set targets, measure progress, or close data gaps.

Until recently, companies could set a combined Scope 1 and Scope 2 target under the SBTi, allowing cleaner electricity procurement to carry flat operational emissions. That matters because superpollutants sit almost entirely outside Scope 2. Fugitive methane from oil and gas systems, refrigerant leakage from cooling and process equipment, fluorinated gas emissions from semiconductor and electronics manufacturing, and sulfur hexafluoride from electrical transmission and distribution equipment are all Scope 1 for many companies. Enteric and manure methane, rice methane, industrial and fertilizer-driven nitrous oxide, supplier F-gas emissions, and waste methane are usually all Scope 3. The scope where corporate reductions have been most readily available, renewable electricity Scope 2, is also the one scope in which these gases barely appear.

Measurement has also compounded the accounting problem. A carbon dioxide inventory can be built from purchase records, because combustion emissions generally follow fuel consumed. Superpollutant emissions are different because they most commonly leak from equipment, escape during maintenance, and sometimes vary with weather, herd, and soil. Estimating these emissions from activity and financial data with default emission factors produces numbers that are challenging to anchor a public target. Recent technological developments have included source-level monitoring, reporting, and verification (MRV), which can resolve that uncertainty at a commercial scale while footprinting standards for superpollutants catch up.



Accounting that treated superpollutants as a subset of aggregate CO₂e is being replaced by scope-level targets with full coverage.

Changing rules are impacting superpollutant footprints

The SBTi Corporate Net-Zero Standard Version 2.0, effective February 1, 2027, removes the combined-scope option for larger companies. Category A companies shall set separate Scope 1, Scope 2, and Scope 3 targets, and near-term Scope 1 targets shall cover 100 percent of Scope 1 emissions, with no materiality carve-out. (Companies may continue to set targets under Version 1.3.1 until January 31, 2028.)¹⁰³

By early 2028, therefore, every large company with material fugitive methane, refrigerant leakage, or industrial F-gas emissions validating a target under Version 2.0 will hold a stand-alone, fully covered Scope 1 target. In refrigeration-intensive retail, upstream oil and gas, semiconductor manufacturing, chemicals, and electrical equipment, superpollutants will constitute a visible share of that new target. The issue facing those companies is not whether superpollutants belong in their climate strategy. It is how quickly they can build the measurement,

abatement, and procurement capabilities to deliver against a target.

A second new provision extends the same logic across the full target horizon. Where emissions remain at the net-zero target year, the revised standard requires that residuals of long-lived greenhouse gases be neutralized with long-lived removals, while residuals of shorter-lived gases may be neutralized with short-lived removals or a combination of both. It also assigns companies direct and unshareable responsibility for neutralizing Scope 1 residuals.¹⁰⁴ An implication for companies carrying sulfur hexafluoride in transmission and distribution equipment or perfluorocarbons in semiconductor manufacturing, for instance, is that eliminating emissions at source is the cheaper option when evaluating current capital decisions. The same financial trade-off analytics will need to be applied to all other capital decisions with greenhouse gas footprints.

Each of these shifts answers the dynamic that preserved the gap between awareness and action: accounting that treated superpollutants as a subset of aggregate CO₂e is being replaced by scope-level targets with full coverage and a neutralization requirement keyed to atmospheric lifetime. The source-level measurement that fugitive and diffuse emissions have always required, and rarely had, is now increasingly available through satellite and continuous-monitoring systems.

Pathfinder companies show moving from awareness to action is a matter of choice

In every sector we evaluated, a small group of companies has taken serious action. While they remain the exception, they offer the strongest case that what separates them from their peers is choice rather than capability.

Three characteristics recur. Companies act where the gas is concentrated and measurable, rather than where the aggregate footprint is largest. They treat superpollutants as a managed program with a baseline, a target date, and an accountable owner, not as a pilot. And several act on pollutants that their own operations do not generate, beyond their value chain.

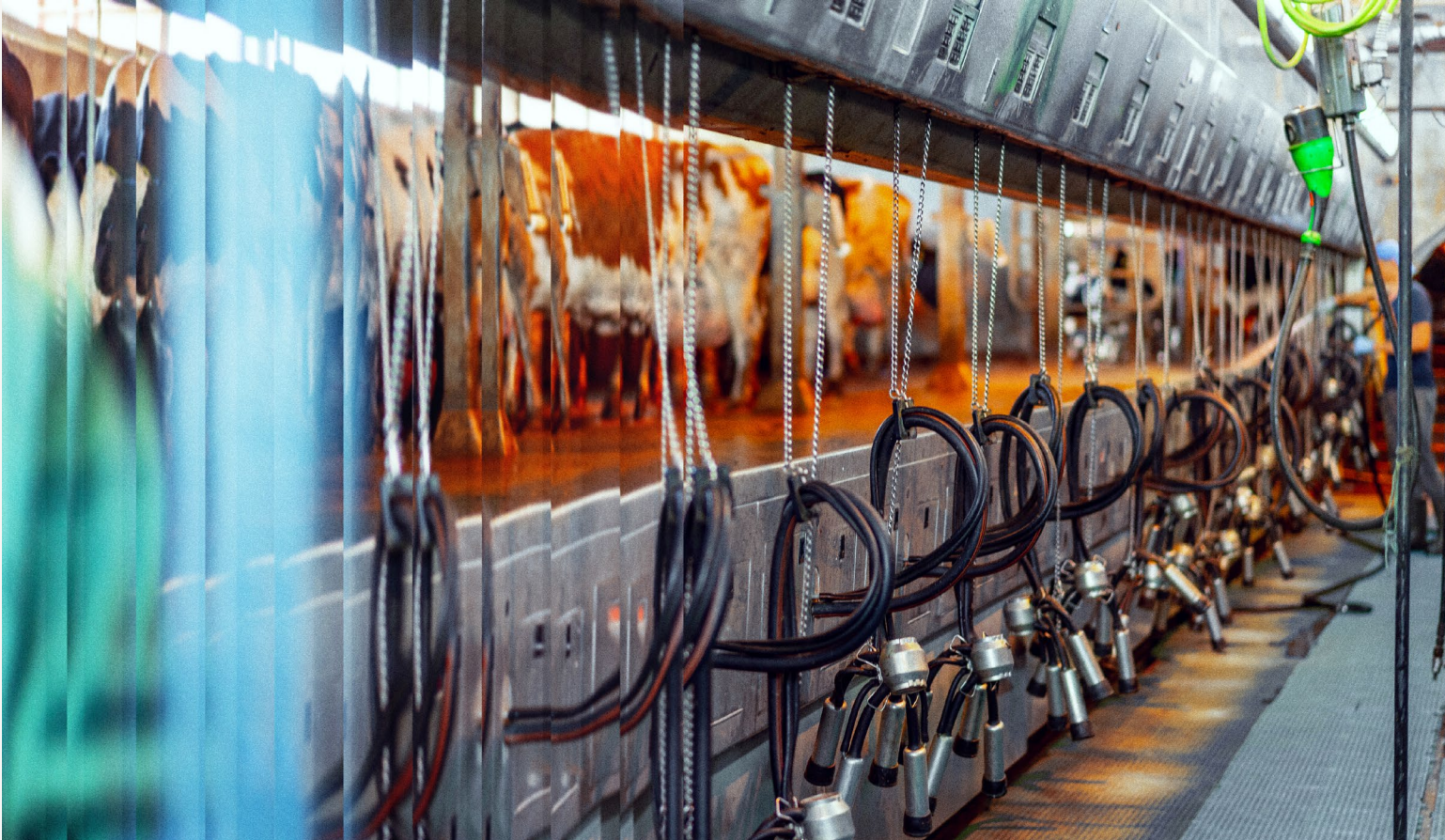


TABLE 3: PATHFINDER EXAMPLES

Company	Superpollutant	Action
ALDI	F-gases	Committed to transition U.S. store network to natural refrigerants by 2035. ¹⁰⁵
Apple	F-gases	Secured commitments from semiconductor suppliers to abate at least 90 percent of F-gas emissions by 2030. ¹⁰⁶
Costco	F-gases	Committed to cut refrigerant emissions by 30 percent by 2030 from a 2020 baseline ¹⁰⁷ and to make 50 percent of all new U.S. and Canadian warehouses use carbon dioxide-based refrigeration. ¹⁰⁸
Danone	Methane	Committed to cut methane from its fresh-milk supply chain by 30 percent by 2030. ¹⁰⁹
Google	Methane & F-gases	Contracted for credits that will eliminate more than 3 million metric tons CO ₂ e (at GWP-20) of methane and HFCs by 2030 through landfill methane destruction and HFC recovery from HVAC systems. ¹¹⁰ Pledged \$50 million through 2030 to scale superpollutant projects as a founding member of the Superpollutant Action Initiative. ¹¹¹
IKEA/Ingka Group	F-gases	Shifting new and retrofit HVAC and refrigeration equipment to natural refrigerants across global portfolio; established a program to detect and repair refrigerant leaks across the company. ¹¹²
JPMorgan Chase	Methane	Authored Methane Emissions Opportunity, with a reduction strategy for its oil and gas portfolio. ¹¹³
Rabobank	Methane	Built methane targets into agricultural lending. ¹¹⁴
WM	Methane	Set an SBTi-validated 1.5°C-aligned target to reduce absolute Scope 1 and 2 emissions by 42 percent by 2031 from a 2021 baseline, having achieved 27 percent as of August 2026. ¹¹⁵
Workday	Methane	Signed a four-year, 200,000-metric-ton offtake agreement with Tradewater to plug orphaned oil and gas wells in the U.S. Midwest. ¹¹⁶

Implications for corporate strategy

The implication for corporate strategy is not that superpollutants should be added to a list of climate priorities. It is that in the next phase, corporations must prioritize superpollutant mitigation to meet their goals. Climate stabilization requires it.

The Superpollutant Action Initiative offers an early model

A model for what this chapter calls for already exists. In March 2026, seven leading companies—Amazon, Autodesk, Figma, Google, JPMorgan Chase, Salesforce, and Workday—announced the Superpollutant Action Initiative, a commitment to deploy \$100 million through 2030 into projects that reduce methane, refrigerant gases, and black carbon. Coordinated by the Beyond Alliance and supported by the Carbon Containment Lab as research partner, the initiative is structured around five guiding principles—catalytic impact, scientific rigor, transparency, urgency, and collaboration—and explicitly designed to champion projects that would not advance without private-sector capital. Participating companies will each identify and finance high-impact projects across the sectors where superpollutants concentrate—energy, agriculture, waste, and cooling—with the Beyond Alliance providing shared research, reporting, and knowledge infrastructure. Welcoming statements from Cascade Climate, the Clean Air Fund, the Climate and Clean Air Coalition, ClimateWorks, EDF, the Global Methane Hub, and the Super Pollutant Action Alliance signal that the initiative has the necessary buy-in from ecosystem partners to attract additional participants.

The initiative addresses, in one structure, several of the gaps this chapter has diagnosed. It treats superpollutants as a distinct climate-action category rather than as a subset of aggregate CO₂e accounting. It mobilizes corporate capital toward the cheapest, fastest near-term abatement at a moment when less than 2 percent of global climate finance reaches methane. It is explicitly catalytic—designed to stand up project supply that would not otherwise be financed—which is the role corporate capital is best positioned to play. And it builds a peer cohort large enough to make superpollutant procurement a recognizable corporate behavior rather than an isolated one. As the participants themselves acknowledge, \$100 million by 2030 is a small fraction of the needed funding. But it sets a precedent that other companies can follow with relatively modest commitments and that other actors—investors, regulators, and project developers—can build around.



03

The Climate Case for Superpollutant Action



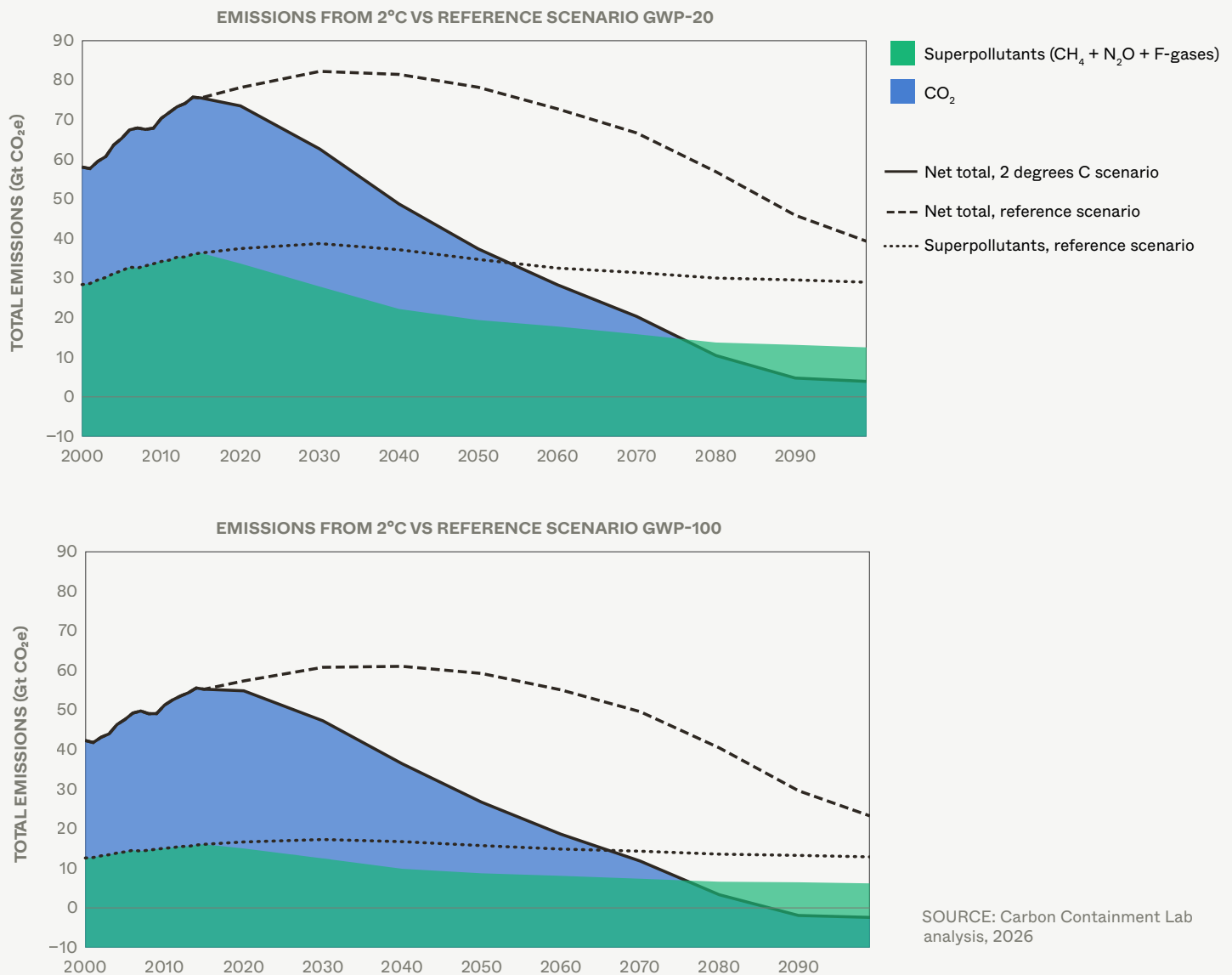
The previous chapter established that superpollutants are largely absent from corporate targets, advocacy, and capital allocation. This chapter will demonstrate the cost of their absence and scale of the mitigation opportunity ahead.

Holding warming to 2°C requires global superpollutant emissions to fall approximately 50 percent by 2050.

The pathway to 2°C assumes deep superpollutant reductions by 2050

The IPCC scenario that keeps the world below 2 degrees Celsius of warming, SSP1-2.6, has served as the corporate and political goalpost for over a decade (henceforth “2 degrees C scenario”). It embeds a near-halving of superpollutant emissions by 2050 alongside a rapid decline of carbon dioxide, as shown in Figure 3. Methane and F-gases are the largest share of the superpollutant reductions in the 2 degrees C scenario—two of the gas groups this roadmap also identifies as highly actionable by companies.

FIGURE 3: EMISSIONS BY GAS GROUP IN 2 DEGREES C SCENARIO (SOLID COLOR), COMPARED TO THE REFERENCE SCENARIO (DOTTED LINES), 2000–2100 SHOWN IN GWP-20 (TOP) AND GWP-100 (BOTTOM)



Because it concentrates the warming effect of short-lived gases like methane into a shorter 20-year window rather than averaging it out over a century, superpollutants carry more weight in GWP-20 than GWP-100. Their emissions appear larger and more front-loaded in the GWP-20 chart (Figure 3) while calculations using GWP-100 dilute their impact by spreading that same warming over a longer horizon. See Appendix A for an explanation of GWP and why it matters.

The Reference scenario (SSP2-4.5) is shown in Figure 3 as dotted lines for comparison. Superpollutant emissions in this scenario remain close to flat across the entire century, while carbon dioxide emissions continue to rise until approximately 2040 before falling to roughly half of current levels by 2100. It does not assume that superpollutant abatement is technically unavailable but that available solutions fail to attract the attention, policy, and capital required to deploy them at scale. The Reference scenario ends the century with approximately 2.7 to 2.8 degrees Celsius of warming. (Note that the reference scenario was formulated prior to the Kigali Amendment, whose implications on the model are addressed in Appendix C.)

The variation between the 2 degrees C scenario and the Reference scenario amounts to the annual reductions by 2050 shown in Table 4.

TABLE 4: MITIGATION GAP SIZE BY GAS GROUP BETWEEN THE 2°C AND REFERENCE SCENARIO, IN 2050

Gas group	Annual gap between 2°C and Reference scenario, 2050
Carbon dioxide	24.7 Gt CO ₂ / yr
Superpollutants	7.0 Gt CO ₂ e / yr

Holding warming to 2°C requires global superpollutant emissions to fall approximately 50 percent by 2050. Cumulatively, this represents

approximately 142 Gt CO₂e of avoided emissions by 2050, distributed across the three modeled superpollutant groups as shown in Table 5.

TABLE 5: CUMULATIVE REDUCTION OF SELECT SUPERPOLLUTANT GASES TO REMAIN BELOW 2 DEGREES CELSIUS

Methane	Nitrous oxide	F-gases
91.9 Gt CO ₂ e	25.7 Gt CO ₂ e	24.7 Gt CO ₂ e

Note: this does not quantify the influence of tropospheric ozone or black carbon as they are poorly suited to quantify their temperature impact. Nonetheless, these pollutants should still incur similar reductions for the support of both human and atmospheric health.

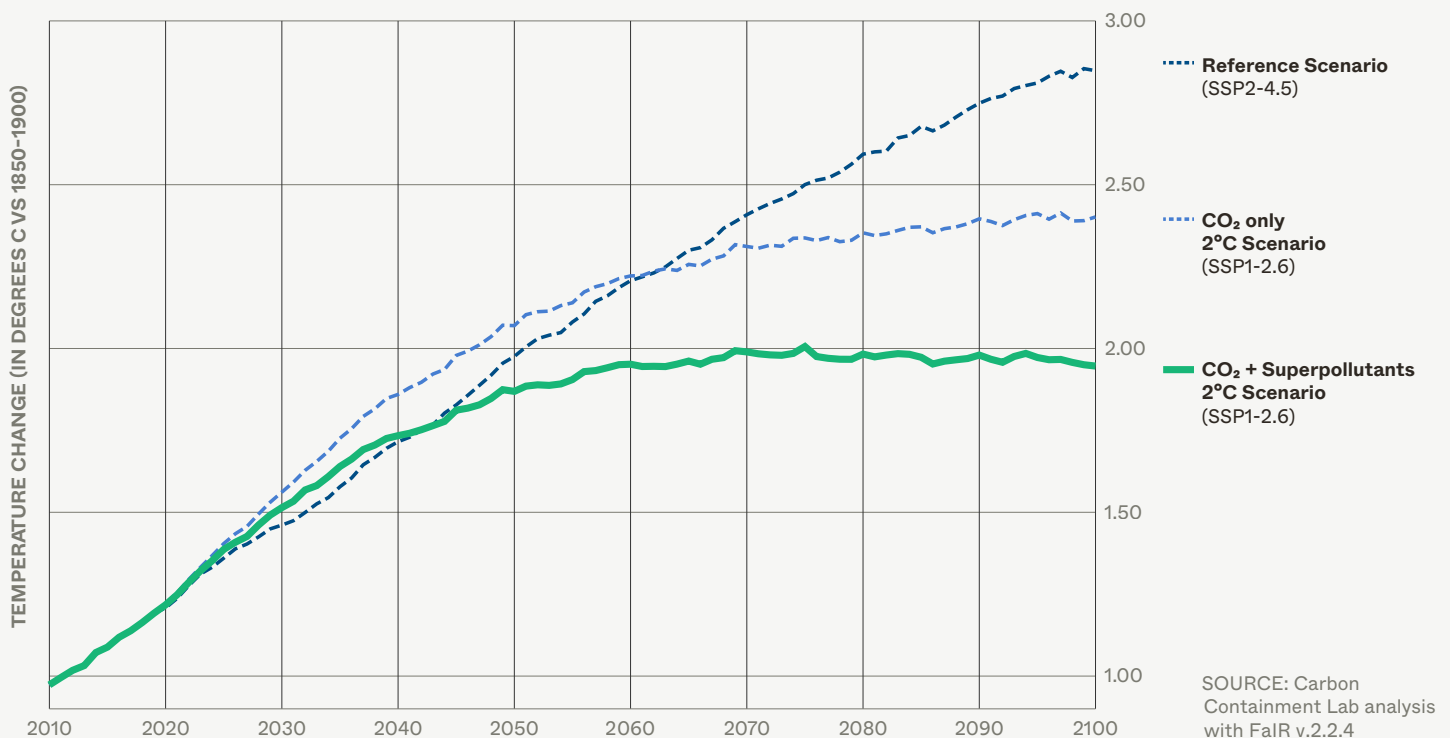
Method in brief

The Carbon Containment Lab’s modeling presented here is based on Intergovernmental Panel on Climate Change (IPCC) emission scenarios. We compared two Shared Socioeconomic Pathways: SSP1-2.6, a deep mitigation scenario consistent with holding warming below 2°C by end-of-century, and SSP2-4.5, a middle-of-the-road “business-as-usual” scenario reflecting our current trajectory. Then, we generated temperature outcomes using the FaIR model—a reduced-complexity climate model used in the IPCC Sixth Assessment Report for scenario temperature assessment. The modeled superpollutant basket comprises methane, nitrous oxide, and fluorinated gases. Black carbon and tropospheric ozone precursors are modeled but are not aggregated with the other superpollutants due to limitations of the GWP metric when applied to pollutants that are not globally well-mixed in the atmosphere. More detailed model specification and parameter choices appear in Appendix C.

Reducing warming in the near-term requires cutting superpollutants

Translating the two emissions pathways into temperature outcomes helps to isolate the contribution of each gas group—with results shown in Figure 4. Of the 0.9°C separating the two scenarios, approximately half comes from carbon dioxide and half from superpollutants.

FIGURE 4: PROJECTED TEMPERATURE CHANGES THROUGH 2100 RESULTING FROM REFERENCE SCENARIO, 2 DEGREES C SCENARIO WITH MITIGATION OF CO₂-ONLY, AND 2 DEGREES C SCENARIO WITH MITIGATION OF BOTH CO₂ AND SUPERPOLLUTANTS



All scenarios in Figure 4 show continued near-term warming, with a pronounced increase in near-term temperature associated with the CO₂-only scenario. This occurs, in part, because fossil fuel combustion co-emits sulfate aerosols, which cool the climate by reflecting sunlight. So, as we decarbonize and phase out fossil fuels, we also remove the cooling effect, which effectively “unmasks” warming that had previously been offset. Superpollutant mitigation helps dampen this effect because reducing superpollutants delivers a benefit without triggering the same aerosol trade-off. This makes superpollutant action a more direct lever for near-term mitigation than decarbonization alone.

Moreover, given their mostly short-lived atmospheric lifetimes, mitigation of superpollutants can

immediately have an effect on warming. A metric ton of methane abated in 2027 has largely ceased to influence the climate system by the 2040s, which means its comparatively outsized abatement benefit is fully realized inside the current century. Meanwhile, a metric ton of carbon dioxide abated in 2027 spreads its benefit across the following centuries.¹¹⁷ Two mitigation portfolios of identical carbon dioxide-equivalent tonnage therefore produce materially different temperature trajectories depending on their gas composition.

Each ~35 Gt CO₂e reduction in superpollutants would require about 300 Gt of CO₂ abatement to have the same temperature impact by 2050.



Implications for corporate strategy

Sequencing becomes a key strategic variable.

The analysis indicates that early superpollutant action cannot replace carbon dioxide mitigation, but it does create the runway for action. Carbon dioxide abatement in heavy industry, aviation, and long-lived infrastructure depends on capital replacement cycles measured in decades. Much of superpollutant abatement—leak detection and repair, lifecycle refrigerant management, venting and flaring elimination, industrial abatement retrofits—occurs in cycles measured in months to a few years. Acting quickly on superpollutants extends the window in which carbon dioxide can scale without peak warming (and climate tipping points) being breached in the interim. Companies with credible net-zero commitments and limited near-term options should pay particular attention.

Superpollutant action complements rather than replaces carbon dioxide action. This analysis supports treating short- and long-lived gases along different time horizons within a single strategy: companies can invest in superpollutant projects to help with near-term temperature stabilization, as well as carbon dioxide mitigation and removal to support longer-term climate stabilization. Companies that structure their targets to reflect that distinction gain a clearer view of the climate impact their own portfolio and investments can deliver and when. Some companies, such as Google, are already articulating an approach to combating warming via combined action on superpollutant elimination and carbon removal,¹¹⁸ which could be highly effective in scaling both categories.

The required abatement is disproportionately cheap and disproportionately available. The finance gap identified above is large, but the marginal abatement costs behind it are among the lowest in the global mitigation portfolio. A substantial share of this opportunity sits inside or adjacent to corporate value chains.

Two features of superpollutant abatement pathways work in companies' favor:

- First, a significant share of methane and F-gas abatement carries negative or low net cost, because the abated substance has commercial value and therefore pays for itself over time. Equipment upgrades deliver energy efficiency alongside emissions reductions or the intervention is a maintenance practice rather than a capital-intensive project.
- Second, many (though not all) superpollutant emissions are concentrated in identifiable point sources and specific equipment classes rather than diffused across every combustion process in an economy, as is the case with CO₂. Concentrated sources are easier to locate, attribute to a responsible party, fix, and, eventually, regulate.

A meaningful share of global superpollutant mitigation opportunities lies outside any single company's direct value chain, often in geographies and sectors where the abatement is cheapest but the capital is scarcest. Companies can reach these mitigation measures through the carbon market lever described in Chapter 5 and can help build the policy and measurement infrastructure that unlocks it through the engagement lever described in Chapter 6. The value chain lever in Chapter 4 addresses the portion that sits within corporate control and influence, where numerous negative- or low-cost opportunities also exist.

Corporate action is imperative. The major reductions assumed in the 2 degrees Celsius scenario are concentrated in oil and gas systems, cooling and refrigeration, waste management, industrial chemical production, and agricultural supply chains. These predominantly reside in corporate systems. Although governments can regulate them and finance can support them, companies ultimately operate them. This modeling and its related research indicate that the 2 degrees Celsius pathway is not reachable without mitigation actions coming from corporate operations, ownership, and procurement.

Resource reallocation is needed. With this understanding, the present allocation of resources appears to be drastically disproportionate. Methane abatement, for example, is among the fastest and cheapest ways to slow near-term warming, yet a Climate Policy Initiative (CPI) study finds that less than 2 percent of global climate finance in recent years

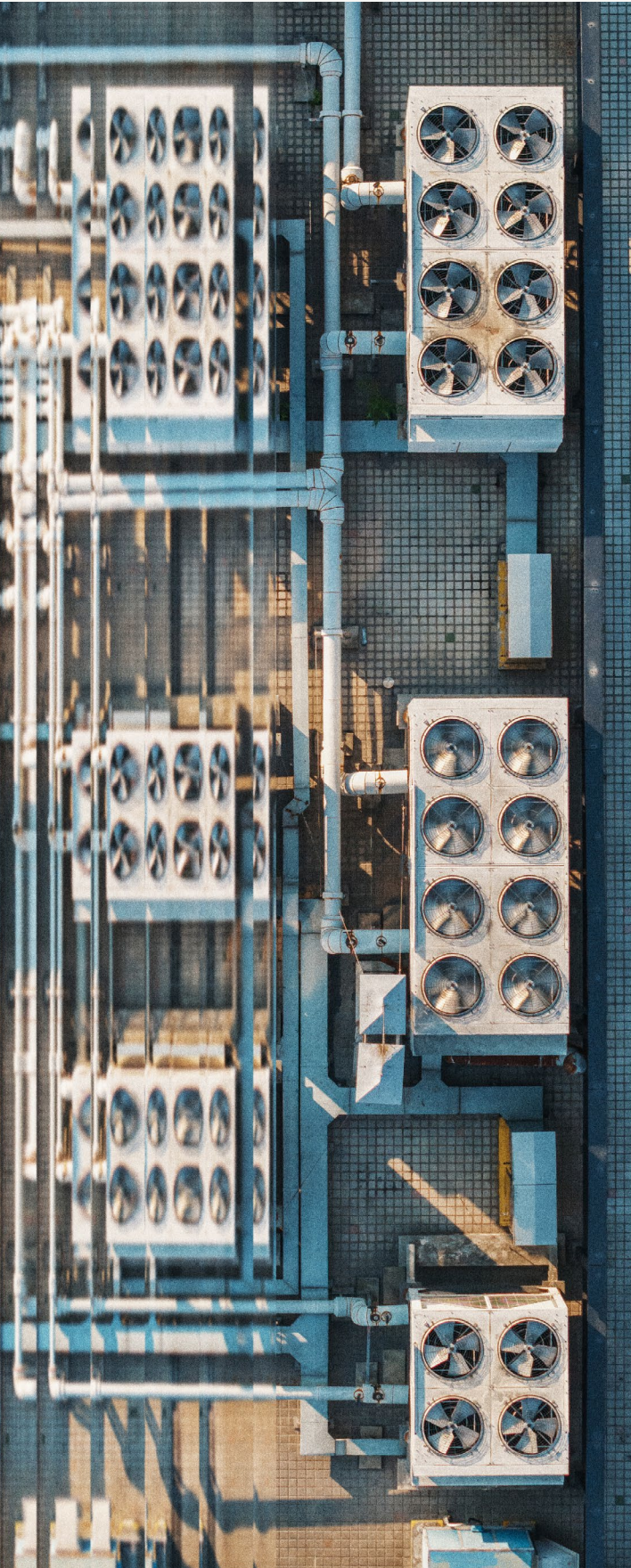
has been directed to methane action.¹¹⁹ A subsequent CPI study estimated that global methane abatement finance averaged USD 13.7 billion per year in 2021–2022 against an estimated need of roughly USD 48 billion annually by 2030 under a 2 degrees Celsius pathway.¹²⁰ A commitment of that size simply cannot deliver half of the required temperature outcome.

Superpollutant action can no longer remain a corporate afterthought. It is one of the most significant pillars of climate change engagement needed in the coming years. With these takeaways in mind, the goal of this roadmap is to present the tools necessary to effectively and efficiently reduce a corporate superpollutant footprint across three key levers—value chain intervention, voluntary carbon markets, and policy engagement—not just because it is one of the best ways to extend the breadth of corporate environmental efforts, but because it simply cannot be done without corporate action.



04

Lever 1: Value Chain Intervention

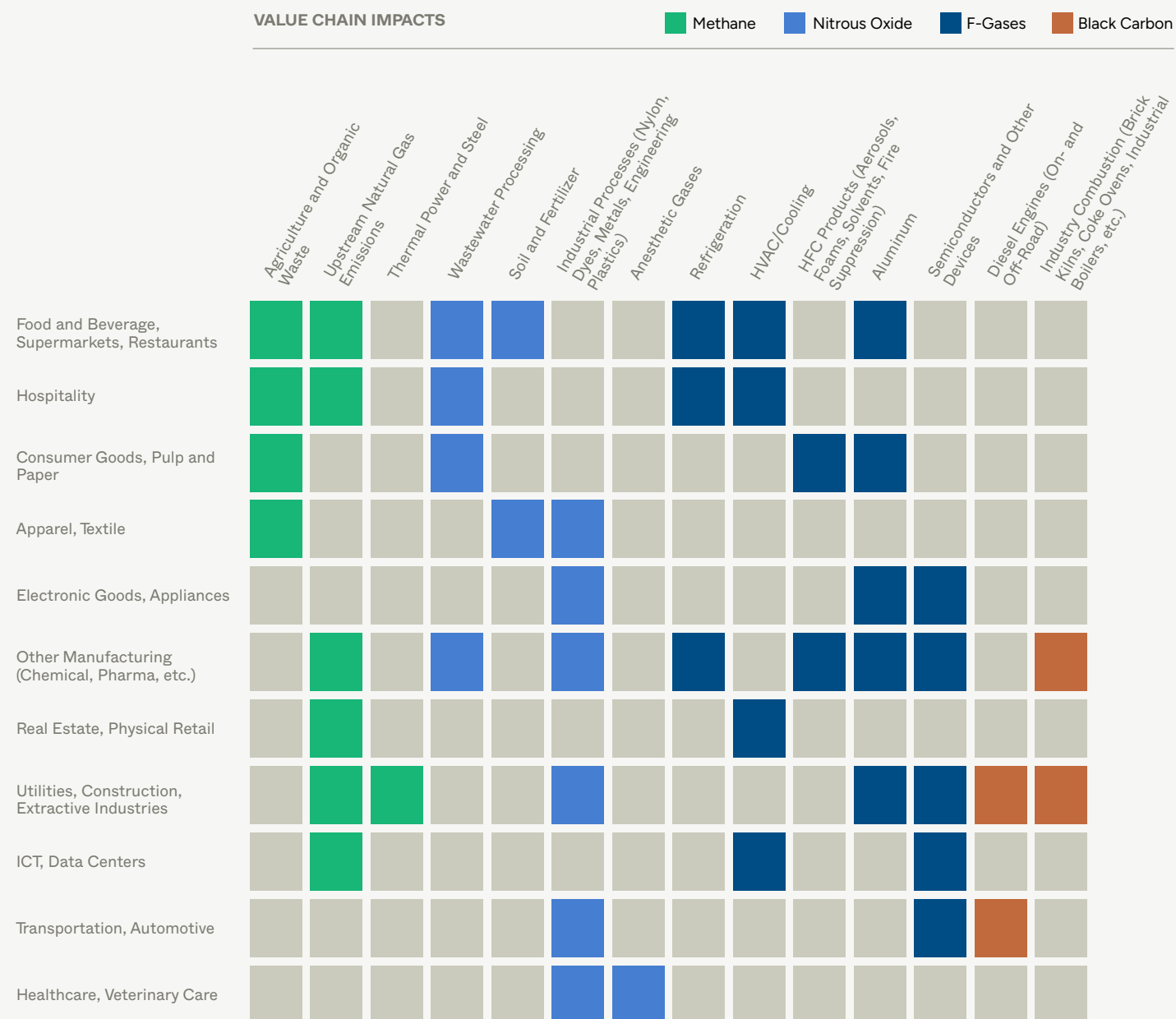


This chapter identifies common superpollutant hotspots across many companies as well as compelling mitigation opportunities for them. Then it dives into how each company can find superpollutant hotspots in its own value chains. The chapter shares the three main mechanisms available to address hotspots and applies a practical decision framework for evaluating them. It also provides examples and case studies of companies already acting on superpollutants using these mechanisms.

Finding superpollutant hotspots

Some superpollutant hotspots show up across many sectors. Upstream activities with significant superpollutant footprints include raw material extraction (such as fossil fuels), agricultural production, and input processing and manufacturing. Downstream activities concentrate around distribution, retail, consumer use, and disposal. Logistics and transportation have hotspots upstream and downstream.

FIGURE 5: COMMON SUPERPOLLUTANT VALUE CHAIN HOTSPOTS



SOURCE: Carbon Containment Lab analysis, 2026

While each company will have its own superpollutant emissions profile based on its activities and location, some clear industry-wide hotspots demand immediate attention and can be addressed through market-based value-chain interventions. (Additional information on all of these and how we selected them is in Appendix D):

- 
- Agriculture and organic waste generate superpollutant emissions** across multiple sectors and gases. Livestock, crop, and waste-derived methane are integral to food, apparel, and packaging supply chains, while soil, fertilizer, and wastewater emissions extend the footprint to textiles, aquaculture, and manufacturing.
- **Immediately actionable:** Capturing methane from agricultural waste (manure and other organic material) using anaerobic digesters to produce biogas, which is then converted into Renewable Natural Gas (RNG) and sold via Book and Claim certificates.
- 
- Fossil energy** includes significant hotspots as well. Upstream natural gas operations release methane that can enter the inventories of oil and gas companies through Scope 1, electricity users through Scope 2, and nearly every other company through Scope 3. Companies could avoid 77 percent of the annual 2.4 Gt of CO₂e from methane leaks (roughly 5 percent of all anthropogenic emissions) with existing technology. More than a third of those emissions could be abated at a net profit.¹²¹ Coal mining carries a parallel methane footprint, driven by demand from thermal power generation and steel production.¹²² Diesel and combustion engines of vehicles are major sources of black carbon in construction, utilities, manufacturing, retail, and transportation.
- **Immediately actionable:** Buy from the supplier with the lowest verified intensity, favoring those with no satellite-observed emissions and membership in programs such as OGMP 2.0.
- 
- F-gases** are widespread wherever companies use refrigeration or climate control, including HVAC in data centers and large building portfolios and refrigerants in food and cold chains. Industrial processes (from electronics manufacturing, heavy metal production, and electricity infrastructure) also use and emit highly potent F-gases, including PFCs, sulfur hexafluoride, and nitrogen trifluoride, in aluminum and semiconductor production. Electricity transmission systems likewise use sulfur hexafluoride in transformers and switchgear.
- **Immediately actionable:** Purchase reclaimed F-gases with forward offtakes, and/or through Book and Claim certificates. Engage suppliers to ensure other F-gases are being properly managed throughout their lifecycle, and that high-GWP gas equipment is phased out in procurement cycles.



Chemical manufacturing and heavy industrial processes generate high-potency nitrous oxide emissions across multiple sectors and specialized product lines. The production of intermediate bulk nitric and adipic acids and chemical precursors creates a large superpollutant footprint in downstream consumer goods, automotive engineering, and construction markets. Specifically, manufacturing facilities release concentrated nitrous oxide emissions during steps required to make synthetic fertilizers, performance nylon fibers, polyurethane insulation foams, and synthetic dyes. Small volumes of highly potent industrial nitrous oxide emissions also escape into the atmosphere from high-temperature fossil fuel combustion, inside heavy manufacturing machinery, and as part of the silicon wafer electronics fabrication processes.

- **Immediately actionable:** Specify to “buy clean” materials in key sectors that rely on these chemicals (such as textiles, furniture, mattresses, car powertrains, and the agriculture and food industries.)
- **Immediately actionable:** Provide financing via insetting projects; and/or engage suppliers on best practices.



Three mechanisms for action

Companies have three main mechanisms for mitigating superpollutants in their value chain: direct operational action, supplier engagement, and market-based instruments. SBTi recognizes all three as allowable pathways for claiming GHG reductions.

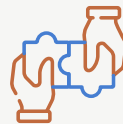
The right approach depends on where a hotspot sits on the control spectrum, as well as on a company's supplier relationships, available contractual mechanisms, budget, and risk appetite. A mitigation measure's level of maturity also matters: for example, some measures will benefit from more flexible forward offtake agreements while they scale up in new jurisdictions, while others are highly mature and can more easily be integrated into existing supplier engagement relationships and requirements. Appendix B describes how these different mechanisms map to the maturity levels of the mitigation measures.

FIGURE 6: THREE TYPES OF VALUE CHAIN ACTION



Direct operational action

Seizing abatement opportunities that sit fully within a company's own control



Supplier engagement

A company collaborates with its suppliers of products and services to reduce superpollutant emissions



Market-based instruments

Contractual tools that enable companies to claim mitigation outcomes (i.e. reductions or removals). These include insetting, where a company works directly with a supplier, and environmental attribute certificates, which are logged in a third-party registry

At one end of that spectrum is *direct operational action*. A company could purchase certified low-carbon natural gas, phase out high-GWP refrigerants, upgrade on-site combustion equipment, and capture the reduction directly in its own Scope 1 inventory.

Moving into Scope 2 and 3, a company no longer controls the source directly but can still influence the activities that generate those emissions by providing capital, technical support, or other market incentives.

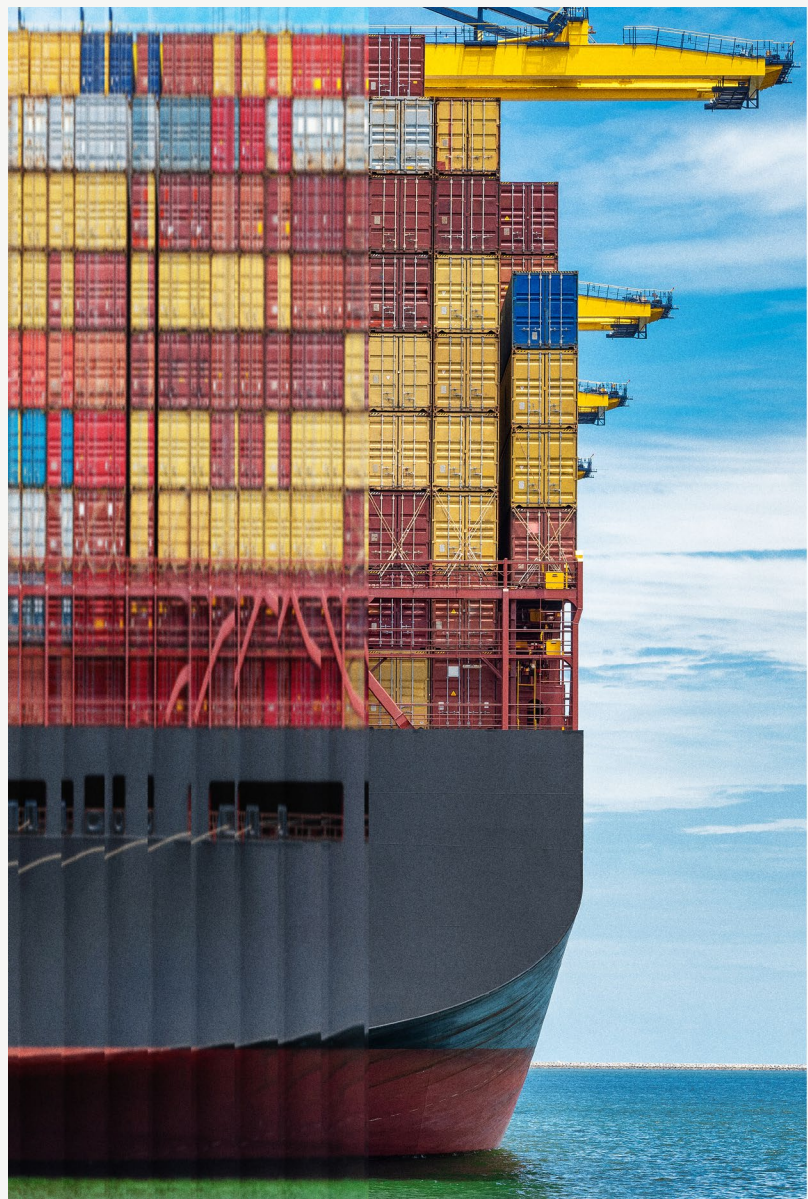
Supplier engagement fills that gap: through a structured, usually multiyear program, a company works with upstream or downstream partners to mitigate their direct emissions, which then count as a reduction for the company itself.

Insetting is one example of this type of value chain intervention. A company developing mitigation projects directly with an existing business partner is still engaging a supplier, even where accounting convention has historically grouped it with market tools.

Deep in Scope 3, a company may have little or no operational relationship with the source of a superpollutant emission. **Market-based instruments**—such as environmental attribute certificates and Book and Claim credits—allow a company to support and claim mitigation outcomes achieved elsewhere in the value chain. Reductions are verified by third-party certifiers rather than a direct relationship.

Emerging standards, including the AIM Platform and the upcoming GHG Protocol Actions and Market Instruments (AMI) standards, establish value chain association rules, certification standards, and an appropriate reporting framework.¹²³

Market-based value chain instruments are distinct from voluntary carbon markets. When a company uses these instruments, it claims credit for an outcome tied to its own value chain. For example, a shipment allocated to certified low-carbon fuel remains part of that company's transportation footprint. Voluntary carbon markets, discussed in the next chapter, work differently: they finance verified mitigation beyond a company's own footprint entirely, reaching sources that value chain action cannot touch. The two levers are therefore complements, not overlapping paths to the same claim.



Finding corporate superpollutant hotspots

For Scope 1 emissions, identifying hotspots is usually straightforward. Most greenhouse gas footprint and reporting frameworks already require companies to track emissions by gas, making it relatively easy to pinpoint where superpollutants occur. The one exception is ozone-depleting substances, which the GHG Protocol lists as optional to report on (these “non-Paris” gases are governed instead by the Montreal Protocol; despite being classified as optional, they are in fact potent greenhouse gases).

For Scope 2, while some superpollutant emissions are produced during combustion, most of the associated superpollutant impact sits further upstream, landing in Scope 3 Category 3, “fuel- and energy-related activities.” Specifically, Scope 3.3 includes the methane, black carbon, and tropospheric ozone released during the extraction and processing of the coal, oil, and gas burned to generate a company’s purchased electricity.

For Scope 3 emissions, identifying superpollutant hotspots within existing footprinting tools becomes more challenging. Hotspots often occur in low-spend, low-tonnage, or low-energy activities, which means the spend- and energy-based screening and estimation models that companies commonly use to quantify Scope 3 emissions can miss them entirely. Locating these hotspots therefore requires additional detective work and analysis.



A decision framework for action

Corporate decision-making on superpollutants follows the same logic as other climate investments: evaluate risk, cost, and benefit; set targets aligned with strategy; and prioritize the actions that deliver the greatest ROI. To begin, companies can follow five steps.

Step 1: Identify hotspots

A value-chain superpollutant hotspot for a company is the point in a product or company's value chain where a small volume of a short-lived, high-GWP gas represents an outsized share of near-term warming. A hotspot can be identified by three criteria: 1) size, using a common materiality threshold of 5 percent of Scope 3, consistent with standard assurance practice; 2) influence over reduction potential, where a small number of suppliers account for significant superpollutant emissions or where technology is readily available and at scale; and 3) cost, since some opportunities are available at negative or near-zero net cost and merit priority treatment on that basis alone. Regulatory risk, such as emerging methane rules in oil and gas, is also a consideration.

Purchasing cleaner natural gas.

Remote sensing now allows oil and gas buyers to see order-of-magnitude differences in methane intensity between operators in the same basin. Some companies emit as little as 0.2 percent of production, the industry benchmark, while neighbors run more than ten times higher.¹²⁴ The procurement standard should be to purchase from the supplier with the lowest verified intensity, favoring those with no satellite-observed emissions and membership in programs such as OGMP 2.0. Technology companies generating their own power behind-the-meter face this choice most directly, since they also control on-site combustion equipment. These companies can reduce methane slip by choosing turbines over engines and conducting leak detection and repair (LDAR) quarterly or monthly, more frequently than industry norms. These actions may be some of the lowest-cost mitigation options available today.

Step 2: Identify mitigation actions

Table 6 maps common actions to superpollutants and the Scope 3 categories they typically affect. See more about these measures at superpollutantroadmap.org.

TABLE 6: SUPERPOLLUTANTS AND RELEVANT SCOPE 3 CATEGORIES

Superpollutant	Value Chain Hotspot	Available Mitigation Actions
Methane/ Nitrous Oxide	Agriculture and organic waste	Aerobic composting; anaerobic digesters; food-waste diversion; manure management; methanotrophic bioreactors; solid waste separation.
Methane	Upstream natural gas and coal mining emissions	Leak detection and repair (LDAR); capture and destruction or oxidization of gas from mines and oil & gas fields; orphaned/marginal well plugging; waste gas utilization for energy/fuel; vapor recovery.
	On-site power generation, particularly behind-the-meter natural gas for data centers and other large energy users	Select gas suppliers with: lowest verified methane intensity (0.2% or below), no satellite-observed emissions, and/or membership in OGMP 2.0; slip control via turbines; vapor recovery; regular leak detection and repair.
Nitrous Oxide	Soil and fertilizers	4R nutrient stewardship (codified framework); biochar soil amendments; biological nitrogen fixation (legume rotation/inoculation); enhanced-efficiency fertilizers and nitrification inhibitors; optimized nitrogen-fertilizer use and precision agriculture techniques. Improved soil management to reduce the conditions leading to microbial nitrous oxide formation in agricultural soils.
	Wastewater processing	Deployment of continuous nitrous oxide sensors coupled with dissolved oxygen/aeration control loops to actively suppress nitrous oxide production in wastewater.
	Industrial processes: nitric acid, adipic acid, and caprolactam production (nylon, polyurethane foam, synthetic fiber inputs)	Catalytically decomposing nitrous oxide into nitrogen and oxygen using zeolite- or metal-oxide-based catalysts; Installing emission control technologies or process substitutes to reduce nitrous oxide generated as a by-product of nitric or adipic acid production; Installing catalytic or thermal nitrous oxide tail-gas destruction technology downstream of caprolactam, glyoxal, or glyoxylic acid production process vents, converting nitrous oxide to nitrogen and oxygen before atmospheric release.
F-Gases	Refrigeration; HVAC cooling; industrial production	Equipment installation/retrofit; leak detection and repair; low-GWP refrigerant replacement (drop-ins); refrigerant recovery, reclamation or destruction; cooling load reduction measures.
Black Carbon	Industrial combustion; diesel engines; owned and contracted freight fleets and non-road mobile machinery (construction, agricultural equipment)	Vehicle electrification; ultra-low sulfur diesel with particulate filters; hydrogen fuel-cell trucks; heavy-duty truck idle reduction; diesel locomotive retrofits/replacement.
	Shipping	Alternative marine fuels (such as “low carbon” methanol or ammonia); fuel switch to distillates; exhaust filtration; maritime emission control areas (ECAs); reduce vessel speeds; shore-power at berth; voyage optimization; wind-assisted propulsion.

Step 3: Calculate emissions savings

Savings are calculated as baseline activity levels multiplied by an emission factor minus project emissions. For oil and gas methane specifically, facility-average emission factors can understate savings relative to directly measured emissions so companies working in this sector should treat modeled baselines as a floor, not a ceiling.

FIGURE 7: EMISSIONS SAVINGS CALCULATION

Savings =

Baseline emissions -

Project emissions

Project emissions can be calculated for all individual projects/actions to estimate total savings

01

Baseline emissions =

activity level without the project ×

baseline emission factor

This is likely to be the annual greenhouse gas inventory

02

Project emissions =

activity level with the project ×

relevant emission factor

Mitigation is a result of lowering the activity level and/or the emission factor

03

Therefore, Savings =

Baseline emissions -

Project emissions

Step 4: Build the business case

Many value chain superpollutant mitigation measures achieve cost savings or are low-cost on a per-ton basis—some examples can be seen in Table 6. Two tools are widely used to shortlist actions: an impact/effort matrix and a marginal abatement cost curve.

Placing actions in a two-by-two matrix with axes of impact and effort groups actions by expected reduction and implementation difficulty, cost, and time.

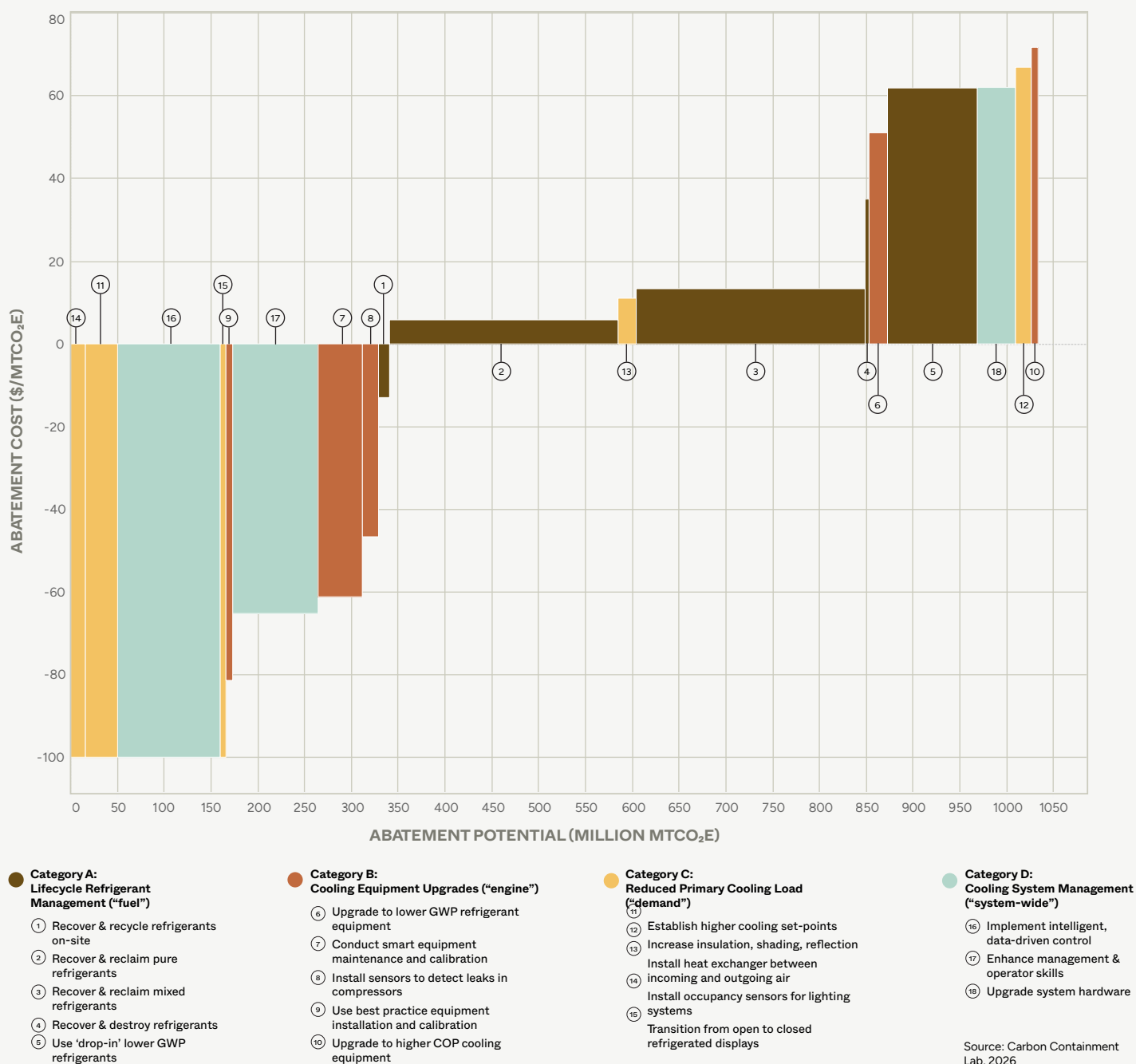
TABLE 7: IMPACT/EFFORT MATRIX

		High Impact	
Low Effort	High Effort	Quick Wins – highest priority	High Effort, valuable – strategic long-term bets
		Easy Wins – implement quickly	Low Priority – deprioritize
		Low Impact	

If there is appetite to conduct a more detailed assessment, generating a marginal abatement cost curve (MACC) will lend quantitative support to the cost component of an effort. A MACC plots reduction potential in metric tons of CO₂e (MTCO₂e) per year against marginal cost per MTCO₂e. Actions to the left of the curve’s inflection point are the lowest cost, and those below the x-axis pay for themselves outright, making them no-regrets moves for corporate actors.

For example, the Carbon Containment Lab generated the following marginal abatement cost curve for cooling-related emission reduction measures in the commercial real estate sector in the U.S. and China (Figure 8).¹²⁵ This was modeled using GWP-100, so near-term benefits are conservatively stated. Economically attractive mitigation measures have the potential to reduce total cumulative commercial cooling emissions by 45 percent, representing some 5.7 Gt CO₂e of avoided emissions from 2026 to 2060. A subset of these measures generates cost savings. For example, improving system controls and smarter maintenance and operations could avoid 1.4 Gt CO₂e of emissions in the U.S. and China if implemented between 2026 and 2060.

FIGURE 8: MARGINAL ABATEMENT COST CURVE EXAMPLE FOR U.S. COMMERCIAL REAL ESTATE COOLING SECTOR EMISSIONS MITIGATION MEASURES



Beyond GHG reduction, many actions carry multiple additional benefits that should be accounted for in impact assessments: waste and energy-efficiency measures cut operating costs, fertilizer-reduction actions improve soil health and farmer income stability, and reductions in methane, tropospheric ozone, and black carbon improve air quality, a leading driver of respiratory and cardiovascular illness. A new study by the Climate and Clean Air Coalition (CCAC) quantifies the broader economic and health benefits potentially generated from 25 selected superpollutant mitigation measures. The study finds that for each \$1 spent on superpollutant and air quality mitigation, some \$15 in economic benefits are generated.¹²⁶

TABLE 8: SAMPLE OF VALUE CHAIN SUPERPOLLUTANT ACTIONS AND COSTS

Category	Action	Available Cost Information
Methane/Agriculture	Anaerobic digesters at dairy farms and feedlots	Typically results in net savings for farmers; RNG/biogas production provides revenue, with additional benefit from selling environmental attributes. ¹²⁷
	Sustainable rice sourcing	Can provide water savings of up to 30 percent and yield stability for farmers. ¹²⁸
Methane/Oil & Gas	Leak detection and repair, pneumatic device replacement, eliminating routine flaring, vapor recovery units	About 39 percent of oil and gas methane abatement pays for itself outright, since the resold gas value exceeds the cost of capture; nearly all remaining abatement is cost-effective below \$20 per metric ton CO ₂ e. ¹²⁹
Black Carbon/Ocean Freight	Book and Claim for biodiesel, green methanol, and ammonia	Typically a 10 to 20 percent cost premium depending on route and fuel; programs available through Maersk, Hapag-Lloyd, CMA CGM, MSC, and COSCO. ¹³⁰
Black Carbon/Air Freight	Sustainable aviation fuel (SAF)	Two to three times the cost of jet fuel, a \$0.50 to \$1.50/gallon premium, translating to \$60 to \$190/MTCO ₂ e in a Book and Claim program; pricing is volatile and access can be scarce. ¹³¹
F-gases/Fugitive Emissions	High-efficiency low-GWP HVAC upgrades	Payback typically five to fifteen years via operational energy savings, depending on existing system efficiency, electricity rates, and available incentives. ¹³²

Step 5: Implement and integrate into your portfolio of climate commitments and claims

Once actions have been prioritized, companies can model emission targets and create commitments for superpollutant emissions reductions. The SBTi Corporate Net-Zero Standard provides a useful framework for setting holistic targets across Scopes 1 to 3, including superpollutant reductions achieved through value-chain engagement. As a reminder, SBTi rests on GWP-100 and does not currently offer dedicated standards for setting superpollutant-specific reduction targets that reflect their potency and unique time signatures. Superpollutants like methane and nitrous oxide fall under SBTi's general corporate near-term and net-zero frameworks, which cover all GHGs (Scopes 1–3) aligned with 1.5°C pathways.¹³³ However, sectoral guidance covers superpollutants, such as nitrous oxide in agriculture.



Seeing mitigation in action: Value chain project examples

The mechanisms above are already in use. The examples below range from single unilateral actions to multiyear partnerships.

TABLE 9: VALUE CHAIN PROJECT EXAMPLES

Company	Mechanism	Action	Result
ALDI	Direct Operational Action	The first U.S. food retailer to commit to a full HFC phase-out by 2035	600-plus stores converted to HFC-free; reduced average store potential emissions by 50 percent per year; ranked #1 U.S. supermarket by the EIA. ¹³⁴
Nestlé	Direct Operational Action	Used Maersk ECO delivery for 100 percent of its 2023 ocean shipments	Reduced shipping emissions by more than 80 percent. ¹³⁵
TSMC	Supplier Engagement	Reviews Tier 1 suppliers' carbon reduction plans, including F-gas abatement for silicon wafer suppliers	Goal of reducing Tier 1 supplier emissions 30 percent by 2030. ¹³⁶
Tesco	Supplier Engagement	"Tesco Exchange" platform redistributes supplier food waste surplus across the supply chain	Mitigates methane from food waste disposal. ¹³⁷
Mars	Supplier Engagement (Insetting)	\$20 million investment in sustainable rice sourcing	Reduces methane; co-benefits in water use and crop resilience. ¹³⁸
United Airlines	Market Instrument (Book and Claim)	Sustainable aviation fuel Book and Claim certificates	Mitigates carbon dioxide, black carbon, upstream methane. ¹³⁹
Meta	Market Instrument (Book and Claim)	RFP for MiQ-certified low-methane-intensity natural gas certificates to cover Meta's onsite/behind-the-meter generation	RFP live as of May 2026, seeking 2026-vintage certificates; MiQ's own modeling suggests a 100 megawatt (MW) facility running on Grade A gas could cut methane emissions roughly 95 percent versus the U.S. benchmark. ¹⁴⁰

Aircarbon: Amazon Climate Tech Accelerator (Supplier Engagement/Innovation)

Amazon Devices launched the Climate Tech Accelerator in 2025 to accelerate the decarbonization of its devices. The program selects companies from around the world—startups and publicly traded companies alike—to evaluate the commercial viability of their technologies for reducing the carbon impact of millions of Amazon devices. Each cohort works directly with the Amazon Accelerator team to evaluate integration potential, helping streamline the path from validation to adoption opportunity.¹⁴¹

Newlight Technologies, part of the inaugural cohort, uses microorganisms to metabolize sustainably sourced methane into a solid material called PHB, or Aircarbon. Currently being scaled in product development for Amazon, Aircarbon has been demonstrated to match incumbents on durability and manufacturing efficiency in a variety of applications. Scale, rather than the underlying technology, remains the primary constraint on cost. For durable products, methane is converted into material, and this material remains sequestered for the life of the product; it can be converted to far less potent CO₂ only if the product is incinerated at end of life.

Aircarbon can be used across electronics, foodware, fiber, apparel, and furniture applications and is cost-competitive with other GHG-reduction technologies. Newlight has prioritized sourcing methane at sites such as dairy digesters and abandoned industrial point sources where methane would otherwise become part of the air. In its partnership with Amazon, Newlight plans to convert methane into Aircarbon to help make high-performance electronic parts.¹⁴²

PepsiCo x Yara International: Decarbonizing Agricultural Supply Chains (Supplier Engagement)

PepsiCo collaborated with Yara International to tackle fertilizer at both ends of its supply chain, from production to field application. The partnership targets both nitrous oxide released when farmers apply fertilizer and the fossil fuel emissions embedded in fertilizer production. Since fertilizer use underpins crop yields and food security, elimination is not viable. Instead, the partnership aims to decouple agricultural productivity from fertilizer's climate impact.¹⁴³

Yara supplies its lower-emission Climate Choice fertilizers, made using renewable or low-carbon ammonia and nitrous oxide catalytic abatement. PepsiCo pairs these products with more efficient application through precision agriculture tools, including soil diagnostics and data-driven nutrient management. The program launched in 2024 across roughly 1,000 farms in the European Union and United Kingdom and has cut emissions 20 to 40 percent per ton of potatoes produced (results vary by crop system and fertilizer variant).

The program expanded to Latin America in 2025 and aims to supply 165,000 tons of fertilizer annually by 2030 (a quarter of PepsiCo's European fertilizer needs).¹⁴⁴

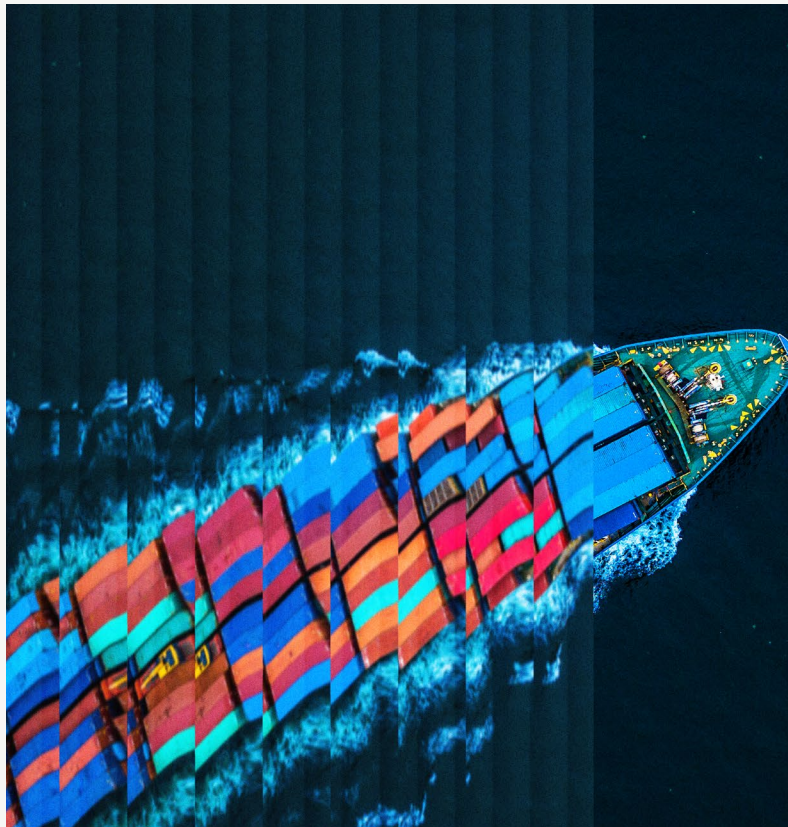
Maersk ECO Delivery Certificates (Market Instruments)

Maersk's ECO Delivery certificates enable customers to claim more than 80 percent lower well-to-wake GHG emissions for eligible shipments. The program uses a mass-balance approach, so customers can claim the emissions benefit without requiring their specific container to travel on a vessel powered by the certified fuel.¹⁴⁵

Customers allocate certified low-GHG fuels—biofuels from waste feedstocks or green methanol—to their bookings in place of fossil fuel, with fleetwide savings confirmed annually through a third-party-verified CO₂e certificate. Biodiesel, the primary ECO Delivery fuel, also reduces black carbon and methane. Maersk's dual-fuel methanol vessels reduce these emissions even further, producing near-zero black carbon or methane as combustion by-products.¹⁴⁶

Biodiesel typically carries a price premium over LNG, increasing the total freight rate by roughly 10 to 15 percent when customers seek full emissions avoidance, depending on the route.¹⁴⁷

Major companies—including Nestlé, Danone, Volvo, H&M, and Amazon—have used ECO Delivery certificates, while competing programs from CMA CGM, MSC, Hapag-Lloyd, and COSCO suggest that the model is gaining traction across the industry.



Checklist 1: Value chain action checklist for companies

Next 12–24 months period:

- ☐ Map where each type of superpollutant arises in your value chain across Scope 1, 2, and 3, distinguishing sources within direct operational control from those several tiers removed.
- ☐ Apply the three hotspot criteria—size, concentration of reduction potential, and cost—to shortlist priority sources.
- ☐ Assign each priority hotspot to a mechanism for action and related mitigation measure (see Appendix B):
 - ☐ Direct operational action for Scope 1 and 2 sources
 - ☐ Supplier engagement or insetting where a hotspot sits with an existing partner
 - ☐ Market instruments where no direct relationship exists or where there is significant near-term impact potential and existing standards.
- ☐ Build an impact/effort matrix and/or marginal abatement cost curve for shortlisted actions, and act first on anything with negative or near-zero net cost.
- ☐ Confirm which value-chain mechanisms are creditable under current SBTi guidance, and flag insetting and market-instrument claims where treatment remains unclear.
- ☐ Execute on the actions selected; track progress and report on results.

By 2030:

- ☐ Embed hotspot mapping and mechanism selection into standard procurement, capital planning, and supplier scorecards/engagement processes, rather than treating them as a one-time exercise.
- ☐ Convert priority supplier relationships into structured, multiyear engagement programs, extending to insetting where the partnership already exists.
- ☐ Track how tightening rules and policy—for example, coal mine methane requirements, methane MRV standards, F-gas quotas—change which actions remain voluntary, updating claims appropriately.
- ☐ Publish results from action taken, since demonstrated cost and performance data is what unlocks the next round of supplier or partner engagement, sharing results and methodologies with peers.
- ☐ Use what you have learned on cost, feasibility, and supplier response as you shape your Policy Engagement strategy, since operational evidence is what turns advocacy into implementable rules.



05

Lever 2: Voluntary Carbon Markets



Companies can address warming through the voluntary use of carbon credits for superpollutant mitigation. While value chain interventions target a company's own operations and supply chain, carbon markets enable companies to finance verified superpollutant mitigation beyond their own footprint. This mechanism helps reach the often diffuse, unregulated, or hard-to-abate superpollutant sources, supporting the projects that can reduce emissions where they are fastest and cheapest. For many leading companies without large superpollutant footprints (e.g., technology companies), this lever is how they can make the most immediate contributions to fighting superpollutants.

Superpollutant credits are an underappreciated segment within voluntary carbon markets (VCM). They offer a unique combination of methodologies tested over two decades, quality that outpaces most of the market, and prices that have yet to reflect this value.

Buyers positioned to act at today's prices stand to benefit from favorable economics while playing a meaningful role in shaping which pathways scale into the projects of tomorrow.

This chapter sets out why superpollutant credits differ from the rest of the voluntary carbon market; how the shorter atmospheric lifetime of these gases changes what companies can credibly claim; where a buyer new to this segment should begin thinking about criteria such as quality, value and scalability; and how these projects may one day pave the way for broader policy or more widespread adoption.

The following mitigation measures meet the criteria described below and in Appendix E. The Carbon Containment Lab believes all are reasonable candidates to be prioritized by buyers today, with caveats and ongoing improvement areas specific to each pathway that are detailed in Appendix F's case studies:

- **Landfill gas capture:** Mature, reliable, and impactful, with significant potential to reduce methane emissions from sites where capture remains unregulated, limited by economics, and/or in countries that are transitioning to larger more centralized waste management facilities.
- **Rice methane:** A large methane-reduction opportunity that could see a renaissance as improved measurement, reporting, and verification can generate high-quality projects whose emissions reductions can be quantified and credited.
- **Anaerobic digesters for agricultural waste:** Modular and scalable, with the potential to reduce both methane and nitrous oxide emissions from manure and agricultural residues.
- **Orphaned oil & gas well plugging:** A potentially low-cost, high-impact opportunity to eliminate persistent methane leaks, especially as baseline setting, measurement and verification systems improve with greater investment.
- **Lifecycle Refrigerant Management:** Builds the infrastructure needed for a circular refrigerant economy while preventing high-GWP gases from entering the atmosphere. Crediting activities for ODS and HFC destruction are well complemented by leak detection and repair and reclamation; as well as updating efficient and low-GWP equipment.
- **Industrial nitrous oxide:** Major point source emissions offer a concentrated and potentially cost-effective abatement opportunity where emissions are not otherwise regulated.

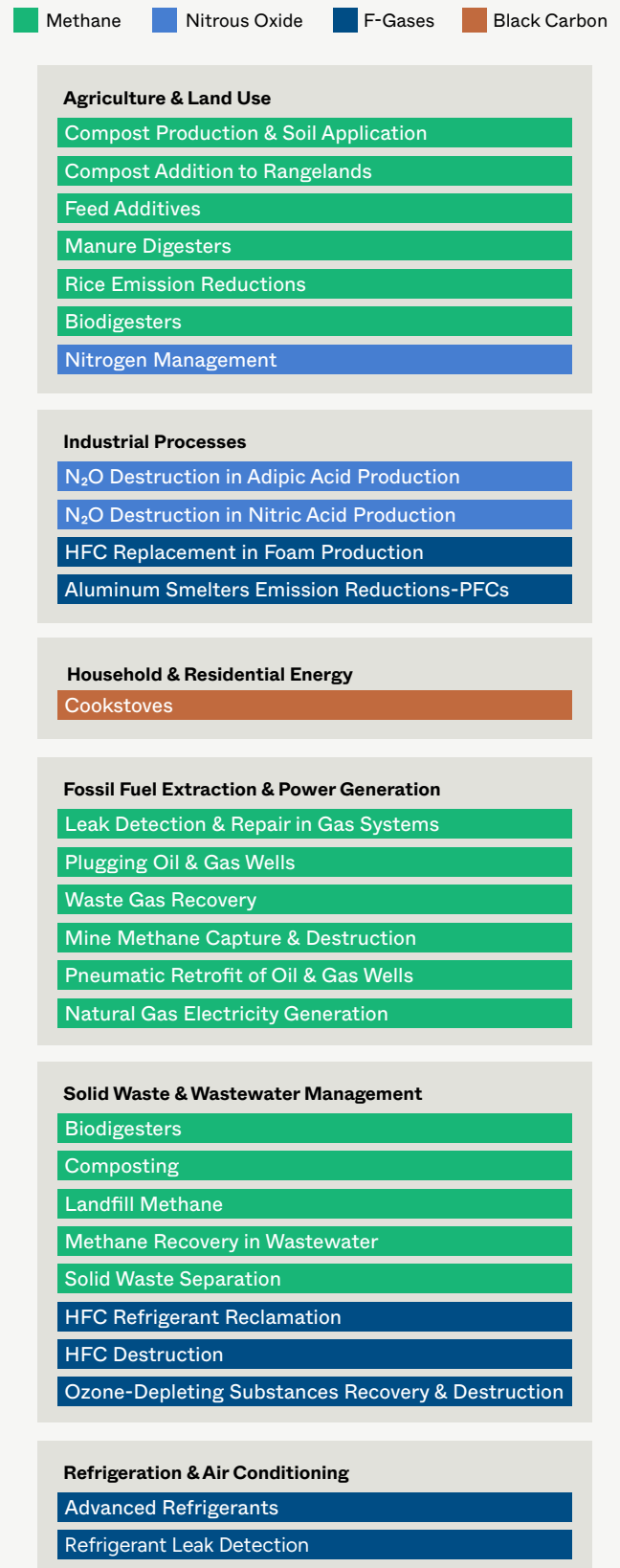
Why Superpollutant Credits Are Different

The carbon credits most often top of mind are nature-based approaches such as reforestation or engineered carbon dioxide removal (CDR) projects like Direct Air Carbon Capture (DACC). However, credits for superpollutant abatement have existed since the early days of carbon markets, beginning with some of the first methodologies under the Clean Development Mechanism (CDM).¹⁴⁸ These credits are not only tested by time and deployment experience, but they also remain significantly cheaper than other categories of credits—and are shown to have higher average quality and integrity than other types.¹⁴⁹

Available supply

The VCM has a large, established base of superpollutant credits, and many are available now on the spot market. As of the end of 2025, superpollutants represented the third-largest category of available credits in the carbon market, as measured by issuance.¹⁵⁰ From 1996 to 2025, approximately 443 million superpollutant credits were issued. Of those already issued, about 229 million have been retired, and 213 million credits are yet to be retired, meaning they may be available for purchase.¹⁵¹

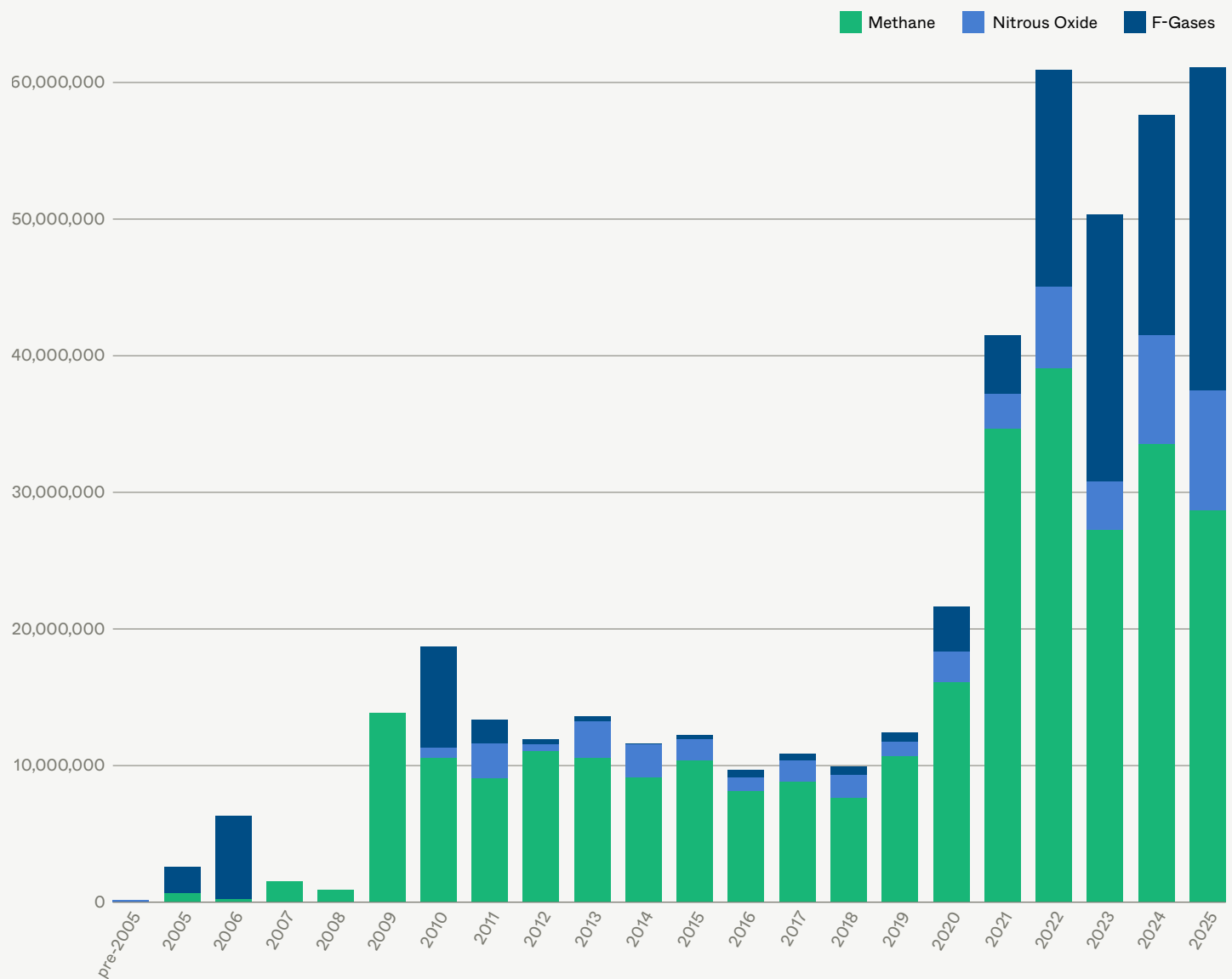
FIGURE 9: SECTORS THAT HOST SUPERPOLLUTANT CARBON CREDITS BY TYPE



Superpollutant credits have experienced a notable revival since 2020, with issuances and retirements increasing rapidly in recent years. In 2025 alone, around 61 million superpollutant credits were issued, approximately 80 percent of which came from F-gas and methane projects.¹⁵² These trends can be seen in Figure 10.

Underpinning this activity is an expanding set of methodologies, many of which are high quality. The Carbon Containment Lab’s global database tracks more than 400 methodologies across 18 registries. Of this total, 154 directly address superpollutants, and 118 are currently active as of May 2026. Methane has the broadest coverage with 87 active methodologies. In the past year alone, 10 new methodologies came online, and at least four more are being drafted by the Open Carbon Protocol and Isometric.

FIGURE 10: SUPERPOLLUTANT CREDITS ISSUED IN THE VOLUNTARY CARBON MARKET BY YEAR



SOURCE: Carbon Containment Lab, 2026

High quality

Superpollutant credits on the VCM are, on average, high-quality, delivering measurable climate benefits and oftentimes important environmental, human health and economic co-benefits as well. As an indicator, Calyx Global, an independent ratings agency with the largest set of superpollutant ratings, found that more than 50 percent of these credits fall into their top integrity tier, rated AAA to A (“Tier 1”), as shown in Figure 11. In contrast, other non-superpollutant credit types, such as forestry and renewable energy, currently account for less than 5 percent in the Tier 1 category. Calyx Global notes that superpollutant projects tend to earn higher ratings

due to robust methodologies, strong additionality, highly measurable emission reductions, and a total absence of permanence risk. For example, ODS destruction projects in Calyx’s ratings have a 95 percent AAA–A rating (across 45 projects), and landfill gas has a 33 percent AAA–A rating (across 150 projects).¹⁵³

Another ratings platform, BeZero, shows similar trends, with superpollutant projects also skewing toward the higher end of ratings compared with CO₂ projects. A clear range of quality still exists across individual projects, so due diligence is needed at the project level (see Figure 12).¹⁵⁴

FIGURE 11: DISTRIBUTION OF CALYX GLOBAL’S RATINGS OF SUPERPOLLUTANT PROJECTS COMPARED TO NON-SUPERPOLLUTANT PROJECTS (JUNE 1, 2026)

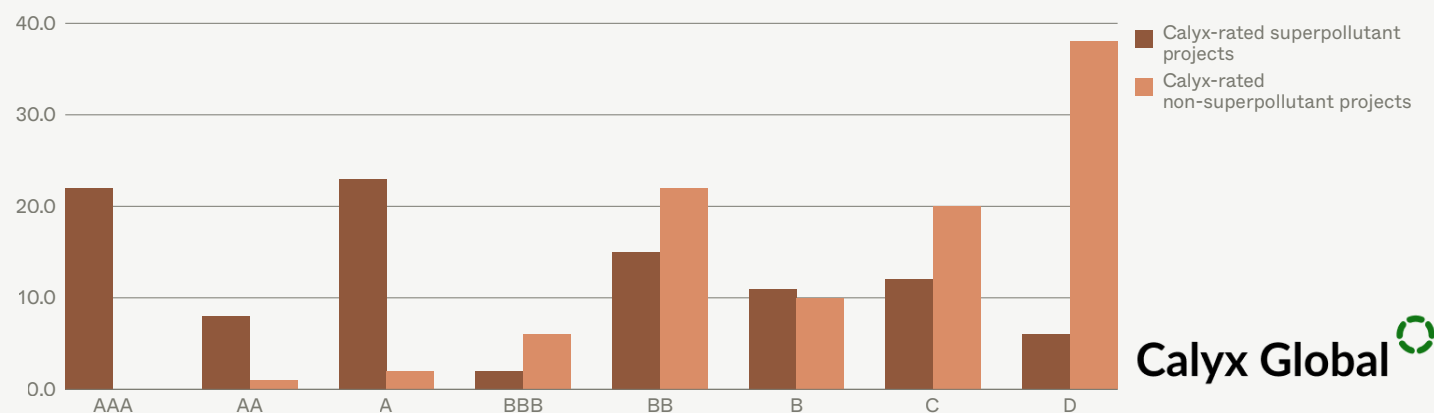
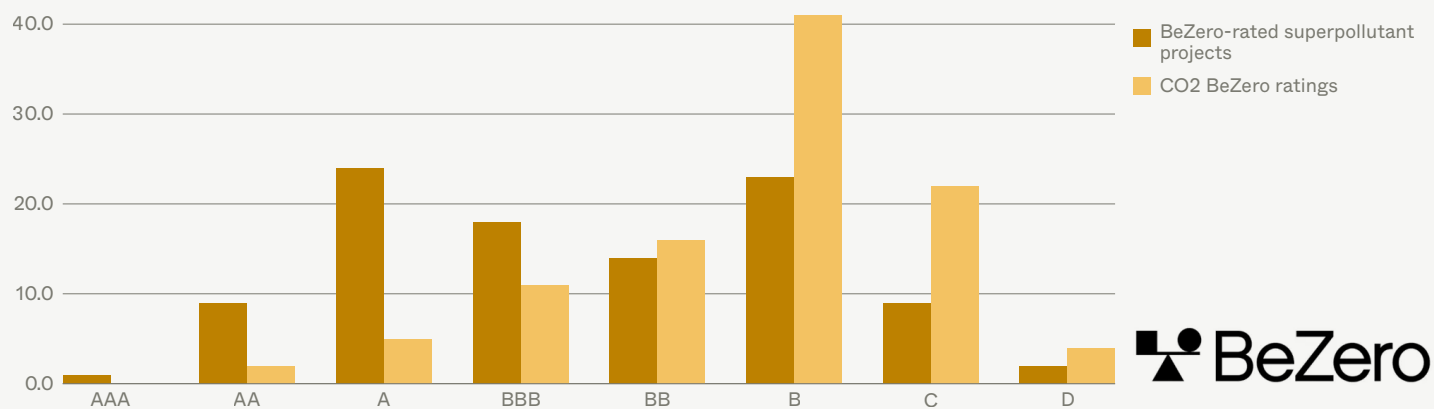


FIGURE 12: DISTRIBUTION OF BEZERO CARBON’S RATINGS OF SUPERPOLLUTANT PROJECTS COMPARED TO NON-SUPERPOLLUTANT PROJECTS (MAY 25, 2026)



NOTE: The two charts above are not directly comparable as they do not represent the same set of rated projects. Differences are therefore expected.

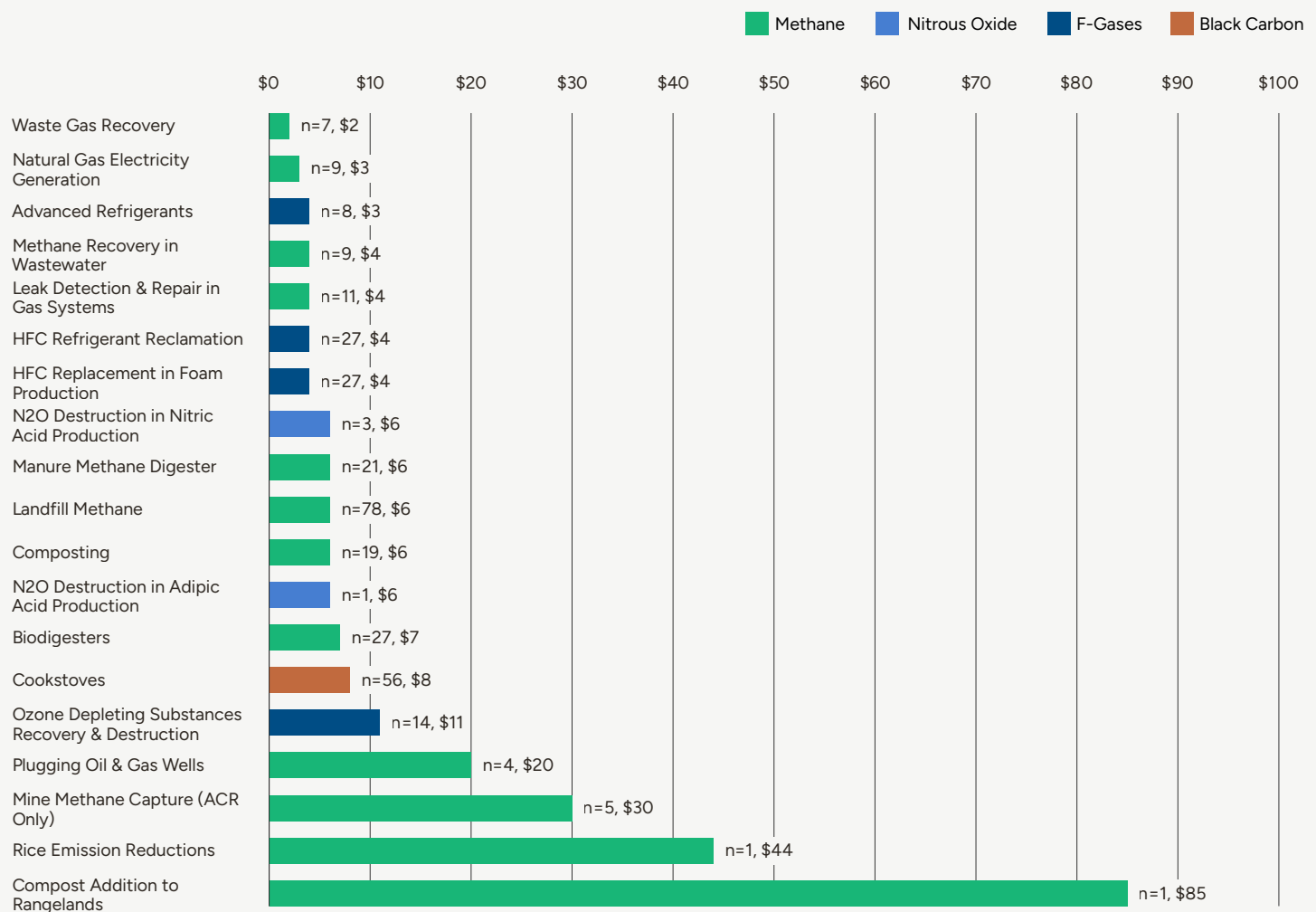
Low prices

Data from ClearBlue Markets shows that across 272 recorded spot-market superpollutant credit transactions from 2021 to 2026, prices vary by vintage year, type, and country, with a median \$4.70 per ton (Figure 13).¹⁵⁵ Certain credit types can attract high prices: a U.S. composting-to-rangeland project sold credits for \$85 per ton in 2025 and a rice methane project sold credits for \$43.87 per ton in 2024. Many of the lower-priced credits are generated in emerging market countries or represent older vintages, reflecting the duration of their availability on the market. Prices also vary by transaction

volume—larger transactions typically get a discount. Projects that follow methodologies and programs vetted positively by the Integrity Council for the Voluntary Carbon Market (ICVCM) and are labeled as following the Core Carbon Principles are beginning to command a modest premium.

The relatively low prices can create the misleading impression that these credits are poor quality, even though that is far from the case. Until the market reflects the true value of superpollutant credits, companies buying them now can stretch their budgets further.

FIGURE 13: AVERAGE PRICES FOR SUPERPOLLUTANT CREDIT TYPES BY CATEGORY, 2021–2026



NOTE: Data retrieved from the Vantage carbon intelligence platform, provided by ClearBlue Markets (Aug. 10, 2026), clearbluemarkets.com.

For companies new to carbon credits

Carbon credits are a market-based mechanism for addressing emissions. They are used in compliance markets, where regulations require entities to purchase credits to offset emissions; in the voluntary carbon market (VCM), where entities purchase credits to meet their climate goals without a legal requirement; and by governments to meet their nationally determined contributions under Article 6 of the Paris Agreement. This chapter focuses on mitigating superpollutants through voluntary mechanisms by companies, but compliance and Article 6 mechanisms share many of the same methodologies and verification structures. The following resources provide grounding in market structure, integrity, and claims.

Understanding carbon markets and emissions accounting

- The [Carbon Offset Guide](#) provides a detailed introduction to carbon market structure and a manual for how to purchase credits, along with other guidance.
- The Science Based Targets initiative (SBTi)'s [Corporate Net-Zero Standard Version 2.0](#) is a prevalent guide to corporate emissions target-setting. Carbon credit purchases earn companies recognition for progress against their Ongoing Emissions Responsibility.
- The [Greenhouse Gas Protocol](#) is the primary rulebook for corporate emissions accounting.

Defining quality credits and claims

- The [Oxford Offsetting Principles](#) are a foundational framework laying out the role of carbon credits within corporate decarbonization and net-zero strategies.
- The Integrity Council for the Voluntary Carbon Market (ICVCM)'s [Core Carbon Principles](#) are the leading standard for carbon credit integrity.
- The Voluntary Carbon Markets Integrity Initiative (VCMI) publishes a [Claims Code of Practice](#) that instructs companies on how to use carbon credit claims responsibly to avoid greenwashing.

Details on credits

- Ecosystem Marketplace's annual State of the VCM reports ([2025 version](#)) and dashboards provide regular data about the wider VCM.
- Ratings agencies such as [Calyx Global](#), [BeZero Carbon](#), [MSCI](#), and [Sylvera](#) provide public-facing reports and resources, along with finance-style ratings of individual projects for paid users.
- U.C. Berkeley's [Voluntary Registry Offsets Database](#) provides project-level issuance and retirement data.
- Platforms such as [Abatable](#), [Allied Offsets](#), [Carbon Pulse](#), [ClearBlue](#), [MSCI \(formerly Trove\)](#), and [Xpansiv's CBL](#) provide pricing, projections, and market intelligence.

Where to Start: A Ladder, Not a Menu

For a company beginning or expanding its superpollutant strategy, carbon credits are best understood as a sequence rather than a set of equivalent options. Each step up the ladder increases the risk a buyer takes on, the level of due diligence required, and control over how the credits are generated.

Start here: Buying spot

Buyers typically purchase already-issued (“ex-post” or “spot”) credits from registries, trading platforms, and brokers, or directly from project developers. These credits represent climate benefits that have already been delivered by a project’s actions and have been fully validated and verified by third-party certification bodies. Credits are issued by registries that write the methodologies and ensure that certifiers are properly accredited to international and national standards. Project information and certification reports can be found on registries, ratings, and retail platforms.

Buying spot minimizes delivery risk because the credits are already issued and enables the buyer to retire them immediately against climate commitments or to hold them as assets. Purchasing spot credits is the most straightforward entry point into superpollutant credits, and companies need only the simple capability to purchase and retire credits (for companies new to this, see page 70 for additional resources). However, buying spot credits does not come with a guarantee of future price levels or long-term supply; and the environmental attribute being transferred may relate to abatement that occurred several years earlier.



For a company beginning or expanding its superpollutant strategy, carbon credits are best understood as a sequence rather than a set of equivalent options.

Next: Buying forward and investing directly

Buying forward means entering into contracts to purchase credits that will be generated by a project in the future, typically spanning several years and governed by an offtake agreement. Such agreements secure long-term supply for buyers and provide price certainty through fixed or formula-based pricing. Projects vary in their level of maturity—and by extension their risk of nondelivery: some are fully validated and have already issued several vintages, while others are still working on documentation and starting operations. This purchasing strategy introduces more delivery risk and contractual complexity, which often requires extensive and costly due diligence to manage. However, buyers who are able to take this approach will be at the forefront of superpollutant mitigation directly supporting the generation of new climate benefits.

Investing directly in a project, especially when paired with a future offtake agreement, can help provide catalytic capital that supports project scale-up, which is often a significant hurdle for early-stage projects. Investing directly also gives the buyer deeper influence over project design and governance but is the highest-risk undertaking. It requires a strong understanding of carbon markets and significant resources to engage in robust due diligence prior to making an investment decision.

Expanding the strategy: Portfolios and ecosystem support

Most buyers will purchase spot credits, especially lower-volume purchasers. Larger, sophisticated buyers can blend all three strategies, using spot purchases to cover near-term claims and offtakes and/or long-term investing to anchor strategic, high-quality projects over the medium to long term. Buyers can also mix superpollutant and CO₂-based credits into one portfolio, which diversifies risk across categories and supports a wider range of co-benefits and local impact. Several intermediary companies in the market already provide high-quality portfolio-style options to buyers, which considerably lowers the capability threshold for buyers.

Finally, with or without buying credits directly, companies can act as strategic partners to project developers by providing host sites, advice, connections, technologies, R&D, referrals, and shared due diligence with other companies and investors. Companies can also catalyze wider superpollutant mitigation by sharing their experiences, publishing best practices, and demonstrating real-world outcomes. This leadership builds market traction and generates interest from a broader circle of companies and investors while legitimizing these climate actions by showcasing verified results.

Selection: What to Look for in Superpollutant Credits

With so many varieties of superpollutant credits available, choosing which credits to include in purchases can be daunting. Numerous criteria can be applied to the selection process, and many of these would apply to any carbon credit type. Issues such as quality, additionality, durability, and leakage cut across all categories. Buyers should weigh their

own risk appetite, budget, and available contracting mechanisms; their preferences on location, industry, marketability, and co-benefits; and their timing and capacity for due diligence and review.

What differs for superpollutants is the purpose of the screen. Here, the goal is to select project types that can help scale deployment over the next five years and contribute to near-term climate stabilization. A five-year lens favors projects where credits do more than pay for abatement: they build supply, absorb early risk, and create momentum for broader adoption and/or regulation. It also implies some tolerance for project types that are still maturing, provided the path to volume is visible and the barriers to scale are surmountable.



The Carbon Containment Lab proposes the following four categories of selection criteria for superpollutant credits which are also further detailed in Appendix E:

- **Scalable.** The project type has the technical and market potential for widespread application, replication, future cost reduction, and, therefore, impact on warming. The constraint for superpollutants is not generally whether abatement is technically possible, but whether the same intervention can be delivered multiple times. Five key factors drive scalability: 1) the size and accessibility of the source of emission in aggregate; 2) the technical and methodological readiness of the mitigation measure; 3) repeatability across geographies and asset classes; 4) the absence of binding input, supplier, or workforce constraints; and 5) the ability to absorb capital in a way that unlocks a larger pipeline. Given the potency of superpollutant gases, even small and dispersed sources are worth accessing, provided a collection and verification pathway exists.
- **Value.** The project has strong unit economics and a credible path to economies of scale. Credits with higher value have a cost structure that is understood, defensible, and likely to improve with volume. Co-product revenues can add economic resilience, provided they do not raise concerns about financial additionality or risk double counting of the environmental attributes. Price and cost transparency matter, and verification and diligence costs should be reasonable both absolutely and as a share of credit value.
- **Quality.** This category overlaps substantially with common carbon market criteria, and superpollutant credits tend to score comparatively well because the abatement is typically a discrete, measurable, and physically irreversible event. Five aspects warrant particular attention: 1) additionality, which carries unusual weight where compliance obligations vary by jurisdiction and change quickly; 2) net climate benefit assessed across the full life cycle, including trade-offs between gases; 3) timing of impact, since superpollutants share potency but range in atmospheric lifetime, and some methodologies issue credits up front for avoided emissions long in the future; 4) safeguards against perverse incentives, which are a structural risk in a class of gases where the same actors often control both production and abatement; and 5) the potential to deliver co-benefits, which functions as an integrity and maturity signal as much as a marketing one.
- **A path to policy.** The project ideally builds capacity for future regulation. Superpollutants include some of the most heavily regulated classes of greenhouse gas, and voluntary carbon finance is transitional toward broader policy. Carbon finance can provide the funding to support innovation, evolve technologies, improve MRV systems, and reduce costs for new approaches. Policymakers can then point to these advances to justify regulations that scale action and impact.¹⁵⁶ For existing, mature technologies, carbon finance can also help to finance the infrastructure, data, and institutional capacity that regulation needs to function in the window before mandates arrive or in jurisdictions where they have not yet been written. Projects developed with this path to policy in mind should also have a crediting period scoped to expected policy timelines or with cutoffs sensitive to new regulations.

Making Climate Impact Claims with Superpollutant Credits

Companies should also consider their strategy for using credits in climate impact claims, especially given the considerations discussed in Chapter 4: Value Chain. Companies can use credits to offset emissions to reach net zero or make a “contribution claim” (see guidance from SBTi and VCMI, listed in Box “For companies new to carbon credits” on page 70).

Since many superpollutants have a strong—but shorter-lived—effect on the atmosphere compared with carbon dioxide, the effect of avoided warming from one superpollutant credit is felt for a shorter time than the warming impact of the metric ton of CO₂ emitted that it may be used to offset. Rather than treating this as a limitation, forward-thinking portfolio approaches use it as a structural feature.

Strategies include stacking credits either horizontally or vertically to neutralize not just net emissions but also their total warming impact over time. By vertically stacking credits, a buyer purchases multiple shorter-duration credits up front. By horizontally stacking credits, buyers replace each short-lived credit with another credit when its impact on warming ends.¹⁵⁷ Companies can secure these credits through forward purchase agreements or by establishing an escrow-type account to ensure that funds are available to purchase future credits. Google is a leading example of this approach, proposing a common metric of sustained warming neutralization that translates the climate impact of both shorter- and longer-lived emissions into a single metric.¹⁵⁸

Temperature impact-based approaches, metrics and portfolios are still emerging and being tested. However, in the near term they can help to address durability or volatility concerns, mitigate risks through diversification, and address concerns of taking short-lived mitigation actions against long-lived emission liabilities. Regardless of the structure,

when used well, superpollutant credits can absorb near-term volume and cost pressure and reduce the burden on CDR and nature-based VCM projects to meet climate goals in a period when those project types are still scaling.

Buyer Call to Action

Fully utilizing the VCM means both purchasing more available superpollutant credits today via the spot market and—if there is capacity—buying forward and investing to help build tomorrow’s supply. In both cases, the selection criteria outlined above should guide buyers on which credits and projects to prioritize. Credits that meet these criteria are more likely to deliver the outcomes superpollutant mitigation is best positioned to offer: genuine, near-term reductions in warming impact. A portfolio approach is more defensible than attempting to optimize for any single criterion.

Companies can also act as project hosts, contribute to R&D, innovate on MRV systems, and share their experiences and best practices to help build the field.

Carbon markets are best understood as a bridge and a financing mechanism rather than an end state. The trajectory of renewable energy is instructive: carbon finance helped attract early capital, build infrastructure, and bring down costs to the point where renewables now largely compete on their own economics, without needing carbon markets to remain viable. Superpollutant mitigation can follow a similar path. Sustained buyer engagement today, through both spot and forward purchasing, can accelerate the point at which refrigerant recovery, methane capture, and nitrous oxide abatement become standard practice: supported by policy, embedded in ordinary business operations, and no longer reliant on carbon credit markets to justify their economics.

Checklist 2: Voluntary carbon market checklist for companies

Next 12–24 months period:

- ☐ Review the superpollutant mitigation measures reachable through carbon markets today—see Appendix B on Mitigation Measures.
- ☐ Confirm how carbon credits can be used toward your company’s climate targets and claims, such as toward a net-zero target or a contribution claim, and in relation to key standards.
- ☐ Screen candidate projects against criteria at the project level (using ratings rather than the category average).
- ☐ Make a spot purchase of a recommended superpollutant credit type directly, or via a broker, platform, or aggregator.
- ☐ Open a conversation with at least one project developer about a forward offtake.
- ☐ Act as a strategic partner to project developers by offering host sites, technical input, research and development support, referrals, and shared due diligence.
- ☐ Publish results and lessons learned, since demonstrated outcomes attract the next tranche of buyers.

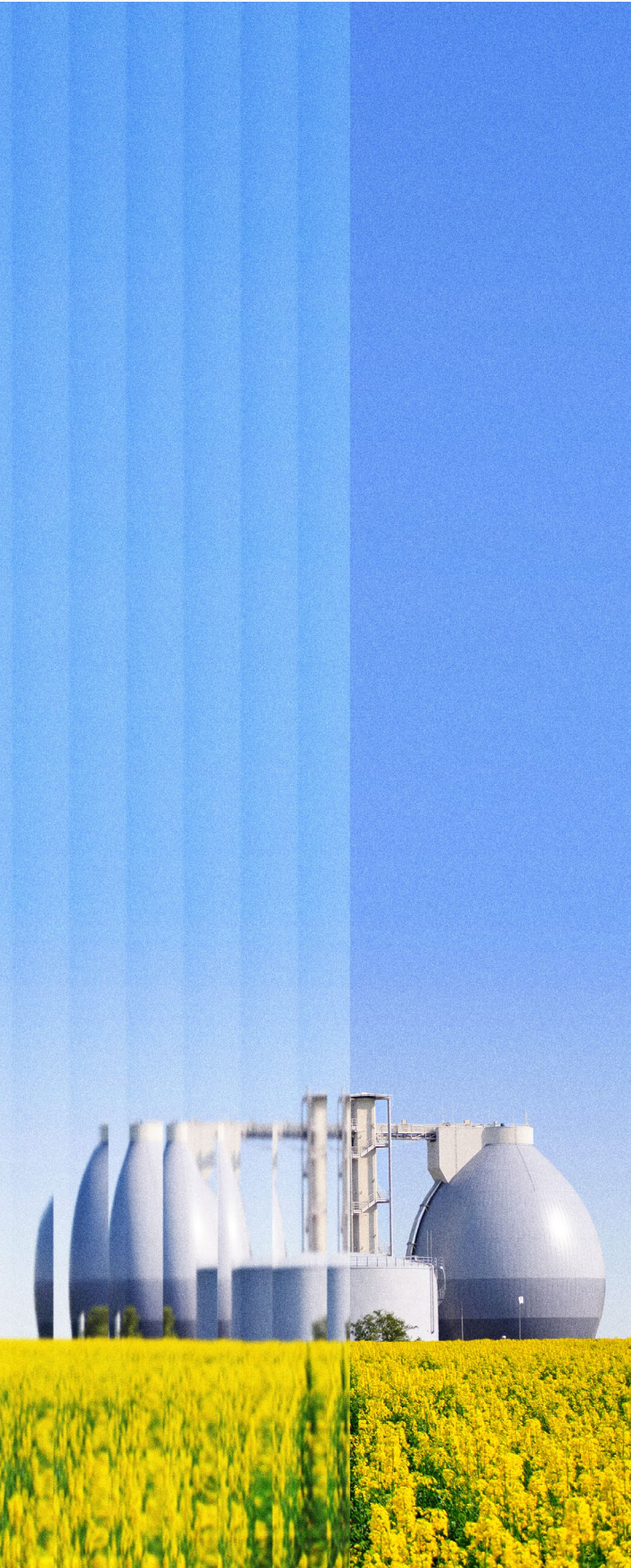
By 2030:

- ☐ Review holdings against rules and policies arriving through 2030, which will erode the additionality of credits.
- ☐ Build a portfolio that blends spot, forward, and direct investment across superpollutant and CO₂ pathways.
- ☐ Move a defined share of credit purchasing into multi-year forward agreements or direct project investment, accepting greater delivery risk in exchange for bringing new mitigation online.
- ☐ Determine whether the shorter atmospheric lifetime of superpollutants is material to the intended claim, and if so, whether vertical or horizontal stacking is the appropriate response. Potentially establish a ring-fenced or escrow-type fund where horizontal stacking is part of the approach, so that successive purchases are financed rather than merely intended.
- ☐ Support methodology development for pathways the market does not yet serve well.
- ☐ Act as a strategic partner to developers by offering host sites, technical input, research and development support, referrals, and shared due diligence.
- ☐ Publish results and lessons learned, since demonstrated outcomes attract the next tranche of buyers.



06

Lever 3: Policy Engagement



Policy engagement is the third lever that companies can pull to enhance the scale and impact of superpollutant action. Policy substantially shapes how quickly superpollutant mitigation can scale, how durable corporate action will be, and the size of the overall impact. Policy encompasses the full range of instruments through which governments and international bodies set expectations and enable action, from binding regulations and emissions standards to national climate plans and pledges. The Carbon Containment Lab also includes voluntary frameworks with public accountability, such as the Global Methane Pledge, in our definition of “policy,” since they often precede or substitute for mandatory rules. Moreover, cap-and-trade compliance programs are also included as policy, such as the EU Emissions Trading System (EU ETS), Australia’s Safeguard Mechanism, and regional approaches such as California’s Cap and Trade Program and Washington’s Cap-and-Invest program.¹⁵⁹

Superpollutant policy differs from carbon dioxide policy in three important aspects.

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- First, superpollutant policy is closely tied to multiple near-term benefits, making a stronger case for political action.** For example, methane reductions can deliver rapid climate relief while reducing ozone-related crop losses and avoiding premature deaths due to air pollution.¹⁶⁰ F-gas and efficient cooling policies can reduce peak electricity demand. LRM improves cooling resilience in rapidly warming regions.¹⁶¹ Reductions in black carbon, such as switching from diesel to electric vehicles, can immediately alleviate public health and air-quality problems associated with particulate matter.¹⁶² Nitrogen management policies can respond to water quality, biodiversity, fertilizer efficiency, food security, and nitrous oxide emissions at the same time.¹⁶³ Companies that connect their superpollutant strategies to these multiple benefits are more likely to find receptive policymakers and community partners.
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- Second, superpollutants are a diverse class of pollutants, and that diversity is reflected in how they are governed.** Unlike carbon dioxide, which is governed under a single overarching framework (Paris Agreement),¹⁶⁴ superpollutants are addressed through a patchwork of international agreements, sector-specific frameworks, and national policies, with some pollutants falling under multiple regimes.¹⁶⁵ Each pollutant has distinct physical and chemical characteristics, mitigation pathways, and institutional authorities. The result is an interconnected but fragmented policy landscape with no single treaty governing all superpollutants, limited understanding of the trade-offs that can exist between mitigation measures, and an accounting and metrics system that undervalues their climate impacts and the mitigation opportunity relative to CO₂. For companies, this fragmentation means tracking separate policy trajectories across pollutants.
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- Third, exposure to superpollutant policy is often distant from the company's own direct operations, residing in value chains—upstream, downstream, or even outside of them.** A technology company procuring data center cooling equipment faces F-gas quota constraints at its equipment supplier, not in its own facilities. A food and beverage company sourcing from livestock or fertilizer-intensive agriculture carries methane and nitrous oxide exposure in its supply chain, not on its balance sheet. Consequently, companies that engage early with suppliers, contractors, and sourcing regions are better positioned for future policy changes than those waiting for direct regulatory pressure.

Superpollutant policy landscape today

Superpollutant policy is moving from voluntary ambition and pledges toward compliance and implementation, but through different pathways. F-gases are governed through a mature treaty-backed architecture; methane policy is accelerating through national and sector-specific rules; and nitrous oxide, tropospheric ozone, and black carbon are still governed largely through fragmented, indirect, or emerging frameworks. At the same time, superpollutants are increasingly being incorporated into national climate policy through Nationally Determined Contributions (NDCs). As of August 2026, 149 countries had submitted NDC 3.0, with many strengthening the inclusion and specificity of methane, black carbon, nitrous oxide, and HFC mitigation measures.¹⁶⁶ Across all of these policy areas, the Climate and Clean Air Coalition (CCAC) is an international platform for translating political commitments into national action, supporting governments with scientific and technical assistance, financing, and partnership opportunities that no single treaty currently provides.¹⁶⁷

TABLE 10: THE CURRENT SUPERPOLLUTANT POLICY LANDSCAPE: SNAPSHOT

Superpollutant	Corporate exposure	Core policy architecture	Policy maturity	Policy pathway	Near-term implications for companies
Methane	Energy procurement, oil and gas supply chains, coal mines, agriculture, waste facilities, wastewater	Global Methane Pledge, IMO methane measures, Nationally Determined Contributions (NDCs), national methane plans, OGMP 2.0, agriculture and industrial sector-specific rules	Accelerating, but uneven across sectors and geographies	Moving from voluntary pledges toward binding national and sectoral regulation	Methane is a compliance, market-access, and supplier-performance issue, especially where measurement-based reporting and import standards emerge
F-Gases	Residential and commercial HVAC systems, refrigeration, cold chains, data centers, electricity infrastructure, semiconductors, fire suppression	Montreal Protocol and its Kigali Amendment, Global Cooling Pledge, NDCs, national HFC rules (e.g., U.S. AIM Act, EU F-gas Regulation), and national cooling action plans	Relatively mature and enforceable	Treaty-backed phasedown translated into quotas, equipment standards, leak rules, procurement requirements, and domestic regulation	Companies face near-term compliance and procurement decisions as high-GWP refrigerants become scarcer, costlier, and more restricted
Nitrous Oxide	Food and agriculture, nylon and chemicals, polyurethane foams, wastewater, and selected healthcare uses	Colombo Declaration on Sustainable Nitrogen Management, Global Nitrous Oxide Assessment, Gothenburg Protocol, NDCs, national nitrogen management initiatives for industrial and agricultural sectors	Emerging with clear industrial mitigation opportunities	Stronger industrial regulations and agricultural nitrogen management	Industrial nitrous oxide can move quickly through supplier standards, while agricultural nitrous oxide requires earlier engagement on nitrogen-use efficiency and MRV

Continued →

Superpollutant	Corporate exposure	Core policy architecture	Policy maturity	Policy pathway	Near-term implications for companies
Tropospheric Ozone	Transport and logistics, industrial facilities, solvents, petrochemicals, agriculture, methane-intensive supply chains	Gothenburg Protocol, Convention on Long-range Transboundary Air Pollution, WHO Air Quality Guidelines, NDCs, regional and national air quality standards, and NO _x /VOC rules	Stronger as air quality policy while slowly emerging as climate policy	Governed indirectly through controls on precursor pollutants, including nitrogen oxides, non-methane volatile organic compounds, carbon monoxide, and methane	Companies already reducing nitrogen oxides, volatile organic compounds, and methane can make tropospheric ozone benefits explicit and support integrated climate and air-quality policy
Black Carbon	Freight, shipping, diesel fleets, mining, construction, manufacturing supply chains, agricultural burning, cookstoves	Gothenburg Protocol, Convention on Long-range Transboundary Air Pollution, Arctic Council, IMO standards, NDCs, regional and national PM2.5 and air quality standards, Euro VII (EU), EPA HD nitrogen oxide rules (U.S.), Clean Cooking Initiatives, Malé Declaration, Acid Deposition Monitoring Network in East Asia	Relatively stronger as air quality and health policy, and slowly emerging as climate policy	Governed mostly through air-quality, diesel, shipping, fuel, combustion, and technology standards	Corporate effort needed on clean transport, fuel quality, particulate controls, and supplier standards. Companies already transitioning to electric vehicles can also describe the contribution to black carbon mitigation

This uneven landscape calls for selective policy engagement by companies that have a strategic interest in ambitious implementation or even new business lines that can serve these new markets. Companies with investments in cleaner operations, equipment, and supply chains are undermined when markets face weaker or unenforced standards or when lobbying by industry associations favors another direction. Where rules already exist, as with F-gas policies, the priority is implementation, enforcement, and resistance to rollback. Where ambition is strong but regulation remains uneven, as with methane, companies can use a combination of voluntary action and active policy engagement by adopting rigorous measurement and abatement practices while advocating for the binding standards, MRV requirements, and finance mechanisms that convert political pledges into enforceable market expectations. Where governance remains fragmented, as with nitrous oxide, tropospheric ozone, and black carbon, companies can advocate for these pollutants to be included in NDCs, national action plans, and stronger sector standards. Consistent, quantified targets support compliance strategy and create a level playing field across markets. Companies can also push for change in their own value chains.

Corporate action in superpollutant policy

The most useful corporate role varies by superpollutant and market, but the same set of engagement strategies could apply across all superpollutants and geographies.

TABLE 11: CORPORATE ACTIONS IN ACCELERATING SUPERPOLLUTANT POLICY

Corporate policy role	Purpose	Most relevant policy context	Actions companies can take
Support implementation and finance	Turn existing commitments into real emissions reductions	Mature or semi-mature policy environments where ambition exists but implementation capacity has been slow	- Advance market commitments - Strike offtake agreements - Support public and blended finance - Co-invest in supplier upgrades - Participate in implementation partnerships - Back technical assistance - Engage with multilateral banks to co-invest
Advocate for strong sectoral standards and MRV	Convert corporate best practice into enforceable market expectations	Sectors where rules are developing but coverage remains uneven	- Advocate for clear sectoral standards, timelines, MRV requirements, leak detection rules, equipment requirements, and sector-specific emissions limits - Participate in technical working groups and standards consultation
Use procurement to drive policy	Demonstrate that higher standards are commercially feasible and help to build the market for new solutions	Markets where regulation is emerging and/or where suppliers need demand certainty to invest	- Publish procurement specifications, require supplier performance thresholds, aggregate demand with peers, support and respond to public procurement efforts - Share implementation evidence with policymakers who themselves work on sustainable public procurement
Elevate superpollutants into climate planning	Bring underaddressed superpollutants into NDCs' consultation processes, regional policy arrangements, national action plans, and sectoral strategies	Nitrous oxide, tropospheric ozone, black carbon, and underspecified F-gases or methane plans	Advocate for explicit targets, sector pathways, implementation plans, and multiple benefits accounting for air quality, health, and food security
Align lobbying and trade associations	Ensure corporate political activity supports stated climate goals	Policy areas where implementation is contested or standards face delay	- Review trade association positions, oppose rollbacks, support ambitious implementation timelines - Disclose alignment between climate commitments and policy advocacy

Policy is a force multiplier for value chain

interventions and carbon market strategies. Well-designed methane policies, F-gas regulations, nitrogen strategies, air-quality rules, and measurement systems create enabling conditions for project pipelines, high-integrity carbon credits, supplier transitions, and finance solutions. Policy also creates consistency and standards that promote trust and verifiability for secondary markets. Value chain interventions then generate evidence about costs, barriers, supplier incentives, and multiple benefits. Carbon market participation fuels demand for high-integrity project types and methodologies and pays for building core MRV and other physical infrastructure. Policy uses the evidence of commercially achievable higher standards and demand to make further action easier, more secure, and cheaper. The roadmap's three levers are complementary and form a strong feedback loop.

Methane illustrates the feedback loop between policy, value chain and voluntary carbon market (VCM) most clearly: companies that improve methane performance across operations and supply chains generate the implementation evidence that regulators need to set measurement-based standards. Meanwhile, high-integrity credit purchases aligned with national methane plans create demand signals that justify new project investment. The dynamic is consistent across all superpollutants. Companies that approach these three levers as one integrated system are better positioned to contribute to near-term warming reduction and protect the value of the actions they have already taken.

Checklist 3: Superpollutant policy action checklist for companies

Next 12–24 months period:

- ☐ Map where each superpollutant emission arises across the company's operations, procurement categories, and priority suppliers.
- ☐ Identify the policies in key markets that already affect those sources or are likely to do so before 2030, including methane rules, F-gas regulations, nitrogen measures, and air-quality standards.
- ☐ If the company has compliance obligations in regulated cap-and-trade systems, prefer buying superpollutant mitigation credits to meet obligations.
- ☐ Prioritize the superpollutants and jurisdictions that create the greatest combination of regulatory exposure, value-chain risk, and mitigation opportunity (e.g., EU Methane and F-Gas Regulation, China's HFC controls, U.S. HFC phasedown, NDCs under the Paris Agreement, tightening diesel-emission standards and Arctic shipping regulations).
- ☐ Review the company's current public-policy positions, advocacy, and trade association memberships for alignment with its climate and superpollutant goals.
- ☐ Issue internal guidance for government affairs, sustainability, procurement, and legal teams on which superpollutant policies the company will support, monitor, or avoid undermining.
- ☐ Choose one or two active policy processes where the company can add value, such as sectoral methane regulations, national cooling action plans, nitrogen management, criteria air pollutant mitigation and/or air-quality regulations.
- ☐ Use procurement and supplier management to show that higher standards are feasible—for example, by buying certified lower-emission natural gas, requiring methane measurement, selecting low- or zero-GWP cooling equipment, and buying cleaner, verified commodities.
- ☐ Join or deepen participation in credible implementation-focused initiatives, such as CCAC Hubs, OGMP 2.0, or relevant sector platforms.

By 2030:

- ☐ Embed superpollutant policy action into the company's climate and sustainability work, with named executive responsibility and regular board visibility.
- ☐ Publicly disclose the company's approach to supporting the implementation of key superpollutant actions.
- ☐ Adopt a formal policy stating that lobbying, trade association activity, and political spending will not be used to delay, weaken, or oppose science-aligned superpollutant policy.
- ☐ Integrate superpollutant expectations into procurement standards, supplier scorecards, transition plans, research and development plans, and capital allocation processes.
- ☐ Review progress annually and update the company's policy priorities as regulations, market signals, and sector pathways evolve.

Conclusion

Superpollutants are the most immediate, cost-effective, and scalable opportunity to slow near-term warming and reduce the risk of reaching dangerous climate tipping points. The science is settled enough to act on, the levers proven, and the tools mostly exist today. What is missing is not knowledge or technology. It is corporate action at scale.

Superpollutants account for roughly half of today's warming. Since they leave the atmosphere within years or decades, cutting them slows warming on a timeline that carbon dioxide mitigation measures cannot touch. This roadmap's forward-looking modeling demonstrates just how much is at stake: roughly half of the warming prevented on a 2°C-consistent pathway comes from superpollutants. Companies readily name these gases but rarely commit to reducing them. Outside of oil and gas, where regulation has already compelled target-setting, superpollutant targets remain nearly absent. This roadmap sets out to address that mismatch between sources of warming and existing efforts.

The chapters laid out three reinforcing ways to close it: reducing emissions inside the value chain, financing verified mitigation through the voluntary carbon market, and engaging on the policies that make both durable. These are not three separate tactics, but one integrated strategy: value chain action generates the evidence; market participation supplies the finance; and policy engagement turns both into lasting rules applied to all. This strategy is already working in practice: the companies that launched the Superpollutant Action Initiative demonstrate as much. The pathfinders are showing the gap is closable. What remains is to close it at scale and with more urgency.

The gap will not close on its own. The near-term, superpollutant-driven warming is happening now,

and the window to bend that curve spans years, not decades. Governments are moving, but unevenly and slowly; voluntary markets are maturing, but remain thinly capitalized and volatile. Corporations hold what this moment requires: the catalytic capital, the procurement leverage over the supply chains where these emissions are concentrated, and the standing to make superpollutant action a normal expectation rather than a rare exception. On the current trajectory, the targets the world has set will not be met. They can be—if the companies with the means decide to act.

The rules are also changing in ways that make the choice less optional than it once was. Under the revised science-based target architecture, superpollutant emissions such as fugitive methane, refrigerant leakage, or industrial F-gases will move from the margins to the center of the target for larger companies.

The case for tackling superpollutants only grows stronger with time. Measurement is improving, sharpening accountability and derisking investment. The set of credible, near-term actions is expanding as science advances and entrepreneurs deploy new solutions. And the stakes are rising as a warming climate pushes natural methane and nitrous oxide sources upward—making early action more valuable and waiting more costly.

The opportunity is a rare one. The companies that move now will help write the standards, secure the lowest-cost abatement, and protect the value of the commitments they have already made. Those that wait will inherit rules written by others and pay more to meet them. This roadmap is an invitation, but it is also a challenge. The half of the climate problem that moves fastest is the half still waiting for corporate leadership. It is time to take it on.

Endnotes

- 1 “Super Pollutants” Climate & Clean Air Coalition, 22 July 2024. www.ccacoalition.org/news/super-pollutants.
- 2 International Energy Agency, “Global Methane Tracker 2025: Methane Abatement Costs in the Energy Sector,” IEA, <https://www.iea.org/reports/global-methane-tracker-2025>.
- 3 Ibid.
- 4 Chris Casey, “Danone Commits to 30% Methane Reduction from Milk Supply by 2030,” Food Dive, January 17, 2023, <https://www.fooddive.com/news/danone-methane-30-percent-2030-dairy-regenerative-environmental-defense-fund/640534/>.
- 5 Environmental Investigation Agency, “ALDI Becomes First U.S. Food Retailer to Commit to Natural Refrigerants Across All Stores,” January 11, 2024, <https://eia.org/blog/aldi-becomes-first-u-s-food-retailer-to-commit-to-natural-refrigerants-across-all-stores/>.
- 6 Apple Inc., “Apple Unveils Environmental Progress, Surpassing 60 Percent Reduction in Global Greenhouse Gas Emissions,” Apple Newsroom, April 16, 2025, <https://www.apple.com/newsroom/2025/04/apple-surpasses-60-percent-reduction-in-global-greenhouse-gas-emissions/>.
- 7 Heather Clancy, “Why Office Software Vendor Workday Is Paying to Plug ‘Orphaned’ Oil and Gas Wells,” Trellis, December 13, 2024, <https://trellis.net/article/workday-tradewater-deal-addresses-methane-emissions/>.
- 8 Carbon Containment Lab, “Announcing Our Partnership with Beyond Alliance to Develop a Global Corporate Roadmap on Superpollutant Action,” March 3, 2026, <https://carboncontainmentlab.org/updates/posts/superpollutant-roadmap>.
- 9 “Super Pollutants” Climate & Clean Air Coalition, 22 July 2024. www.ccacoalition.org/news/super-pollutants.
- 10 “Super Pollutants” Climate & Clean Air Coalition, 22 July 2024. www.ccacoalition.org/news/super-pollutants.
- 11 Sophie Szopa et al., “Short-Lived Climate Forcers. 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 University Press, 2021), 817–922, <https://www.ipcc.ch/report/ar6/wg1/chapter/chapter-6/> <https://doi.org/10.1017/9781009157896.008>
- 12 <https://www.nature.com/articles/s41467-026-68586-y> and <https://www.pnas.org/doi/10.1073/pnas.2123536119>
- 13 <https://www.nature.com/articles/s41612-025-01131-8>
- 14 Shine, K., Fuglestvedt, J. S., Hailemariam, K., & Stuber, N. (2005). Alternatives to the Global Warming Potential for Comparing Climate Impacts of Emissions of Greenhouse Gases. *Climatic Change*, 68(3), 281-302. <https://doi.org/10.1007/s10584-005-1146-9>
- 15 IPCC, V. Masson-Delmotte, P. Zhai, et al., “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* (2021), <https://doi.org/10.1017/9781009157896.001>.
- 16 Chris Smith et al, “Table 7.SM.6: Greenhouse gas lifetimes, radiative efficiencies and metrics,” 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* (2021), https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Chapter07_SM.pdf.
- 17 “Accelerating Action on Tropospheric Ozone: A Strategic Roadmap for 2025-2030,” Clean Air Fund, June 26, 2025, <https://www.cleanairfund.org/resource/accelerating-action-on-tropospheric-ozone/>.
- 18 J. Jason West et al., “Global health benefits of mitigating ozone pollution with methane emission controls,” *Proceedings of the National Academy of Sciences* 103, no. 11 (March 14, 2006): 3988–3993, <https://doi.org/10.1073/pnas.0600201103><https://pubmed.ncbi.nlm.nih.gov/16537473/>.

- 19 United Nations Environment Programme and Climate and Clean Air Coalition (2021). “Global Methane Assessment: Benefits and Costs of Mitigating Methane Emissions.” Nairobi: United Nations Environment Programme.
- 20 Ibid.
- 21 Ibid.
- 22 Ibid.
- 23 “Methane Emissions,” Overview of Greenhouse Gases, United States Environmental Protection Agency, last modified March 10, 2026, <https://www.epa.gov/ghgemissions/methane-emissions>.
- 24 Z. Zhang, et al, “Emerging role of wetland methane emissions in driving 21st century climate change,” *Proc. Natl. Acad. Sci. U.S.A.* 114 (36) 9647-9652 (2017), <https://doi.org/10.1073/pnas.1618765114>.
- 25 Qing Zhu et al, “Advancements and opportunities to improve bottom-up estimates of global wetland methane emissions,” *Environ. Res. Lett.* (20) 023001, (2025) DOI:10.1088/1748-9326/adad02. “Methane,” Earth Indicators, National Aeronautics and Space Administration,, accessed June 15, 2026, <https://science.nasa.gov/earth/explore/earth-indicators/methane/>. National Academies of Sciences, Engineering, and Medicine 2024 *A Research Agenda Toward Atmospheric Methane Removal* (Washington, D.C.: National Academies Press) Online: <https://nap.nationalacademies.org/catalog/27157>
- 26 Center for Climate and Energy Solutions (C2ES), “Accelerating the Substantial Reduction of Methane Emissions by 2030,” (2025), <https://www.c2es.org/document/accelerating-the-substantial-reduction-of-methane-emissions-by-2030/>. Thomas Stoerk et al., “Global Methane Action Pays for Itself at Least Six Times Over,” *Science* 390, no. 6772 (October 2025), <https://doi.org/10.1126/science.adu7392>.
- 27 “Methane abatement options,” Methane Tracker 2020, IEA, 2020, <https://www.iea.org/reports/methane-tracker-2020/methane-abatement-options>
- 28 “Oil and Gas Methane Mitigation Program,” Methane, Clean Air Task Force, accessed August 11, 2026, <https://www.catf.us/methane/mitigation-program/>. “Global Methane Tracker 2025: Methane Abatement Costs in the Energy Sector,” Reports, International Energy Agency, May 7, 2025, <https://www.iea.org/reports/global-methane-tracker-2025>.
- 29 Aklilu W. Alemu et al., “3-Nitrooxypropanol Decreased Enteric Methane Production From Growing Beef Cattle in a Commercial Feedlot: Implications for Sustainable Beef Cattle Production,” *Frontiers in Animal Science* 2 (February 16, 2021): 641590, <https://doi.org/10.3389/fanim.2021.641590>.
- 30 “Waste Sector Solutions,” *Short-Lived Climate Pollutants*, Climate and Clean Air Coalition, accessed August 11, 2026, <https://www.ccacoalition.org/content/waste-sector-solutions>. Patrick S. Sullivan, The Importance of Landfill Gas Capture and Utilization in the U.S., Earth Engineering Center, Columbia University and SCS Engineers, April 2010, https://www.scsengineers.com/wp-content/uploads/2015/03/Sullivan_Importance_of_LFG_Capture_and_Utilization_in_the_US.pdf.
- 31 United Nations Environment Programme and Food and Agriculture Organization of the United Nations, “Global Nitrous Oxide Assessment,” (Nairobi: UNEP, November 2024), <https://wedocs.unep.org/items/fe972a7d-7aa2-4337-b27d-0cd857046eb9>.
- 32 Chris Smith et al, “Table 7.SM.7: Greenhouse gas lifetimes, radiative efficiencies, global warming potentials (GWPs), global temperature potentials (GTPs) and cumulative global temperature potentials (CGTPs),” 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* (2021), https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Chapter07_SM.pdf.
- 33 United Nations Environment Programme and Food and Agriculture Organization of the United Nations, “Global Nitrous Oxide Assessment,” Nairobi: UNEP and FAO, 2024, <https://doi.org/10.59117/20.500.11822/46562>. A. R. Ravishankara, Josh. S. Daniel, and Robert W. Portmann, “Nitrous Oxide (N₂O): The Dominant Ozone-Depleting Substance Emitted in the 21st Century,” *Science* 326,123-125(2009). DOI:10.1126/science.1176985
- 34 William F. Lamb et al., “Emissions Trends and Drivers,” in *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge: Cambridge University Press, (2022), doi: 10.1017/9781009157926.004 <https://www.ipcc.ch/report/ar6/wg3/chapter/chapter-2/>

- 35 Tian H., et al., "Global nitrous oxide budget (1980-2020)," *Earth Syst. Sci. Data*, 16, 2543–2604, (2024). <https://doi.org/10.5194/essd-16-2543-2024>
- 36 Ibid.
- 37 "Nitrous Oxide Emissions," Overview of Greenhouse Gases, United States Environmental Protection Agency, March 2, 2026, <https://www.epa.gov/ghgemissions/nitrous-oxide-emissions>.
- 38 Andrew J. Thomson et al., "Biological Sources and Sinks of Nitrous Oxide and Strategies to Mitigate Emissions," *Philosophical Transactions of the Royal Society B: Biological Sciences* 367, no. 1593 (May 5, 2012): 1157–68, <https://doi.org/10.1098/rstb.2011.0415>.
- 39 US EPA, "Global Mitigation of Non-CO₂ Greenhouse Gases: Nitric and Adipic Acid Production." https://19january2017snapshot.epa.gov/global-mitigation-non-CO2-greenhouse-gases/global-mitigation-non-CO2-greenhouse-gases-nitric-and_.html
- 40 D. Ferland, et al., "Improved Nitrogen Fertilizer Management Reduces Nitrous Oxide Emissions in a Northern Prairie Cropland," *Science of The Total Environment* 956 (December 15, 2024), <https://doi.org/10.1016/j.scitotenv.2024.177211>.
- 41 Gu, B., et al., "Cost-effective mitigation of nitrogen pollution from global croplands," *Nature* 613, 77–84 (2023). <https://doi.org/10.1038/s41586-022-05481-8>. "Improve Nutrient Management," Cut Emissions, Project Drawdown. last updated December 23, 2025, <https://drawdown.org/explorer/improve-nutrient-management>
- 42 Singh U, et al., "Technological avenues and market mechanisms to accelerate methane and nitrous oxide emissions reductions," *iScience*, (November 24, 2022), 24;25(12):105661. doi: 10.1016/j.isci.2022.105661.
- 43 "Fluorinated Gas Emissions," Greenhouse Gas Emissions, U.S. Environmental Protection Agency, March 10, 2026, <https://www.epa.gov/ghgemissions/fluorinated-gas-emissions>.
- 44 Molina, M. and Rowland, F, "Stratospheric sink for chlorofluoromethanes: chlorine atom-catalyzed destruction of ozone., " *Nature* 249, 810–812 (1974). <https://doi.org/10.1038/249810a0>. World Meteorological Organization (WMO). Executive Summary. Scientific Assessment of Ozone Depletion: 2022, GAW Report No. 278, 56 pp.; WMO: Geneva, 2022.
- 45 Chris Smith et al, "Table 7.SM.7: Greenhouse gas lifetimes, radiative efficiencies, global warming potentials (GWPs), global temperature potentials (GTPs) and cumulative global temperature potentials (CGTPs)," 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* (2021), https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Chapter07_SM.pdf. "About Montreal Protocol," Ozone Action, United Nations Environment Programme, accessed August 11, 2026 <https://www.unep.org/ozonaction/who-we-are/about-montreal-protocol>.
- 46 Ozone Secretariat, United Nations Environment Programme, "Handbook for the Montreal Protocol on Substances that Deplete the Ozone Layer," Fourteenth Edition, (2020), <https://ozone.unep.org/sites/default/files/Handbooks/MP-Handbook-2020-English.pdf>
- 47 "Figure 1: Global ODS Banks in kt of Substance," in *Global Banks of Ozone Depleting Substances (ODS) and Hydrofluorocarbons (HFCs): A Country-Level Estimate 2024*, Climate and Ozone Protection Alliance, (2025), https://www.copalliance.org/imglib/publications/2025-04_COPA_Global%20Banks%20ODS%20HFC_update.pdf.
- 48 Chris Smith et al, "Table 7.SM.7: Greenhouse gas lifetimes, radiative efficiencies, global warming potentials (GWPs), global temperature potentials (GTPs) and cumulative global temperature potentials (CGTPs)," 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* (2021), https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Chapter07_SM.pdf.
- 49 Velders, G. J. M., et al, "Projections of hydrofluorocarbon (HFC) emissions and the resulting global warming based on recent trends in observed abundances and current policies," *Atmos. Chem. Phys.*, 22, 6087–6101, (2022), <https://doi.org/10.5194/acp-22-6087-2022>.
- 50 United Nations Environment Programme. "Global Cooling Watch 2023: Keeping it Chill: How to meet cooling demands while cutting emissions," (2023). Nairobi.

- 51 “Fluorinated Gas Emissions,” Greenhouse Gas Emissions, United States Environmental Protection Agency, March 10, 2026, <https://www.epa.gov/ghgemissions/fluorinated-gas-emissions>.
- 52 Chris Smith et al., “Table 7.SM.7: Greenhouse gas lifetimes, radiative efficiencies, global warming potentials (GWPs), global temperature potentials (GTPs) and cumulative global temperature potentials (CGTPs),” 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 (2021), https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Chapter07_SM.pdf.
- 53 X. Wu, et al., “State of the art on the flammability of hydrofluoroolefin (HFO) refrigerants,” *International Journal of Refrigeration*, 108:209-223, (2019), <https://doi.org/10.1016/j.ijrefrig.2019.08.025>.
- 54 Michael Garry, “The Rising Threat of HFOs and TFA to Health and the Environment,” *ATMOsphere*, (July 2025), https://atmosphere.cool/wp-content/uploads/2025/07/2025_HFO_TFA_report.pdf.
- 55 “Time to Leapfrog over the Chemical Industry’s Next Generation of Climate-Wrecking Refrigerants,” *News*, Environmental Investigation Agency, July 10, 2025, <https://eia-international.org/news/time-to-leapfrog-over-the-chemical-industrys-next-generation-of-climate-wrecking-refrigerants/>. Cool Up Programme, “Why Refrigerant Choice Matters: The Impact of “Forever Chemicals” on Our Environment,” (July 2025), hosted by the United Nations Environment Programme, https://ozone.unep.org/system/files/documents/Cool%20Up_%20OEWG47_PFAF_final.pdf.
- 56 Ibid.
- 57 Jens Mühle et al., “Perfluorocarbons in the global atmosphere: tetrafluoromethane, hexafluoroethane, and octafluoropropane,” *Atmospheric Chemistry and Physics* 10, no. 11 (June 2010): 5145–5164, <https://doi.org/10.5194/acp-10-5145-2010>.
- 58 M. An, et al., “Substantial increase in perfluorocarbons CF₄ (PFC-14) and C₂F₆ (PFC-116) emissions in China,” *Proc. Natl. Acad. Sci. U.S.A.* 121 (30) e2400168121, (July 15, 2024), <https://doi.org/10.1073/pnas.2400168121> (2024).
- 59 Ibid.
- 60 Shengyao Shi et al., “Recent advances in degradation of the most potent industrial greenhouse gas sulfur hexafluoride,” *Chemical Engineering Journal* 470 (August 15, 2023): 144166, <https://doi.org/10.1016/j.cej.2023.144166>.
- 61 “Sulfur Hexafluoride (SF₆): The Most Potent Greenhouse Gas,” IFEAA, accessed October 22, 2024, <https://www.ifeaa.com/2024/10/22/sulfur-hexafluoride-sf6-the-most-potent-greenhouse-gas/>.
- 62 Simmonds, P. G., et al., “The increasing atmospheric burden of the greenhouse gas sulfur hexafluoride (SF₆),” *Atmos. Chem. Phys.*, 20, 7271–7290, (2020), <https://doi.org/10.5194/acp-20-7271-2020>. An, M., et al., “Sustained growth of sulfur hexafluoride emissions in China inferred from atmospheric observations,” *Nat Commun* 15, 1997 (2024). <https://doi.org/10.1038/s41467-024-46084-3>
- 63 Chris Smith et al., “Table 7.SM.7: Greenhouse gas lifetimes, radiative efficiencies, global warming potentials (GWPs), global temperature potentials (GTPs) and cumulative global temperature potentials (CGTPs),” 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 (2021), https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Chapter07_SM.pdf
- 64 Stephen Russell, “Nitrogen Trifluoride Now Required in GHG Protocol Greenhouse Gas Emissions Inventories,” *World Resources Institute*, May 22, 2013, <https://www.wri.org/insights/nitrogen-trifluoride-now-required-ghg-protocol-greenhouse-gas-emissions-inventories>.
- 65 RF Weiss, J Muhle, PK Salameh, CM Harth, 2008, Nitrogen trifluoride in the global atmosphere, *Geophysical Research Letters*, 35, L20821, <https://doi.org/10.1029/2008GL035913>
- 66 Willem Vriesendorp, Anastasia O’Rourke, Ethan Olim, Selin Gören, Sage Wen, *Bending the curve: Cost-effective cooling emissions reduction pathways for commercial real estate in China and the U.S.* (Carbon Containment Lab, 2026,) <https://carboncontainmentlab.org/publications/bending-the-curve>
- 67 Christina Theodoridi et al., *Lifecycle Refrigerant Management: How minimizing leaks and maximizing reclaim can avoid up to 91 billion metric tons CO₂-eq emissions* (Natural Resources Defense Council; Environmental Investigation Agency; Institute for

- Governance & Sustainable Development, 2022), 4, <https://www.nrdc.org/sites/default/files/lrm-90-billion-ton-opportunity-report-20221020.pdf>
- 68 Technological and Economic Assessment Panel, TEAP Task Force Report on Lifecycle Refrigerant Management (United Nations Environmental Program, 2024), <https://ozone.unep.org/system/files/documents/TEAP-May2024-DecXXXV-11-TF-Report.pdf>
 - 69 “Glossary: Tropospheric ozone precursors,” Statistics Explained, European Commission, accessed August 11, 2026, https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Glossary:Tropospheric_ozone_precursors.
 - 70 Clean Air Fund, “Accelerating Action on Tropospheric Ozone: A Strategic Roadmap for 2025–2030,” (June 26, 2025), <https://s40026.pcdn.co/wp-content/uploads/Accelerating-Action-on-Tropospheric-Ozone-Clean-Air-Fund.pdf>.
 - 71 Wei Song et al., “Important contributions of non-fossil fuel nitrogen oxides emissions,” *Nature Communications* 12 (January 2021): 243, <https://doi.org/10.1038/s41467-020-20356-0>.
 - 72 Sophie Szopa et al., “Short-Lived Climate Forcers,” 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*, ed. Valérie Masson-Delmotte et al. (Cambridge and New York: Cambridge University Press, 2021), chap. 6, pp. 817–922, https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Chapter06.pdf.
 - 73 Ibid.
 - 74 Ibid.
 - 75 Shiri Avnery et al., “Global Crop Yield Reductions due to Surface Ozone Exposure: 2. Year 2030 Potential Crop Production Losses and Economic Damage under Two Scenarios of O₃ Pollution,” *Atmospheric Environment* 45, no. 13 (April 2011): 2297–2309, <https://doi.org/10.1016/j.atmosenv.2011.01.023>.
 - 76 Yuan Wang et al., “Substantially Underestimated Global Health Risks of Current Ozone Pollution,” *Nature Communications* 16 (2025): 285, <https://doi.org/10.1038/s41467-024-55450-0>.
 - 77 Ibid.
 - 78 World Economic Forum, “Black Carbon Reduction: A Rapid Action Plan,” White Paper, World Economic Forum, (October 2024), https://www3.weforum.org/docs/WEF_Black_Carbon_Reduction_2024.pdf. Xuping Song et al., “Is Short-Term and Long-Term Exposure to Black Carbon Associated with Cardiovascular and Respiratory Diseases? A Systematic Review and Meta-Analysis Based on Evidence Reliability,” *BMJ Open* 12, no. 5 (2022): e049516, <https://doi.org/10.1136/bmjopen-2021-049516>. GBD 2021 Risk Factors Collaborators, “Global burden and strength of evidence for 88 risk factors in 204 countries and 811 subnational locations, 1990–2021: A systematic analysis for the Global Burden of Disease Study 2021,” *Lancet* 403, 2162–2203 (2024).
 - 79 Tami C. Bond et al., “Bounding the Role of Black Carbon in the Climate System: A Scientific Assessment,” *Journal of Geophysical Research: Atmospheres* 118, no. 11 (2013): 5380–5552, <https://doi.org/10.1002/jgrd.50171>.
 - 80 “Black carbon,” Short-Lived Climate Pollutants, Climate and Clean Air Coalition, <https://www.ccacoalition.org/short-lived-climate-pollutants/black-carbon>.
 - 81 Yusuf Jameel, Paul C. West, and Dawn Jasper, “Sources, Regional Patterns, and Trends,” in *Reducing Black Carbon: A Triple Win for Climate, Health, and Well-Being*, Project Drawdown, 2023, <https://drawdown.org/publications/reducing-black-carbon/sources-regional-patterns-and-trend>.
 - 82 “A Vision for Clean Cooking Access for All,” International Energy Agency, 2023, <https://www.iea.org/reports/a-vision-for-clean-cooking-access-for-all>
 - 83 Yusuf Jameel, Paul C. West, and Dawn Jasper, “Sources, Regional Patterns, and Trends,” in *Reducing Black Carbon: A Triple Win for Climate, Health, and Well-Being*, Project Drawdown, 2023, <https://drawdown.org/publications/reducing-black-carbon/sources-regional-patterns-and-trend>. “Black carbon,” Short-Lived Climate Pollutants, Climate and Clean Air Coalition, <https://www.ccacoalition.org/short-lived-climate-pollutants/black-carbon>.
 - 84 Jin Li et al., “Mitigating black carbon emissions: key drivers in residential usage and coke/brick production,” *National Science*

Review 11, no. 10 (October 2024), <https://doi.org/10.1093/nsr/nwae283>.

- 85 “Black Carbon.” Climate and Clean Air Coalition, accessed August 11, 2026, <https://www.ccacoalition.org/short-lived-climate-pollutants/black-carbon>. United Nations Environment Programme & World Meteorological Organization, “Integrated Assessment of Black Carbon and Tropospheric Ozone,” UNEP/WMO, (2011), https://www.ccacoalition.org/sites/default/files/resources/2011_integrated-assessment-FULL_UNEP-WMO.pdf
- 86 The World Bank, “Reducing Black Carbon Emissions from Diesel Vehicles: Impacts, Control Strategies, and Cost-Benefit Analysis,” Climate and Clean Air Coalition / The World Bank, (2014), <https://www.ccacoalition.org/sites/default/files/resources/Reducing%20Black%20Carbon%20Emissions%20from%20Diesel%20Vehicles.pdf>.
- 87 James Hansen and Larissa Nazarenko, “Soot Climate Forcing via Snow and Ice Albedos,” *Proceedings of the National Academy of Sciences* 101, no. 1 (December 2003): 423–28, <https://doi.org/10.1073/pnas.2237157100>.
- 88 United Nations Environment Programme & World Meteorological Organization, “Integrated Assessment of Black Carbon and Tropospheric Ozone,” Nairobi, Kenya: United Nations Environment Programme, (2011) https://www.ccacoalition.org/sites/default/files/resources/2011_integrated-assessment-FULL_UNEP-WMO.pdf
- 89 “Emission Impossible: Corporate Climate Goals Moving from Adoption to Execution,” The Conference Board, accessed July 2026, <https://www.conference-board.org/publications/Emission-impossible-corporate-climate-goals-moving-from-adoption-to-execution>.
- 90 “Net Zero Stocktake 2025,” New Climate Institute, September 22, 2025, <https://newclimate.org/resources/publications/net-zero-stocktake-2025>. McKenna Smith, “10,000 companies in 10 years: Companies leading the net-zero transformation,” Science Based Targets initiative (blog), February 17, 2026, <https://sciencebasedtargets.org/blog/10000-companies-in-10-years-companies-leading-the-net-zero-transformation>.
- 91 The 40 company data set included: ADNOC, ALDI, Amazon, Apple, Aviva, BlackRock, BP, Cargill, Carrefour, Chevron, Costco, Danone, Disney, ENI, Equinor, ExxonMobil, Google, HSBC, IKEA/Ingka, JBS, JPMorganChase, Kroger, Meta, Microsoft, Nestlé, Netflix, NVIDIA, PepsiCo, Petrobras, QatarEnergy, Salesforce, SAP, Saudi Aramco, Shell, Tesco, TotalEnergies, Tyson Foods, Unilever, Walmart, Workday
- 92 European Parliament and Council of the European Union, “Regulation (EU) 2024/1787 on the Reduction of Methane Emissions in the Energy Sector and Amending Regulation (EU) 2019/942,” June 13, 2024 (entered into force August 4, 2024). eur-lex.europa.eu/eli/reg/2024/1787/oj. “About OGDC,” Oil & Gas Decarbonization Charter, launched at COP28 under the Global Decarbonization Accelerator, December 2023. ogdc.org/about. “The Oil & Gas Methane Partnership 2.0,” United Nations Environment Programme, ogmpartnership.org.
- 93 Targets are the right diagnostic here because they are correlated with operational change. Analysis by the Federal Reserve Bank of San Francisco finds that companies setting climate targets report emissions approximately 14 percent lower five years after announcement than firms making no such pledge. On that evidence, a gas named in an inventory and absent from a target is a gas that will not be abated.
- 94 “2024 Climate-Friendly Supermarket Scorecard,” Environmental Investigation Agency, May 6, 2024, <https://eia.org/report/2024-climate-friendly-supermarket-scorecard/>. “Leaking Havoc: Exposing Your Supermarket’s Invisible Climate Pollution,” Environmental Investigation Agency, February 15, 2021, <https://www.climatefriendlysupermarkets.org/leaking-havoc>.
- 95 Andrew Jones, “Emission Impossible: Corporate Climate Goals Moving from Adoption to Execution,” July 15, 2026, <https://www.conference-board.org/publications/Emission-impossible-corporate-climate-goals-moving-from-adoption-to-execution>.
- 96 Kapoor, Sanchita. “Lobbying and Climate Goals: Corporate Alignment with the Paris Agreement.” S&P Global Sustainable1, CSA Data Briefs, July 18, 2025, <https://www.spglobal.com/sustainable1/en/csa/insights/lobbying-and-climate-goals-corporate-alignment-with-the-paris-agreement>.
- 97 “US Corporate Climate Advocacy Going Into 2025,” InfluenceMap, December 2024, <https://influencemap.org/briefing/US-Corporate-Climate-Advocacy-Going-Into-2025-30736>.
- 98 “EU Energy Companies & Industry Associations Diverging on the EU Methane Regulation,” InfluenceMap, April 2026, <https://>

influencemap.org/briefing/EU-Methane-Regulation-Investor-Briefing-37683.

- 99 “Investors Representing over €4.85 Trillion Sign Letter Urging EU to Uphold Methane Emissions Regulation,” Institutional Investors Group on Climate Change, October 1, 2025, <https://www.iigcc.org/media-centre/investors-sign-letter-urging-eu-to-uphold-methane-emissions-regulation>.
- 100 U.S. Environmental Protection Agency, “The Montreal Protocol, Kigali and HFCs Transition Briefing Paper” (Washington, DC: EPA, January 2025. “Background on HFCs and the AIM Act,” U.S. Environmental Protection Agency, <https://www.epa.gov/climate-hfcs-reduction/background-hfcs-and-aim-act>.
- 101 Science Based Targets initiative, “SBTi Corporate Net-Zero Standard Version 2.0 Criteria for Category B Companies,” June 2026, <https://files.sciencebasedtargets.org/production/files/Corporate-Net-Zero-Standard-V2-Cat-B-Minimum-Criteria.pdf>.
- 102 Deloitte, “6.1 Purpose and Scope,” in Greenhouse Gas Protocol: Reporting Considerations (Deloitte Accounting Research Tool, 2024), chap. 6, <https://dart.deloitte.com/USDART/home/publications/deloitte/additional-deloitte-guidance/greenhouse-gas-protocol-reporting-considerations/chapter-6-ghg-protocol-scope-3/6-1-purpose-scope>.
- 103 Science Based Targets initiative (SBTi), “Corporate Net-Zero Standard, Version 2.0,” June 11, 2026. <https://files.sciencebasedtargets.org/production/files/Corporate-Net-Zero-Standard-version-2.pdf>.
- 104 Ibid.
- 105 “Refrigeration,” ALDI US, corporate.aldi.us/corporate-sustainability/climate-and-energy/refrigeration.
- 106 “Apple surpasses 60 percent reduction in global greenhouse gas emissions,” Apple Newsroom, April 16, 2025, apple.com/newsroom/2025/04/apple-surpasses-60-percent-reduction-in-global-greenhouse-gas-emissions.
- 107 “2024 Climate Action Plan,” Costco Wholesale, mobilecontent.costco.com/staging/resource/img/25w03130/5a_ClimateActionPlan_FY24.pdf
- 108 “2024 Canadian Supermarket Scorecard,” Environmental Investigation Agency, climatefriendlysupermarkets.org/2024-ca-supermarket-scorecard
- 109 “Danone announces an ambitious plan to reduce its methane emissions,” Danone, January 16, 2023, danone.com/newsroom/press-releases/danone-announces-an-ambitious-plan-to-reduce-its-methane-emissions.html. Anderson, K., Spock, R., Hines, M., Hansen, E., “Danone Commits to Cut Dairy Methane Emissions in Partnership with Farmers and EDF,” EDF Business Insights, January 17, 2023, <https://business.edf.org/insights/danone-commits-to-cut-dairy-methane-emissions-in-partnership-with-farmers-and-edf/>.
- 110 Randy Spock, “We’re pledging \$50 million through 2030 to take action on superpollutants,” News from Google, March 5, 2026, blog.google/company-news/outreach-and-initiatives/sustainability/pledge-to-fight-superpollutants-2030
- 111 Ibid.
- 112 Michael Hines, “The Ingka Group Will Install ‘Renewable Heating and Cooling’ Tech in Its More Than 400 IKEA Stores,” Natural Refrigerants, November 19, 2024, naturalrefrigerants.com/the-ingka-group-will-install-renewable-heating-and-cooling-tech-in-its-more-than-400-ikea-stores
- 113 Gissell Lopez and Ben Ratner “The Methane Emissions Opportunity: Our Perspective on Leveraging Technology and Continuous Improvement in the Oil and Gas Sector,” November 2023, JP Morgan Chase & Co, jpm.com/cib/complex/content/redesign-custom-builds/carbon-compass/JPMC_methane.pdf
- 114 “Rabobank’s Climate Plan 2022 Summarized,” Rabobank, October 19, 2023, rabobank.com/about-us/impact/article/011407129/rabobanks-climate-plan-2022-summarized
- 115 “Energy is Renewable,” WM Sustainability Report 2026, accessed August 2026 <https://sustainability.wm.com/energy-is-renewable/>.
- 116 Erik Hansen, “Maximizing Our Climate Impact Through Multi-Year Offtake Agreements,” Workday, June 10, 2024, blog.workday.com/2024/06/10/maximizing-our-climate-impact-through-multi-year-offtake-agreements/.

[com/en-us/maximizing-our-climate-impact-through-multi-year-offtake-agreements.html](https://www.carbon-direct.com/en-us/maximizing-our-climate-impact-through-multi-year-offtake-agreements.html)

- 117 Carbon Direct. Integrating Superpollutant Mitigation into Corporate Climate Action. March 2026. carbon-direct.com/research-and-reports/integrating-superpollutant-mitigation-into-corporate-climate-action
- 118 Hughes, Ella, Hausfather, Zeke, Spock, Randall, Van Arsdale, Christopher. “Sustained Neutralization of the Warming Response to Emissions through a Portfolio of GHG Mitigation Strategies,” CDRXIV, preprint, published May 13, 2026, <https://cdrxiv.org/preprint/521>
- 119 Rosane, Paul, Baysa Naran, Angela Ortega Pastor, Jake Connolly, and Dharshan Wignarajah. *The Landscape of Methane Abatement Finance*. Climate Policy Initiative, July 2022. globalmethanepledge.org/sites/default/files/documents/2023-11/Landscape-of-Methane-Abatement-Finance.pdf
- 120 de Aragão Fernandes, Pedro, Baysa Naran, Ishrita Gupta, Dharshan Wignarajah, Jake Connolly, Luke Patience, and Tinglu Zhang. *Landscape of Methane Abatement Finance* 2023. Climate Policy Initiative, November 2023. <https://www.climatepolicyinitiative.org/wp-content/uploads/2023/11/Landscape-of-Methane-Abatement-Finance.pdf>
- 121 IEA, *Global Methane Tracker 2023* (IEA, 2023), <https://www.iea.org/reports/global-methane-tracker-2023>.
- 122 “Coalbed Methane Outreach Program (CMOP),” U.S. Environmental Protection Agency, accessed August 11, 2026, <https://www.epa.gov/cmop>. Sudhanshu Mathur, *Plugging the Leaks: An Investor Guide to Oil and Gas Methane Risk* (Environmental Defense Fund, 2023), <https://library.edf.org/AssetLink/6c7u05cgb77ohg3jhy7mq4q76bp040es.pdf>.
- 123 Ibid.
- 124 Christopher P. Donahue et al., “Aerial LiDAR-Based, Source-Resolved Methane Emissions Inventory: Permian Basin Case Study for Benchmarking U.S. Emissions,” *Environmental Science & Technology* 60, no. 19 (2026): 13968–79, <https://doi.org/10.1021/acs.est.5c15184>. “OGCI’s Methane Intensity Target,” Oil and Gas Climate Initiative, accessed August 11, 2026, <https://www.ogci.com/methane-emissions/methane-intensity-target/>.
- 125 Willem Vriesendorp, Anastasia O’Rourke, Ethan Olim, Selin Gören, Sage Wen, *Bending the curve: Cost-effective cooling emissions reduction pathways for commercial real estate in China and the U.S.* (Carbon Containment Lab, 2026,) <https://carboncontainmentlab.org/publications/bending-the-curve>.
- 126 United Nations Environment Programme and Climate and Clean Air Coalition (2026). *Global Economic Assessment of Integrated Climate and Clean Air Action*. Nairobi (forthcoming)
- 127 Carolyn Betts Liebrand and K. Charles Ling, *Cooperative Approaches for Implementation of Dairy Manure Digesters*, Research Report 217 (USDA Rural Business-Cooperative Service, 2009), <https://www.rd.usda.gov/sites/default/files/rr217.pdf>.
- 128 Katie Lelito, Anne Liebscht, and Panagiota Boumpalou, “Sustainable Rice Farming: Reducing Methane Emissions and Water Use through AWD and DSR,” BASF Agricultural Solutions, November 19, 2025, <https://agriculture.basf.com/global/en/sustainable-agriculture/climate-smart-farming/carbon-field-trial-program/rice-farming>. Kota Mameno, Takahiro Kubo, and Yasushi Shoji, “Price Premiums for Wildlife-Friendly Rice: Insights from Japanese Retail Data,” *Conservation Science and Practice* 3, no. 6 (2021): e417, <https://doi.org/10.1111/csp2.417>.
- 129 IEA (2023), *Global Methane Tracker* 2023.
- 130 Lynn Loo et al., *Voyaging toward a Greener Future: Insights from the GCMD-BCG Global Maritime Decarbonization Survey* (Global Centre for Maritime Decarbonization and Boston Consulting Group, 2023), <https://www.gcformd.org/wp-content/uploads/2023/09/GCMD-BCG-Voyaging-Toward-a-Greener-Future-vF.pdf>.
- 131 Jade Patterson, “United Airlines Is Betting Big on a Pricy Green Aviation Fuel,” BloombergNEF, March 20, 2024, <https://about.bnef.com/insights/clean-transport/united-airlines-is-betting-big-on-a-pricy-green-aviation-fuel/>.
- 132 At the national average commercial electricity rate of \$0.14/kWh, a \$30,000 HVAC upgrade reduces HVAC electricity consumption by 20%, and results in savings of \$3,000/year, the payback is exactly 10 years. The economics are generally linear—larger system upgrades will still result in a 20% reduction, conservatively, given changes in efficiency standards for commercial HVAC since 2015. Payback can be shorter when replacing older systems and systems used more intensely (e.g.,

- retail, industrial settings), or longer for situations when replacing systems are newer and not used as intensely. <https://www.electricchoice.com/electricity-prices-by-state/> <https://www.shareddocs.com/hvac/docs/1011/Public/OE/CML-001-DN-00.pdf>
- 133 Science Based Targets initiative, *SBTi Corporate Near-Term Criteria*, version 5.3.1 (Science Based Targets initiative, 2026), <https://files.sciencebasedtargets.org/production/files/SBTi-criteria.pdf>.
 - 134 “Refrigeration,” ALDI, accessed August 11, 2026, <https://corporate.aldi.us/corporate-sustainability/climate-and-energy/refrigeration>. Jesse Klein, “Supermarkets Are Tackling Emissions from Their Freezer Aisles,” Trellis, March 14, 2024, <https://trellis.net/article/supermarkets-are-tackling-emissions-their-freezer-aisles/>.
 - 135 Maersk, “Nestlé Cuts Ocean Transport Emissions with Maersk’s ECO Delivery Solution by over 80%,” press release, December 6, 2023, <https://www.maersk.com/news/articles/2023/12/06/nestle-cuts-ocean-transport-emissions-with-maersk-eco-delivery-solution>.
 - 136 TSMC, *TSMC 2024 Sustainability Report* (TSMC, 2025), <https://esg.tsmc.com/en-US/file/public/2024-TSMC-Sustainability-Report-e.pdf>.
 - 137 “Working with Suppliers to Minimize Food Waste,” Tesco PLC, accessed August 11, 2026, <https://www.tescopl.com/sustainability/planet/food-waste/working-with-suppliers>.
 - 138 Mars, “Mars Investing \$20 Million in Sustainable Rice Sourcing to Help Farmers Manage Climate Variability and Protect Livelihoods,” press release, December 4, 2025, <https://www.mars.com/news-and-stories/press-releases-statements/mars-investing-20-million-USD-sustainable-rice-sourcing>.
 - 139 United Airlines, *Response to SBTi Call for Evidence on the Effectiveness of the Use of Environmental Attribute Certificates in Corporate Climate Targets: United Airlines’ Eco-Skies Alliance Program Case Study* (United Airlines, 2023), https://files.sciencebasedtargets.org/production/files/Call-for-Evidence/407_United-Airlines_2023_SBTi-Call-for-Evidence-Submission.pdf.
 - 140 Meta Sustainability, “Request for Proposals: Addressing Upstream Natural Gas Emissions,” May 19, 2026, <https://sustainability.atmeta.com/blog/2026/05/19/request-for-proposals-addressing-upstream-natural-gas-emissions/>.
 - 141 Interview with Juliette Devaney, Amazon
 - 142 Interview with Mark Herrema, Chief Executive Officer, AirCarbon.
 - 143 Mónica Andrés and Jim Andrew, “How Partnerships Can Help Decarbonize Food Value Chains,” World Economic Forum, January 9, 2026, <https://www.weforum.org/stories/2026/01/fertilizer-decarbonize-food-value-chains/>.
 - 144 PepsiCo, “PepsiCo Europe and Yara Partner to Decarbonize Crop Production,” press release, July 16, 2024, <https://www.pepsico.com/newsroom/press-releases/2024/pepsico-europe-and-yara-partner-to-decarbonize-crop-production>.
 - 145 “Maersk ECO Delivery Ocean,” Maersk, accessed August 11, 2026, <https://www.maersk.com/transportation-services/eco-delivery/ocean>.
 - 146 Green Fuel Journal, “Green Methanol: A Rising Star in Low-Carbon Shipping,” January 1, 2026, <https://www.greenfueljournal.com/post/green-methanol-a-rising-star-in-low-carbon-shipping>.
 - 147 Hapag-Lloyd, “Ship Green Fees: Biofuel, Q1 2026,” accessed August 11, 2026, https://www.hapag-lloyd.com/content/dam/website/downloads/pdf/Ship_Green_Fees_BIO_Q1_2026.pdf. Loo et al., *Voyaging toward a Greener Future*.
 - 148 “CDM Methodologies,” United Nations Framework Convention on Climate Change, accessed August 11, 2026, <https://cdm.unfccc.int/methodologies/index.html>.
 - 149 The Carbon Containment Lab and Calyx Global, “Superpollutants: Tackling a Major Climate Threat,” October 2, 2025, <https://calyxglobal.com/research-hub/research/super-pollutant-carbon-credits-paper/>.
 - 150 Ibid.

- 151 Carbon Containment Lab analysis of Pamela Quartson et al., *Voluntary Registry Offsets Database*, version 2026-06 (Berkeley Carbon Trading Project, University of California, Berkeley, 2026), gspp.berkeley.edu/berkeley-carbon-trading-project/offsets-database.
- 152 Ibid.
- 153 Calyx Global, superpollutant and non-superpollutant project ratings spreadsheet (received by author, June 1, 2026).
- 154 BeZero, superpollutant carbon ratings spreadsheet (unpublished dataset, received by author, May 25, 2026).
- 155 ClearBlue Markets. Vantage, carbon intelligence platform, 10 Aug. 2026, clearbluemarkets.com
- 156 “AIM Platform Standard and Guidance,” AIM Platform, accessed August 11, 2026, <https://aimplatform.org/standard-development/aim-platform-standard-and-guidance/>.
- 157 Carbon Direct, *Integrating Superpollutant Mitigation into Corporate Climate Action* (Carbon Direct, 2026), <https://www.carbon-direct.com/research-and-reports/integrating-superpollutant-mitigation-into-corporate-climate-action>.
- 158 Ella Hughes et al., “Sustained Neutralization of the Warming Response to Emissions through a Portfolio of GHG Mitigation Strategies,” preprint, submitted May 13, 2026, CDRXIV, <https://cdrxiv.org/preprint/521>.
- 159 See World Bank’s Carbon Pricing Dashboard for a full overview of these programs, <https://carbonpricingdashboard.worldbank.org/>.
- 160 J. Jason West et al., “Global health benefits of mitigating ozone pollution with methane emission controls,” *Proceedings of the National Academy of Sciences* 103, no. 11 (March 14, 2006): 3988–3993, <https://doi.org/10.1073/pnas.0600201103>,
- 161 Benjamin K. Sovacool, Rexon T. Osuoka, and Tochukwu Akpanyung, “Climate change and industrial F-gases: A critical and systematic review of developments, sociotechnical systems and policy options for reducing synthetic greenhouse gas emissions,” *Renewable and Sustainable Energy Reviews* 141 (May 2021): 110759, <https://doi.org/10.1016/j.rser.2021.110759>.
- 162 Susan C. Anenberg, et al., “Global air quality and health co-benefits of mitigating near-term climate change through methane and black carbon emission controls,” *Environmental Health Perspectives* 120, no. 6 (June 2012): 831–839, <https://doi.org/10.1289/ehp.1104301>.
- 163 United Nations Environment Programme and Food and Agriculture Organization of the United Nations. 2024. *Global Nitrous Oxide Assessment*. Nairobi. <https://doi.org/10.59117/20.500.11822/46562>.
- 164 “The Paris Agreement,” UNFCCC, December 12, 2015, <https://unfccc.int/process-and-meetings/the-paris-agreement>.
- 165 UNEP Ozone Secretariat, *The Kigali Amendment to the Montreal Protocol on Substances that Deplete the Ozone Layer*, (United Nations Environment Programme, 2016), UN Doc. C.N.872.2016.TREATIES-XXVII.2.f, <https://ozone.unep.org/treaties/montreal-protocol/amendments/kigali-amendment-2016-amendment-montreal-protocol-agreed>. “About The Global Methane Pledge,” Global Methane Pledge, accessed August 10, 2026, <https://www.globalmethanepledge.org/>.
- 166 United Nations Framework Convention on Climate Change (UNFCCC), “Paris Agreement Implementation and Compliance Committee: 2026 Milestones,” July 23, 2026, <https://unfccc.int/news/paris-agreement-implementation-and-compliance-committee-2026-milestones>. Climate and Clean Air Coalition Secretariat, “Integrating Non-CO₂ Pollutant Action into Countries’ NDC 3.0s,” January 1, 2026, [https://www.ccacoalition.org/news/integrating-non-CO₂-pollutant-action-countries-ndc-30s](https://www.ccacoalition.org/news/integrating-non-CO2-pollutant-action-countries-ndc-30s)
- 167 “About the Climate and Clean Air Coalition,” Climate and Clean Air Coalition Secretariat, accessed June 29, 2026, <https://www.ccacoalition.org/>

Appendix A

Radiative Forcing and GWP Values at 20 and 100 Years

The IPCC introduced the Global Warming Potential (GWP) concept in its 1990 First Assessment Report, where its authors described it as a simplified approach meant to illustrate the difficulty of the underlying comparison rather than a scientifically settled answer.¹ The IPCC has updated the underlying emission factor values in every assessment report since.

GWP combines physical climate science with policy judgement. The physical part comes from radiative forcing, the extra energy a gas traps in the atmosphere, which can be measured and modeled. It is computed by considering an instantaneous emission pulse, determining the radiative forcing as a function of time following that pulse, summing that radiative forcing over a chosen time horizon, weighting each year equally in that sum, and dividing that quantity computed for a given superpollutant by the same quantity computed for carbon dioxide. The policy judgement concerns the appropriate period of time to include in the sum; there is no objectively correct value.

Because GWP simplifies complex, time-varying physics into a single number, it obscures much of the underlying behavior of the climate system in four key ways:

1. GWP considers a pulsed emission rather than a continuous or repeated emission, which understates the effect of ongoing sources such as methane or F-gases leaking from infrastructure.
2. GWP considers radiative forcing rather than temperature change. Temperature change and its associated impacts are what people and ecosystems experience.
3. GWP relies on an arbitrarily selected time horizon (with some superpollutants having very different GWPs at different time horizons), which can over- or under-prioritize near-term versus long-term effects implicitly.
4. GWP weights each year equally rather than discounting future years. Discounting is common in determining the social cost of GHGs and other metrics such as Net Present Value that cover multiple time horizons.

A key distinction to bear in mind is the difference between emissions and climate impacts. Newer metrics and models in development (such as Hughes et al., 2026) make it possible to convert emissions into temperature impacts over time and avoid many of the shortcomings of GWP and alternative climate metrics. Alternative metrics to GWP shown in Table A2 have been proposed to address these shortcomings, but GWP-100 was the first and still is the most popular metric. It continues to be a useful tool for making quick, standardized comparisons between the impact of different projects designed to reduce emissions of different GHGs. It is also required in many policy frameworks and agreements such as the Paris Agreement.

TABLE A1: RADIATIVE FORCING AND GWP VALUES AT 20 AND 100 YEARS FOR SELECT GREENHOUSE GASES (GHGS)

GHG or Class of GHG	Radiative Forcing (W/m ²)	Types	GWP-20 ²	GWP-100 ²
Carbon Dioxide (CO₂)	2.333 ³		1	1
Methane (CH₄)	0.567	Fossil	82.5	29.8
		Non-fossil	79.7	27
Nitrous Oxide (N₂O)	0.226 ³		273	273
Black Carbon (BC) – see Note	0.3 ⁴		n/a ⁵	n/a ⁵
Tropospheric Ozone – see Note	0.40 ⁶		n/a	n/a
Chlorofluorocarbons (CFCs)	0.298 ⁷	CFC-12	12700	12500
		CFC-11	8320	6230
		CFC-113	6860	6520
		CFC-114	8260	9430
		CFC-115	7410	9600
		CFC-13	12400	16200
		CFC-114a	7510	7420
		CFC-113a	5110	3930
		CFC-112	5620	4620
		CFC-112	5620	4620
Hydrochlorofluorocarbons (HCFCs)	0.06 ⁸	HCFC-22	5690	1960
		HCFC-141b	2710	860
		HCFC-142b	5510	2300
		HCFC-123	325	90.4
		HCFC-124	2070	597
		HCFC-225ca	491	137
		HCFC-225cb	1960	568
		HCFC-21	575	160
		HCFC-133a	1370	388
		HCFC-31	286	79.4
Hydrofluorocarbons (HFCs)	0.048 ⁹	HFC-134a	4140	1530
		HFC-125	6740	3740
		HFC-143a	7840	5810
		HFC-32	2690	771
		HFC-23	12400	14600
		HFC-152a	591	164
		HFC-227ea	5850	3600
		HFC-245fa	3170	962
		HFC-236fa	7450	8690
		HFC-365mfc	2920	914
Hydrofluoroolefins (HFOs)	Negligible ¹⁰	HFO-1234yf	1.81	0.501
		HFO-1234ze(E)	4.94	1.37
		HFO-1336mzz(Z)	7.48	2.08
		HFO-1336mzz(E)	64.3	17.9
		HFO-1234ze(Z)	1.13	0.315
		HFO-1225ye(Z)	1.24	0.344
		HFO-1225ye(E)	0.426	0.118
		HFO-1243zf	0.94	0.261
		HFO-1132a	0.189	0.052
		HFO-1447fz	0.847	0.235

Perfluorocarbons (PFCs)	In AR6 halog. total ¹¹	PFC-14	5300	7380
		PFC-116	8940	12400
		PFC-218	6770	9290
		PFC-C-318	7400	10200
		PFC-31-10	7300	10000
		PFC-41-12	6680	9220
		PFC-51-14	6260	8620
		PFC-61-16	6120	8410
		PFC-71-18	6010	8260
		PFC-91-18	5480	7480
Sulfur Hexafluoride (SF₆)	~0.007 ¹²		18200	24300
Nitrogen Trifluoride (NF₃)	Negligible ¹³		13400	17400

Note on Black Carbon:

Black carbon is not assigned a GWP or compared to well-mixed greenhouse gases on a carbon-equivalency basis. Unlike CO₂ and other gaseous superpollutants, black carbon is a short-lived aerosol whose climate effects depend strongly on when, where, and from what source it is emitted, as well as its altitude, interactions with clouds, and atmospheric aging and mixing. These factors vary across regions and seasons, producing localized “hotspots” of radiative forcing. Black carbon is also co-emitted alongside other pollutants—such as organic carbon and sulfur dioxide—that can have opposing climate impacts, meaning the climate impact of an intervention depends on the full emissions profile, rather than the mass of black carbon alone.

These characteristics make GWP poorly suited to represent black carbon's climate impact. GWP compares emissions on a mass basis, effectively treating one ton of black carbon as equivalent to one ton of CO₂. Yet black carbon's radiative forcing depends on the size, shape, distribution, and atmospheric processing of particles, all of which vary by source and location. This means that equal quantities of black carbon produce very different radiative forcing values. The black carbon-to-CO₂e conversion is therefore not a fixed physical constant, making black carbon and CO₂ unsuitable for direct comparison. The CCAC Scientific Advisory Panel recommends treating black carbon and CO₂ as separate, complementary mitigation targets rather than combining them into a single equivalency metric. Black carbon reductions are better reported in mass terms and evaluated at the source or intervention level, accounting for co-emitted warming and cooling species.

Note on Tropospheric Ozone:

Tropospheric ozone is not assigned a GWP or compared to well-mixed greenhouse gases on a carbon-equivalency basis. Unlike CO₂, tropospheric ozone is not directly emitted; it is a secondary pollutant formed through photochemical reactions among precursor gases (methane, nitrogen oxides (NO_x), carbon monoxide, and non-methane volatile organic compounds (NMVOCs)) in the presence of sunlight.¹⁴ Given that its formation depends on the local mix and ratio of precursors, background atmospheric chemistry, temperature, and sunlight, the same precursor emissions can yield very different ozone and radiative forcing outcomes depending on where and when they occur.¹⁵ It is also short-lived in the atmosphere. These factors produce in turn regional concentration “hotspots” rather than the globally well-mixed distribution that GWP methodology assumes.

GWP is therefore poorly suited to represent tropospheric ozone's climate impact. The IPCC's Sixth Assessment Report classifies ozone as a “direct” short-lived climate forcer but assesses its precursors (NO_x, CO, NMVOCs) as separate “indirect” forcers, reflecting that ozone's own warming contribution cannot be pinned to a single emitted mass. The IPCC has correspondingly not published a GWP for ozone, and UNFCCC Parties have not agreed on one, but rather on frameworks for their reduction.¹⁶

TABLE A2: EMISSION METRICS AND ALTERNATIVE APPROACHES TO QUANTIFYING THE CLIMATE IMPACT OF DIFFERENT GREENHOUSE GASES

Metric	What it Measures	Pro	Con
Global Warming Potential (GWP)	Cumulative radiative forcing from a pulse, relative to CO ₂ , over a fixed horizon	Simple, universal, backward-compatible with decades of policy and reporting	Pulse assumption and arbitrary horizon choice of typically 100 years (GWP-100), and sometimes 20 years (GWP-20)
Global Temperature-change Potential (GTP)	Temperature change at the end of the horizon, relative to CO ₂ , from a pulse	Answers “how much warmer” rather than “how much forcing,” closer to what policy cares about	Only looks at one moment in time, so it can understate warming that peaks and declines before the horizon ends; more model-dependent
Combined/Cumulative Global Temperature-change Potential (CGTP)	Compares the endpoint temperature from a step (sustained) change in a short-lived pollutant’s emission rate against the endpoint temperature from a pulse of CO ₂	Extends GTP to handle a changing emission rate rather than a one-off pulse applied to the temperature-based metric	Newer and much less used, so less standardized reporting infrastructure; units differ from GWP (years, not dimensionless)
GWP-star (GWP*)	CO ₂ -equivalent from a change in a short-lived climate forcer (SLCP) emission rate, not its absolute level	Matches short-lived GHGs’ actual temperature behavior better than GWP-100 for stable or declining emissions	The same emission event scores differently depending on the emitter’s own history
Absolute GWP/Absolute GTP (AGWP/AGTP)	The absolute (not CO ₂ -relative) building blocks underneath GWP and GTP	Useful if you want forcing/temperature units directly, or want to build your own ratio	Not a usable comparison metric on its own—it is the raw ingredient, not the finished product
Global Damage Potential (GDP)	Tying the metric choice explicitly to an economic discount rate rather than a time horizon	Makes the “it is a policy choice” point concrete, since horizon ≈ discount rate	Requires picking a discount rate and a damage function, which just relocates the same value judgment
Present Global Warming (PGW)	Cumulative radiative forcing, relative to CO ₂ , discounted exponentially at a fixed rate	Similar to GWP, but replaces arbitrary selection of time horizon with the same discount rate used for social cost of carbon, net present value, and other metrics. Identical results for pulsed and continuous emissions	Newer and much less used. Requires selecting a discount rate, which is widely studied and broadly applicable but still controversial
Temperature over time	Temperature change caused by the elimination of a given gas, in every year following that intervention	Scientifically accurate, showing exact impact on temperature on every timescale and enabling apples-to-apples comparison of action on gases with different lifetimes	Newer and more innovative approach still being built into market infrastructure, led by emergent scientific work

Appendix B

Selecting Superpollutant Measures

Superpollutant Mitigation Measures Database

In July and August 2026, the Carbon Containment Lab researched and compiled a database of 204 superpollutant mitigation measures. These measures are systematically organized by target gas and classified by typical emission sources, maturity levels, and suitability for market-based interventions including the voluntary carbon market (VCM) and value-chain instruments such as Environmental Attribute Certificates (EACs).

This database serves as a snapshot in time of a rapidly evolving space. Because different reference frameworks describe, bundle, or categorize these strategies in varying ways, our methodology focused on defining each measure as distinctly and succinctly as possible. For expansive structural details and broader macroeconomic assessments, external resources such as [Project Drawdown](#) provide excellent reading. This compilation relies on currently available English-language literature and is not exhaustive or definitive.

Despite these structural boundaries, this compiled database showcases a vast, diverse matrix of technologies, operational practices, and systemic actions already being actively pursued by individuals, cooperatives, corporations, and governments worldwide. Notably, approximately 70 percent of these measures exhibit multi-gas synergies, simultaneously addressing more than one superpollutant class or combining superpollutant reduction with direct CO₂ mitigation. In some cases, mitigation measures can have the unintended effect of generating other emissions elsewhere. Where these are prevalent and supported by literature, they are noted.

The Carbon Containment Lab anticipates continuously expanding, refining, and updating this database within a dynamic, online searchable environment at www.superpollutantroadmap.org and looks forward to learning about and featuring additional measures and data as the space evolves.

See the latest database of superpollutant mitigation measures at:
superpollutantroadmap.org

Summary Statistics

FIGURE A1: PROPORTION OF ALL IDENTIFIED MITIGATION MEASURES BY PRIMARY SUPERPOLLUTANT ADDRESSED

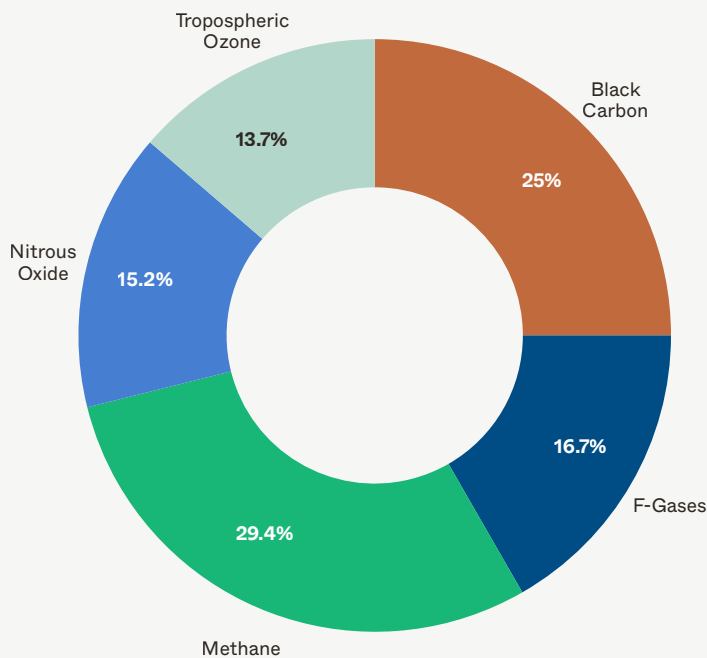


FIGURE A2: MITIGATION MEASURES IDENTIFIED WITHIN EACH EMISSIONS SOURCE TYPE

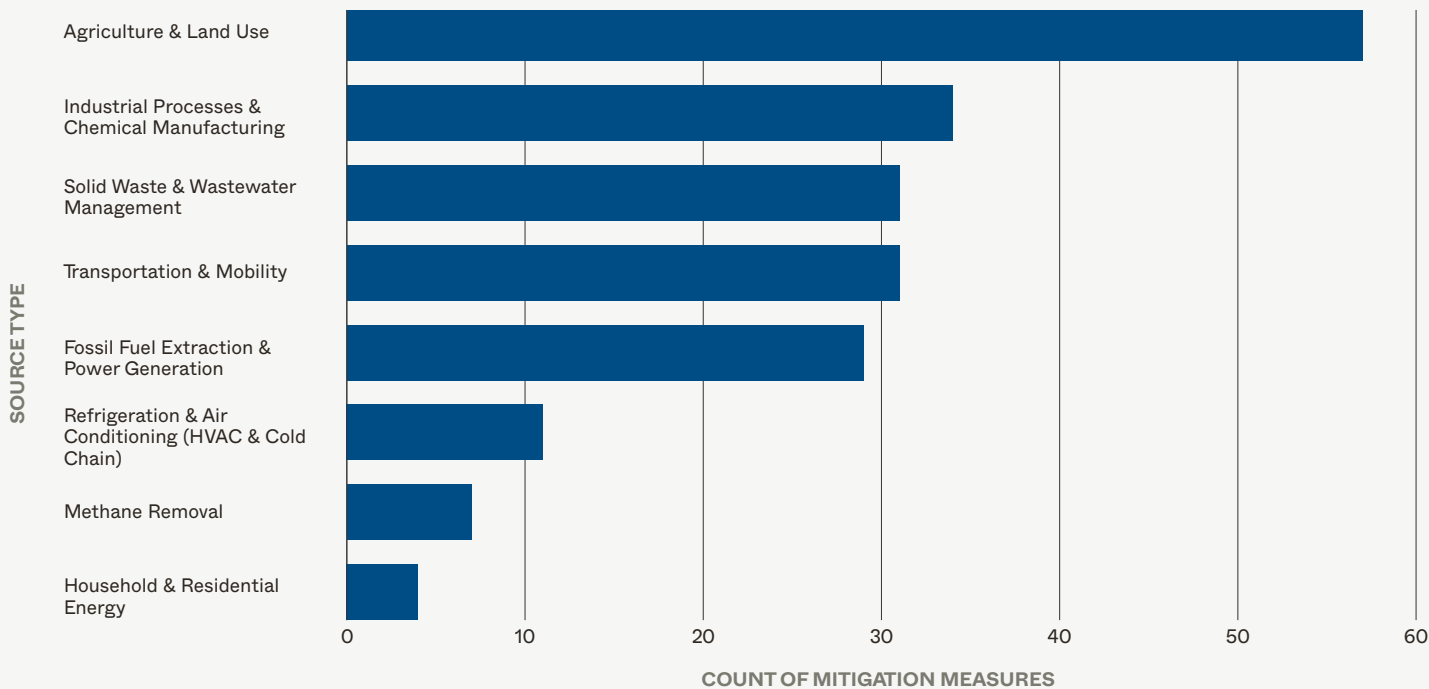


TABLE A3: FIELD DEFINITIONS

Primary Superpollutant	The primary gas being mitigated through the measure.
Other Superpollutants Addressed	Other superpollutants mitigated through the measure in addition to the primary superpollutant.
Mitigation Measures	A physical measure taken to mitigate superpollutants (not a financing, policy, or enabling mechanism).
Source Type	A classification of the main sources of superpollutants to align with the IPCC Guidelines for National Greenhouse Gas Inventories. In some cases these are tailored to describe the sub-sector most closely tied to the mitigation measure.
Maturity Level	A value between one and six indicating how developed, reliable, and ready a technology or process is for widespread use. Each level is further defined in Table A4.
Justification of Maturity Level	Justification for the level of maturity assigned to each measure.
Voluntary Carbon Markets Status	Availability of methodologies in the Voluntary Carbon Market which incentivize this measure. Active indicates one or more active methodologies; Inactive indicates methodologies that have been retired or invalidated; In development indicates methodologies in progress; Not Available indicates a lack of all of the above.
Value Chain Market Mechanisms	This column shows which market-based value chain actions might be appropriate for the measure, including: a standard existing for an EAC or Book and Claim system; a standard is in development; the activity is well suited to supplier engagement; or the activity is unlikely to be suited to these mechanisms.

Maturity level definitions and related corporate actions

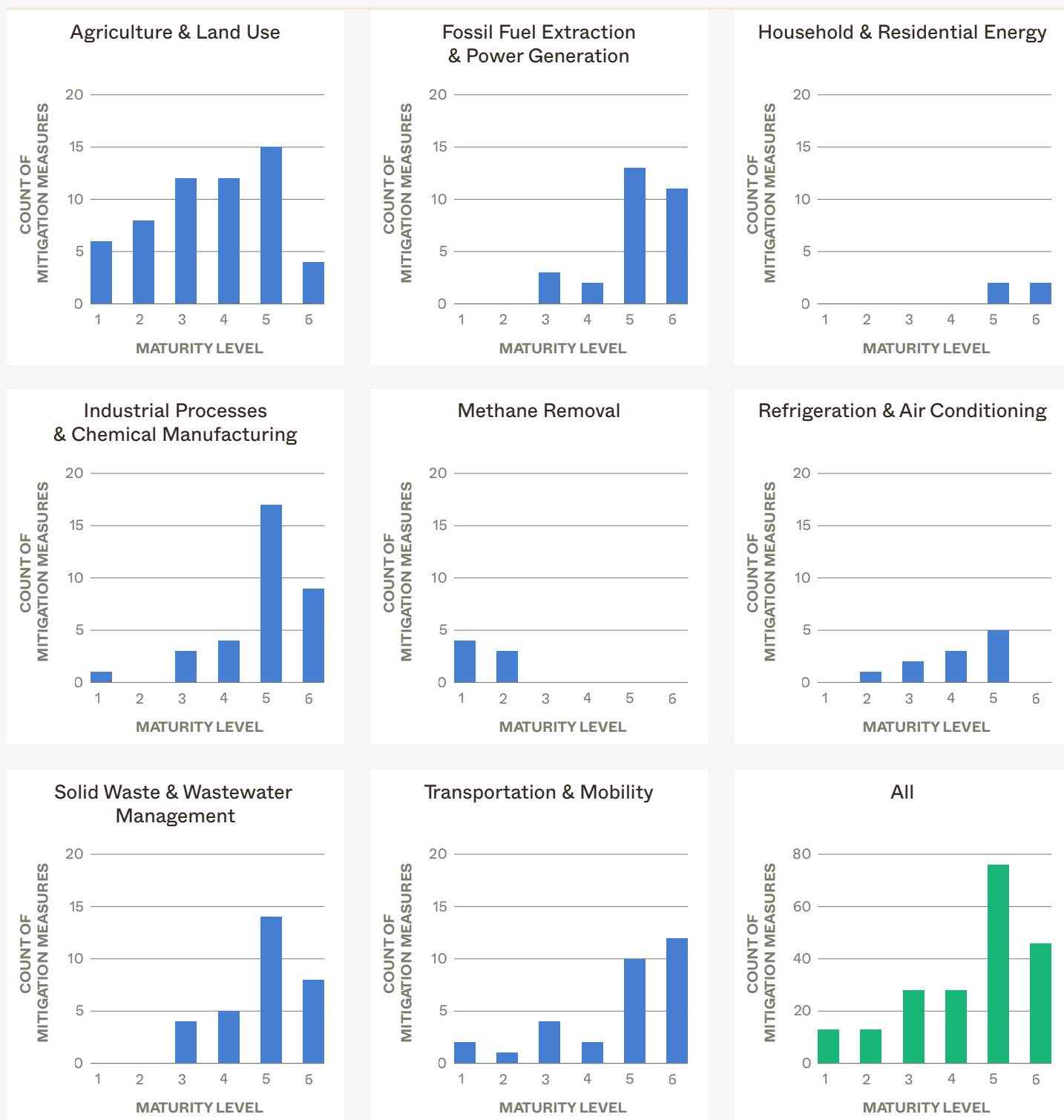
The superpollutant mitigation measures identified reflect diverse levels of technological and commercial maturity. Some established solutions are already standard practice or codified within compliance regimes, such as Best Available Control Technology (BACT) standards under the U.S. Clean Air Act. Other measures are widely known but unevenly implemented globally or regionally. On the other end of the spectrum, frontier measures remain in the conceptual or laboratory phase, requiring robust R&D and field deployment before their economic and physical viability can be fully quantified.

Corporations are essential stakeholders across this spectrum, but their investment capital provides the highest leverage when deployed to scale bridging technologies in the Maturity Level 3–5 bracket; and in helping measures in Maturity Level 6 become global market standards through policy.

TABLE A4: MATURITY LEVEL DEFINITIONS AND EXAMPLES

Maturity Level	Activities at this Maturity Level	Mechanism of Corporate Action	Example Strategic Corporate Action
1. Concept & Research	Laboratory-scale testing, academic research, and theoretical modeling. Low Technology Readiness Level (TRL 1–3); high financial and technical risk.	• R&D Funding (internal) • Sponsored Research (external) • Sponsor Innovation Prizes	Fund university labs or early-stage accelerators directly to prove basic chemistry and unlock the intellectual property needed for new technologies.
2. Proof of Concept	Small pilot plants, prototype modeling, and life-cycle assessment (LCA) projections. Medium-low readiness (TRL 4–6); economic viability unproven.	• Corporate Venture Capital (CVC) investment • Host-Site Provision • Sponsor Innovation Prizes	Invest seed equity through CVC arms to build early prototype hardware. Provide an active physical corporate asset to host the first field pilot.
3. Demonstration & Early Deployment	First-of-a-kind commercial projects, early regulatory approvals, and niche adoption. Medium-high readiness (TRL 7–8); relies on subsidies, grants, or early adopters.	• Project Equity Investments • VCM Forward Offtake Agreements	Invest direct equity into first-of-a-kind (FOAK) infrastructure facilities. Back this with a VCM Forward Offtake contract to guarantee an anchor customer.
4. Early Adoption & Capital Chasm	Early-stage commercial rollout, limited to a few pioneering projects globally; focus on reducing high initial capital expenditures. TRL 8–9. It is a chasm because standard commercial banks view it as too risky, requiring specialized infrastructure funds, private equity, or loan guarantees.	• Project Equity Investments • VCM Forward Offtake Agreements • Market-Based Instruments (Book and Claim/EACs) • VCM Spot Market Credit Purchases	Purchase issued spot market credits from already-established projects to offset immediate corporate footprint gaps while long-term infrastructure scales up.
5. Scaling/ Commercialization	Mass manufacturing, standardized supply chains, declining unit costs, and policy backing. Mature (TRL 9); Some standard commercial financing available.	• VCM Spot Market Credit Purchases • Supplier Engagement Programs • Standards Writing/Engagement	Use procurement mandates and low-interest supply-chain financing to force smaller tier-1 and tier-2 partners to adopt mature, off-the-shelf upgrades.
6. Optimization & System Integration	Continuous technological refinement, circular-economy recycling of materials, and fully integrated grid/infrastructure support.	• Supplier Engagement Programs (global) • Standards Writing/Engagement (global) • Policy Advocacy & Regulatory Support	Lobby for codes, mandates, and bans/standards to turn proven Level 5 solutions into mandatory, industry-wide legal requirements.

FIGURE A3: MATURITY OF MITIGATION MEASURES BY SOURCE TYPE



Appendix C

Modeling Parameters for Chapter 3

Modeling Specifications and Parameters: The visualizations and statistical analysis presented within Chapter 3 were completed utilizing the Finite Amplitude Impulse Response Model (FaIR) version 2.2.4. Sensitivity coefficients for the treatment of methane were derived from Thornhill et al. (2021).¹⁷ Species were filled, per the [documentation](#), from both FaIR calibration data 1.4.1 and the Reduced Complexity Model Intercomparison Project, when possible, to directly reference shared socioeconomic pathway simulations and to reflect AR6 as closely as possible. The NO_x unit conversion fix was also applied to maintain accuracy.

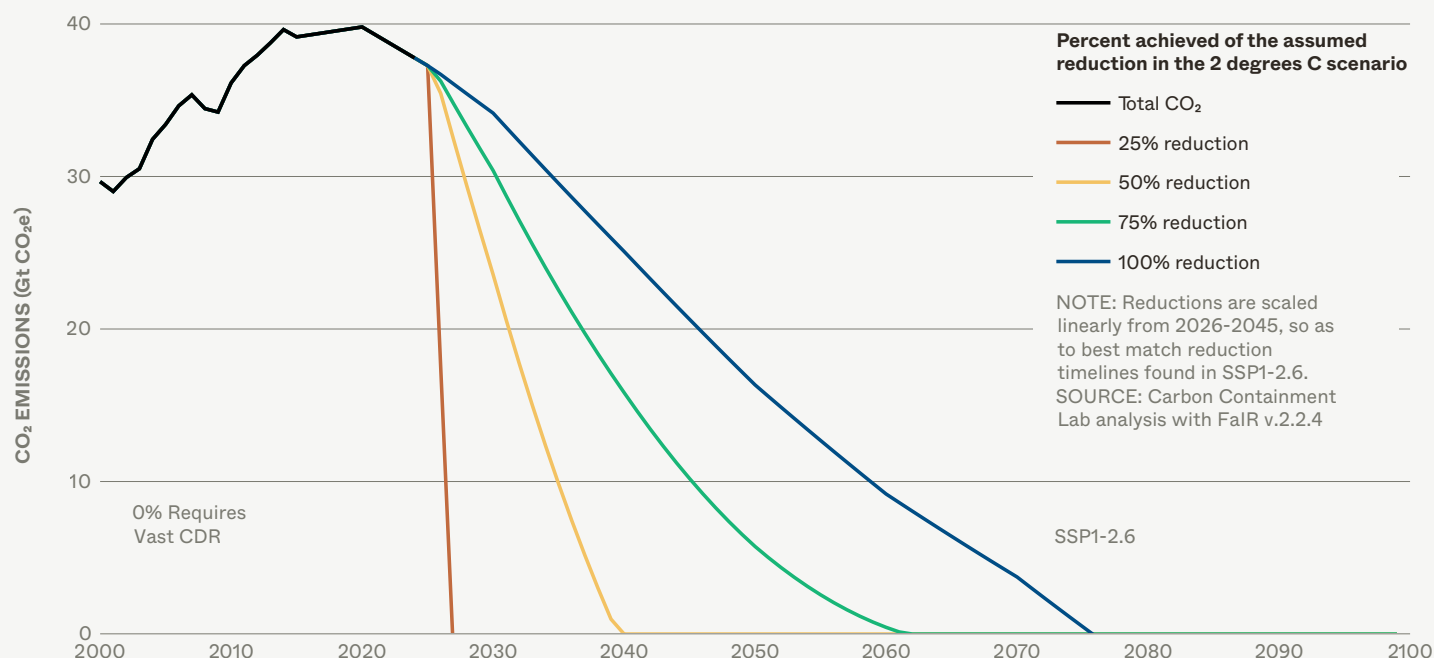
Visualizations: Figure 3 provides a stacked view of projected superpollutant and CO₂ emissions for SSP2-4.5 and SSP1-2.6. It was created purely through FaIR simulation and retrieval. Each superpollutant categorized (methane, nitrous oxide, and all the simulated ODS and F-gases) was then multiplied by their AR6 GWP-100 to create a unified CO₂e projection. Figure 4, the temperature projections,

was made by taking the 66th percentile upper bound of the projections simulated by FaIR (to replicate the definition utilized by the U.N.'s terminology of "likely to stay below"). The middle temperature projection, representative of the SSP1-2.6 pathway "without" superpollutant action, was created by transferring the species emission values of all superpollutants within SSP2-4.5 to SSP1-2.6.

Pathway Recognitions: Though all modeling was performed in relation to established Shared Socioeconomic Pathways, it is important to note that the Integrated Assessment Models performed to produce these pathways were formulated before the Kigali Amendment. As such, its impact on fluorinated gas emissions is not recognized within SSP2-4.5. However, the reductions associated with SSP1-2.6, the deep sustainability transition, assume even greater reductions than the commitments established within Kigali, maintaining the conclusion that urgent reductions in fluorinated gas emissions are necessary.

Impact on Remaining Carbon Budget: In addition to the modeling described in the main text, we also assess the impact of incomplete superpollutant contributions to the 2 degrees C pathway to indicate how much extra CO₂ reduction would be needed. In other words, we model the world achieving 100 percent, 75 percent, 50 percent, and 25 percent of the assumed action on superpollutants from the 2 degrees C scenario, or SSP1-2.6. In each case where the superpollutant action is below 100%, we model the additional CO₂ reductions that would be required in order to remain below 2 degrees C. We find that each fractional reduction of superpollutant emissions extends the carbon budget for keeping the world below 2°C by decades (Figure A4).

FIGURE A4: CARBON DIOXIDE EMISSION REDUCTIONS REQUIRED TO STAY BELOW 2 DEGREES CELSIUS BY 2100, GIVEN INCOMPLETE ACTION ON SUPERPOLLUTANTS



Appendix D

Criteria for Selecting Market-Based Value-Chain Interventions

Value-chain mechanisms can potentially address the full range of mitigation measures, though some stand out as the most appropriate (and ready) for the market-based mechanisms of Environmental Attribute Certificates (EACs) and Book and Claim systems, and for certified insetting projects. As explained in Chapter 4 (Lever 1: Value Chain Intervention), companies should consider a range of factors in selecting project types and specific projects, especially where the resulting climate reductions will count towards their climate goals under frameworks such as the SBTi.

In the Mitigation Measures database—available online at <https://superpollutantroadmap.org>—we selected interventions ready for such mechanisms using the following criteria:

1. **Geographic and Physical Mismatch:** The commodity is too bulky, heavy, or logistically complicated to source physically (e.g., concrete or green steel), so decoupling the “green attribute” from the physical material via a digital certificate may be the only way to fund it.
2. **Fragmented Tier-3+ Supply Chains:** If the emissions occur four or five layers deep in the supply chain (such as a smallholder farm or an offshore marine fuel bunker), direct physical traceability is almost impossible, but the abatement can be measured and certified through other means.
3. **Standards, Certifiers, and Projects Are Ready:** An existing set of consensus standards and accounting rules has been developed for this intervention and already tested by market actors, and certifiers are available. This means there is a greater opportunity to scale these measures up soon.
4. **Stuck in the Capital Chasm:** The underlying technology works well, but developers struggle to secure mainstream commercial bank loans unless they can show guaranteed, long-term, premium revenue contracts. This means corporate support is especially valuable now.
5. **Reasonable and Declining Cost per Metric Ton:** The mitigation measures we selected are mostly technically mature but will benefit from economies of scale and learning effects over time and from further financial support.

Applying these criteria to mitigation measures in the database, we find that the vast majority could potentially be integrated into supplier engagement strategies, and that a small but growing number of market-based mechanisms—such as EACs, Book and Claim systems, and insetting—are emerging with the requisite standards and certification systems either published or in development.

FIGURE A5: MITIGATION MEASURES BY AVAILABLE VALUE CHAIN MECHANISMS

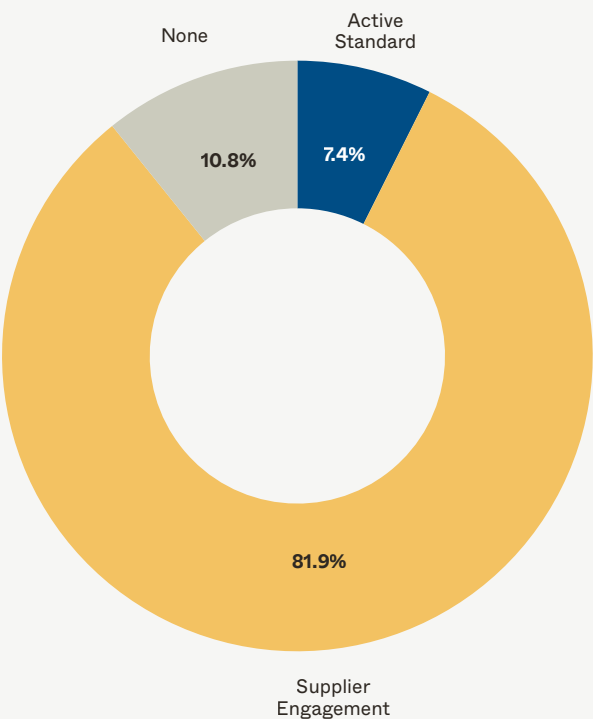


FIGURE A6: MITIGATION MEASURES WITH ACTIVE VALUE CHAIN STANDARDS, BY SOURCE TYPE

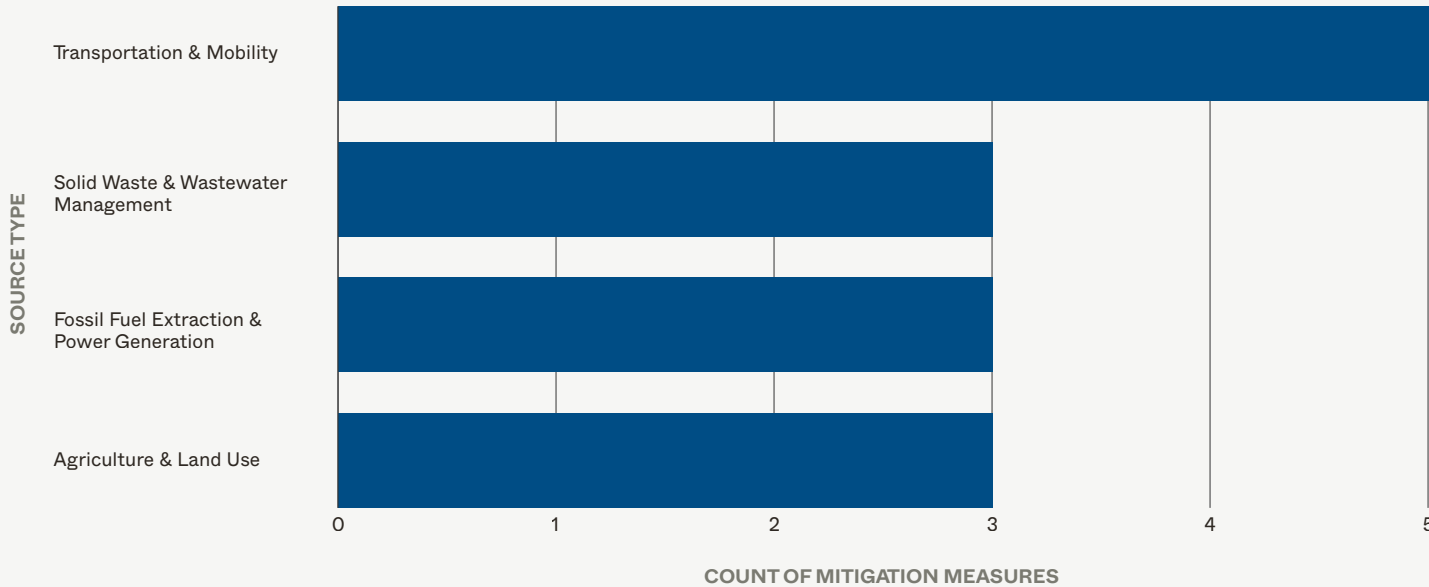


Table A5 provides more detail on the four high-potential opportunities to address superpollutant hotspots featured in Chapter 4.

TABLE A5: DETAIL ON SELECTED SUPERPOLLUTANT MITIGATION MEASURES AND THE VALUE-CHAIN MECHANISMS THAT CAN BE USED TO SCALE THEM

Mitigation Measure	Superpollutant Source	Description	Value-Chain Fix and Mechanism
Biomethane from Manure Storage, Management & Digestion	Storing millions of metric tons of liquid livestock manure in open agricultural lagoons creates a large, ongoing source of methane, as well as ammonia gas—a precursor that contributes to the formation of fine particulate matter and winter smog.	Enclosing agricultural lagoons with airtight covers traps methane, which can then be upcycled to biomethane. Additionally, processing manure through anaerobic digesters (AD) converts waste into methane gas, which is then upgraded into Renewable Natural Gas (RNG). Importantly, AD units require controls for methane slips and careful application of the resulting digestate to limit N ₂ O releases.	Buy Book and Claim certificates. Specify use of certified RNG.
Low-Methane-Intensity Natural Gas	Upstream oil and gas operations release methane through fugitive leaks, venting, and incomplete flaring.	Producers detect and repair leaks and reduce venting using continuous monitoring, aerial and satellite detection, and improved equipment (e.g., replacing high-bleed pneumatic controllers), lowering the methane intensity of the gas they bring to market.	Buy from the supplier with the lowest verified methane intensity, favoring suppliers with certifications (MiQ or Equitable Origin), with no satellite-observed methane emissions, and with membership in programs such as OGMP 2.0. This is especially relevant for companies building data centers with behind-the-meter gas generation.
Refrigerant Recovery and Reclamation	Potent F-gases used across building air-conditioning systems, cold chains, and power grids chronically leak or are vented during servicing and at end of life.	Reclamation of used F-gases cleans and reprocesses the gas to an “as new” standard. Reclamation markets can help establish recovery capacity, which in turn supports the workforce training and physical infrastructure needed for full lifecycle refrigerant management.	Set procurement preferences or mandates for reclaimed gas, and enter forward purchase agreements to secure supply.
Nitrous Oxide Abatement at Nitric and Adipic Acid Plants	Chemical manufacturing and heavy industrial processes generate high-potency N ₂ O emissions across multiple sectors and specialized product lines. This creates a large superpollutant footprint in downstream consumer goods, automotive engineering, and construction markets.	Manufacturers install catalytic or thermal destruction systems and process controls at nitric and adipic acid plants to capture and destroy N ₂ O before it is released, reducing the emissions embedded in downstream fertilizers, nylon fibers, polyurethane foams, and synthetic dyes.	Specify “buy clean” materials in key sectors that rely on these chemicals. Provide financing via inssetting projects. Engage suppliers on best practices.

Appendix E

Selecting Carbon Credits: Criteria and Application

With so many varieties of superpollutant credits now available, choosing which to include in a purchase can be daunting. Numerous criteria can be applied, and most of them would apply to any carbon credit rather than to superpollutant credits in particular. Issues such as quality, additionality, baseline integrity, durability, and leakage cut across every category. Buyers should also weigh their own appetite for risk, their budget, and the contracting mechanisms available to them, alongside preferences on location, industry, marketability, and co-benefits. Finally, they should consider their in-house resources for conducting due diligence and their capacity to work with intermediaries where those resources are thin.

At a high level, the selection criteria for superpollutant projects should differ slightly from a generic carbon credit screen, because the goal is not only quality, cost, and availability, but also whether a project can help scale deployment over the next five years and contribute to near-term climate stabilization. A five-year lens favors projects where credits do more than pay for abatement: they build supply, absorb early risk, and create momentum for broader adoption. It also implies a tolerance for projects that are still maturing, provided the path to volume is visible.

The Carbon Containment Lab proposes the following four categories of criteria, supplemental to the quality standards already present in the market and to any existing company preferences on location, industry, and co-benefits.

1. Scalable

Definition. The project type has the technical and market potential for widespread application or replication, or for future cost reductions.

Given the five-year timeframe, this means favoring project types with tested technologies and verification approaches, where a working methodology has already been developed and some deployments have already occurred. Scalability is the criterion that does the most work in a superpollutant screen, because the constraint is rarely whether abatement is technically possible. It is whether the same intervention can be delivered a thousand times. Five factors determine that.

Size and accessibility of the addressable source

Scale begins with the size of the pool the project can actually reach. Superpollutant sources are a mix of point sources and distributed sources, spanning both industrial and natural systems. Given the potency of these gases, even small and dispersed sources can be worth accessing, provided the collection, handling, and verification infrastructure exists. A single refrigeration system holds a trivial mass of gas but a meaningful tonnage of CO₂e.

The relevant question is therefore not whether the source is large at the unit level, but whether the aggregate pool is material and the individual unit is reachable at acceptable cost. Concentrated point sources with an identifiable owner can be contracted

directly. Distributed sources require an aggregation pathway—an established servicing network, a waste stream with existing custody arrangements, or a regulated collection system. Where no such pathway exists, a large theoretical pool is not yet an accessible one, and the project is better understood as infrastructure-building than as a scalable abatement pipeline.

Technical and methodological readiness

An approved methodology with issuance history is materially different from a concept awaiting registry review. Within a five-year horizon, methodology development timelines alone can consume most of the window. Verification approaches should likewise be tested rather than proposed.

Repeatability

Projects should be repeatable across geographies or asset classes rather than tuned to a single site. The practical test is whether the twentieth deployment is faster and cheaper than the fifth, and whether the design survives changes in climate, grid, and regulatory regime with only local compliance adjustments.

Absence of binding constraints

Projects should face no major binding input or resource constraints, whether in equipment, vendors, suppliers, or available workforce. Workforce is frequently the real ceiling in lifecycle refrigerant management work, where certified technician capacity and incentives, not technology, limits throughput.

Capital absorption and bankability

Scalable projects can absorb corporate capital in a way that unlocks a larger pipeline, and they are bankable enough to attract other private or public capital for build-out. The presence of multiple credible implementers is a useful signal here: it indicates a market rather than a single-vendor pilot.

This criterion deprioritizes projects that are technically sound but too bespoke, too slow, or dependent on one-off circumstances, as well as projects whose scale depends on a single regulatory approval, patent license, or a supplier relationship with no alternative.

2. Value

Definition. The project has strong unit economics and a credible path to economies of scale.

Credits that represent value are not simply cheap credits. They are credits whose underlying cost structure is understood, defensible, and likely to improve with volume. Projects that can generate revenue from co-products may be more economically resilient, so long as that revenue does not raise financial additionality concerns or enable double counting of the environmental attributes. Price and cost transparency matter: buyers should be able to see what they are paying for abatement as distinct from what they are paying for intermediation. The relative costs of verification and due diligence should also be reasonable, both in absolute terms and as a share of credit value.

This criterion favors:

- Transparent cost stacks, where abatement cost, MRV cost, and margin are separable.
- Declining cost curves supported by evidence, not projection alone.
- Co-product or avoided-cost revenue that reduces reliance on the carbon price, disclosed and correctly accounted for.
- Verification and diligence costs that fall as a share of revenue as volume grows.

This criterion deprioritizes:

- Projects where MRV and transaction costs consume a large fraction of credit value with no path to reduction.
- Opaque pricing, or intermediated structures where the buyer cannot identify what the project itself or project partners and local communities receives.
- Projects wholly dependent on credit revenue at prices well above the prevailing market.

3. Quality

Definition. The project meets or exceeds quality expectations and standards, notably for additionality, net climate benefit, timing for impact, strong safeguards, and co-benefits.

This category overlaps substantially with common carbon market criteria such as durability, additionality, measurability, and verifiability. Superpollutant credits tend to score comparatively well on these factors, as noted in Chapter 5 in relation to ratings, because the abatement is typically a discrete, measurable, and physically irreversible event. The following criteria are the ones that deserve particular attention in a superpollutant context.

Additionality

The mitigation should not already be required by regulation, nor delivered by ordinary commercial incentives. This criterion carries particular weight for superpollutants, where compliance obligations vary widely by jurisdiction and are changing. A practice that is genuinely additional in one country may be mandated in another, and may become mandated in both within the crediting period. Buyers should therefore assess not only the current regulatory position but the expected trajectory and should ask how a methodology handles the transition when a voluntary practice becomes a legal obligation. The same test applies to commercial drivers: where the

recovered material has resale value, or where avoided purchase costs alone justify the intervention, the case for additionality needs to be made explicitly rather than assumed.

Net climate benefit

Baselines and counterfactuals are always important, as is the degree to which they are knowable and rest on generally accepted methodologies. For superpollutants this extends to the full life-cycle emissions associated with the mitigation itself, including other greenhouse gases and the trade-offs between them. Destruction processes consume energy and may generate their own emissions. Replacement technologies carry their own refrigerant or energy footprint. Substitutes with lower global warming potential may introduce other environmental or human health concerns, including atmospheric breakdown products. A credible claim of net benefit accounts for these effects rather than crediting the avoided gas in isolation.

Timing of impact

Superpollutants persist in the atmosphere for very different periods; this variation is larger than is often assumed. Methane has a perturbation lifetime of roughly 11.8 years, whereas nitrous oxide persists for about 109 years and HFC-23 for about 228 years, with a 100-year GWP of approximately 14,600.¹⁸ Some HFCs are far shorter-lived; HFC-32 has a lifetime of about five years. “Superpollutant” therefore describes potency rather than a common atmospheric fate, and the timing of climate benefit varies accordingly.

Special attention should therefore be paid to the fate of the specific gas and to when the benefit is realized. Preference should generally be given to projects that deliver an immediate positive impact on the atmosphere. Buyers should also distinguish between abatement that occurs at the moment of the transaction, such as destruction of a recovered stock, and abatement that accrues over years, such as avoided leakage across an equipment lifetime. The former is easier to verify and delivers its benefit immediately;

the latter depends on continued performance and carries more counterfactual risk.

Strong safeguards against perverse incentives

Superpollutant crediting has a checkered history, and the risk is structural rather than incidental: these gases are embedded in industrial systems and waste streams where the same actors control both production and abatement. The clearest precedent is HFC-23 destruction under the Clean Development Mechanism, where credits were priced far above the cost of destruction and plants appeared to adjust HCFC-22 production to maximize creditable by-product, prompting the CDM Methodologies Panel to acknowledge that the rules could create perverse incentives.¹⁹

The lesson is not that superpollutant crediting should be avoided, but that methodologies must be read for the incentives they create as well as the emissions they measure. Buyers should look for:

- Production-independent crediting, so that no participant can increase creditable volume by generating more of the gas.
- Verified chain of custody from recovery through destruction, sufficient to prevent virgin material being presented as recovered, or the same ton being claimed more than once.
- Conservative default factors where direct measurement is contestable, so that uncertainty does not resolve in the project's favor.
- Caps and benchmarks tied to technically feasible ratios rather than observed plant behavior.
- Prices that bear a defensible relationship to abatement cost, since very large margins are themselves a warning sign.
- Independent verification, particularly where material is mobile or fungible.

Potential to deliver co-benefits

Co-benefits are often treated as a marketing consideration, but in a superpollutant context they also function as an integrity signal: projects that deliver value beyond the credit are less likely to exist solely to generate credits. Relevant co-benefits include improved air quality and reduced ozone-depleting substance emissions, energy efficiency gains from equipment replacement or servicing, occupational health and safety improvements for technicians handling refrigerants and industrial gases, formalization and improvement of waste-handling systems, and local employment and skills development in servicing and reclamation trades. Where co-benefits are claimed, they should be described specifically and, where possible, measured, rather than asserted in general terms. Where they carry independent monetary value, that value should be disclosed and reflected in the additionality assessment.

4. Provides a pathway or bridge to policy

Definition. The project builds capability that regulation will later require, rather than occupying a gap that regulation will eventually close.

This criterion follows directly from the five-year lens. Superpollutants are the most heavily regulated class of greenhouse gas: the Kigali Amendment has now been ratified by 173 of 198 parties,²⁰ the U.S. AIM Act mandates an 85 percent HFC phasedown from baseline by 2036,²¹ and the revised EU F-gas Regulation drives bulk HFC supply to a complete phase-out by 2050.²² Voluntary carbon finance is not the primary instrument in this space and should not pretend to be. Its most defensible role is transitional: paying for the infrastructure, data, and institutional capacity that regulation needs in order to function,

in the window before mandates arrive or in the jurisdictions where they have not yet been written.

Read this way, a good superpollutant project is one that works toward its own obsolescence. That is a feature rather than a contradiction, and it sits comfortably alongside the additionality test, provided the crediting period is scoped to the policy timeline rather than extending past it.

The EU F-gas Regulation illustrates the logic well. The HFC phase-down applies only to virgin HFCs placed on the market for the first time, not to gas recovered and reclaimed within the EU, and servicing of high-GWP systems is progressively restricted to reclaimed or recycled material.²³ Regulation has therefore created a structural requirement for reclamation capacity that does not yet exist at the necessary volume. Credits that fund the building of that capacity now are a bridge to a policy outcome, not a substitute for it.

This criterion favors:

- **Regulatory-grade MRV.** Measurement systems, registries, and traceability infrastructure built to a standard a regulator could adopt, so the crediting program leaves behind reusable public infrastructure rather than a proprietary dataset.
- **Data that closes an evidentiary gap.** Emissions factors, leak rates, recovery rates, and cost benchmarks are frequently the reason regulation stalls. Projects that generate defensible, publishable data on abatement cost and feasibility lower the political cost of a future mandate.
- **Compliance readiness ahead of schedule.** Practices, equipment, and certifications that will be required at a known future date, deployed early. Early movers absorb the learning costs that later compliance depends on.

- **Institutional and workforce capacity.** Certification schemes, technician training, licensed handling and destruction facilities, and custody systems — the delivery capacity a mandate assumes but does not itself create.
- **Jurisdictional relevance.** Deployment in countries where the relevant regulation is being drafted or where policy implementation is pending, and where a demonstration project can inform the design of the rule.
- **A defined sunset.** An explicit account of what happens to the project when regulation absorbs the activity, with crediting periods and baselines that step down as mandates take effect rather than continuing to claim credit for legally required action.
- **Alignment with national accounting.** Clear treatment of how reductions interact with NDCs, national inventories, and Article 6 authorization, so that voluntary purchases do not obscure or double-count sovereign progress.

This criterion deprioritizes:

- Projects that depend on a regulatory gap persisting, and whose economics deteriorate if policy tightens.
- Structures that create a commercial constituency with an interest in delaying regulation, which is the deeper lesson of the HFC-23 episode.
- Crediting periods that extend materially past the date on which the activity becomes mandatory.
- Projects that build proprietary or closed measurement systems where an open standard would serve the eventual regulator better.

Applying the four together

These criteria pull against one another, and that tension is deliberate. The most rigorously additional projects are often the least scalable, because bespoke circumstances are what make the counterfactual clear. The cheapest credits frequently carry the weakest safeguards. And the policy criterion is in open tension with the others by design: a project that successfully bridges to regulation eliminates its own market, which means the buyer is funding a diminishing asset. That is the correct outcome, but it should be understood at the point of purchase rather than discovered later.

A portfolio approach is usually more defensible than optimizing any single criterion. Pair a core allocation

of high-quality, well-established project types with a smaller allocation aimed explicitly at building supply and policy capability in categories that are scalable but not yet mature.

For any candidate project, we suggest identifying which of the four criteria is binding, and whether that constraint is cost-reducible or structural. Verification cost and unit economics generally improve with volume and are therefore worth funding through. A source that cannot be accessed, a methodology that cannot resist gaming, or an activity that regulation is about to mandate outright will not improve with scale.

TABLE A6: SUMMARY OF CARBON CREDIT CRITERIA

Criterion	Core question	Strongest signal	Clearest disqualifier
Scalable	Can this be repeated at volume within five years?	Material and accessible source pool, approved methodology with issuance history, multiple implementers	Bespoke, single-vendor, or dependent on one-off circumstances
Value	Do the unit economics improve with scale?	Transparent cost stack, declining costs, co-product resilience	MRV and transaction costs consuming credit value
Quality	Is the ton real, additional, and durably beneficial?	Production-independent crediting, verified custody, immediate atmospheric benefit	Methodology that rewards generating the gas
Policy bridge	Does this help to build what regulation will require?	Regulatory-grade MRV, capacity ahead of mandate, defined sunset	Reliance on a regulatory gap persisting

Appendix F

Carbon Credit Case Studies

- *Industrial N₂O Abatement: High Value Today, Constrained by a Closing Additionality Window*
- *ODS and HFC Destruction: Building the Path for a Circular Economy of Refrigerants*
- *Rice Methane Mitigation: A Frontier in Dispersed Emissions Mitigation*
- *Anaerobic Digesters: Established Technology, Uneven Additionality*
- *Landfill Gas Capture, Destruction, and Utilization: Mature but Regulation-Exposed*
- *Plugging Orphaned Oil and Gas Wells: High Potential, but Currently Constrained by Measurement and Additionality Concerns*

CASE STUDY

Industrial N₂O Abatement: High Value Today, Constrained by a Closing Additionality Window

Nitrous oxide (N₂O) is one by-product of the industrial manufacture of adipic and nitric acids, among others. It is a potent climate forcer: an ozone-depleting substance with a GWP of 273. Adipic acid is a precursor in the production of nylon, polyurethanes, and polyester. Nitric acid is widely used as a raw material for synthetic fertilizer, as input for adipic acid, and for explosives.

Proven nitrous oxide abatement technology is readily available, can be installed in existing plants, and can reach very high abatement efficiencies of up to 99 percent.²⁴ To address nitrous oxide emissions, facilities install catalytic or thermal decomposition units.²⁵ Capital costs range from \$1.2 million to more than \$25 million depending on the type, size of the facility, and treatment option. Monitoring equipment and downtime for installation and testing can add costs.²⁶ New technologies show promise to reduce these costs further.²⁷

This crediting pathway has matured significantly since the 2000s, when the CDM methodology created

perverse incentives that distorted global adipic acid markets and led to carbon leakage and criticism.²⁸

In particular, Climate Action Reserve's (CAR) new China adipic acid protocol uses a 90 percent baseline and production caps to explicitly correct for these weaknesses. In compliance markets, the European Union's ETS has driven near-universal EU adoption of mitigation measures.

Why it meets our criteria

Scalability: The potential adipic acid abatement in developing countries alone totals roughly 2.6 Gt CO₂e cumulative 2013 through 2030.²⁹ Of roughly 500 to 580 nitric acid plants around the world, fewer than one in five run abatement technology. This leaves roughly 350,000 metric tons of nitrous oxide (roughly 95 million metric tons of CO₂e) vented annually.³⁰ The key constraint to scaling with carbon finance is high up-front costs and engineering complexity, coupled with uncertainty around the market demand for credits and the possibility of changing regulations.

Opportunity size: Legacy CDM issuance was enormous: more than 160 million CERs from just four adipic acid projects by 2012. Most of that volume is now retired or expired.³¹ New-generation VCM volume is early and small, gated by which plants remain unabated and eligible.

Value: Abatement costs sit near the bottom of any marginal abatement curve (<\$0.50 to \$5 per ton CO₂e). Today, adipic acid credits sell for around \$4.75 per ton, and nitric acid credits sell for around \$5.95 per ton.³²

Quality: Mitigation of these emissions is directly measurable, and there is no reversal risk as the gases are destroyed. Overcrediting due to leakage and

baseline manipulation has been a concern for this credit type in the past, and although methodologies have been significantly strengthened in response, buyers should be cautious of any credits issued following significant increases in the plant's chemical production, particularly at adipic acid plants. CAR's U.S. and China adipic acid methodologies were recently CCP-approved, signaling a step change in quality.³³ Although nitric acid methodologies have not yet been fully reviewed for CCP approval, several U.S. N₂O projects have received high ratings. A new nitric acid CAR protocol is also in development.³⁴ Regulatory additionality risk is typically well-constrained by methodologies, which explicitly rule out crediting for any abatement that becomes required by law. Corporate credit purchases can encourage above-standard abatement even after a regulation is established. For example, China has signaled the intent to set a floor for industrial N₂O abatement and then progressively strengthen these requirements.³⁵ Strong ongoing MRV is critical to ensure installations are maintained and continue to mitigate emissions, and to protect against perverse incentives such as rewarding facilities for delaying adoption of emission controls that more responsible peers had already voluntarily installed.

Policy pathway: Carbon markets, alongside “buy clean” efforts for commodity materials, can play a critical role in delivering capital to support near-term abatement. This activity paves the way for

strengthened national policies, and delivers additional abatement above regulatory thresholds once those national policies are in place. Already, there is policy action. Unlike ODS, N₂O is included in the Paris Agreement, so companies can access compliance markets directly: the Article 6.4 Supervisory Body approved AMM-002 for nitric acid in May 2026.³⁶ An intergovernmental body, the Nitric Acid Climate Action Group (NACAG), finances plant retrofits to mitigate N₂O and requires host countries to commit to permanent abatement and NDC inclusion, explicitly barring the resale of resulting reductions into carbon markets.³⁷ As more countries sign NACAG's Statement of Undertaking, the pool of plants still eligible and additional for carbon finance will shrink. The EU regulates industrial N₂O emissions in Europe via the ETS, and in the future will regulate imports via the EU's Carbon Border Adjustment Mechanism (CBAM).

Support most needed from buyers today

Companies can contribute to demand for CCP-approved adipic acid credits to validate the new methodologies commercially. On nitric acid credits, however, the ICVCM and registries are still resolving additionality and baseline concerns.

CASE STUDY

ODS and HFC Destruction: Building the Path for a Circular Economy of Refrigerants

Destruction is the last step in the Lifecycle Refrigerant Management (LRM) chain, alongside other credit-generating steps such as equipment replacement (swapping out old, high-GWP systems), leak detection and repair, and reclamation (purification and reuse to displace virgin gas production). Across all these systems, gas recovery is needed: pulling used gas from chillers, AC units, refrigerators, foams, and cylinders. Sending equipment and materials to either be destroyed or reclaimed helps to build the circular refrigerant economy of the future. Carbon credits can play a critical role today in building this capacity.

ODS destruction is the established pathway of this category: credited under registries since the 2010s, highly rated, and CCP-labeled. HFC destruction is the newer “second act,” targeting high-GWP HFC refrigerants being phased down under the Kigali Amendment. It addresses earlier pitfalls by targeting dispersed end-of-life gas rather than a production-linked by-product while introducing much stronger safeguards.

Why it meets our criteria

Scalability: ODS destruction is mature and repeatable, with established chain-of-custody and

waste destruction facility standards. Production of most ODS is now banned, but legacy banks in equipment and stockpiles keep leaking—the unrecovered legacy bank is estimated to be approximately 9 billion tons CO₂e through 2100.³⁸ HFC destruction is at an earlier stage but uses the same infrastructure and MRV systems as ODS. HFC volumes will grow sharply with rising cooling demand: Carbon Containment Lab modeling projects more than 30 billion tons CO₂e of refrigerant could be vented by 2050 if left unmanaged.³⁹ The constraints to scaling include a lack of certified destruction facilities. They are currently available in only 16 countries that accept cross-border waste imports, creating significant bottlenecks in collection and transport and adding cost and administrative complexity.⁴⁰ Meanwhile, limited access to capital and lengthy permitting processes constrain the expansion of destruction capacity. Recovery of gases is constrained by technician shortages and inadequate field equipment, even where cash incentives exist.⁴¹

Opportunity size: Roughly 7 million ODS credits have been issued to date, with about 1.9 million still unretired.⁴² HFC issuance is small (about 10,000 credits to date) but expected to scale substantially over the next five to ten years, with credits concentrated in countries with large cooling stock and weak end-of-life capture. Google’s multiyear 250,000-credit commitment to Recoolit signals early buyer demand.⁴³

Value: ODS credits have historically traded from about \$5 to \$17 a ton.⁴⁴ By contrast, HFC credits sold through wholesale and multiyear deals currently cost \$30⁴⁵ to \$75⁴⁶ per ton, reflecting the logistically complex and labor-intensive process of collecting end-of-life equipment, recovering refrigerants, and moving them to certified destruction facilities.

Quality: ODS projects are generally rated highly by raters such as BeZero, Calyx Global, and Sylvera. ODS destruction is CCP-labeled via CAR and

ACR methodologies.⁴⁷ HFC destruction is not yet CCP-labeled or CORSIA-eligible and remains “in assessment.”⁴⁸ Three new methodologies (Isometric, Open Carbon Protocol, and Verra VM0016 v2.0) have recently been adopted. Stakeholder concerns on quality in this category include creating perverse incentives that result in increased production of virgin gas, and whether MRV guards against this; additionality complexity from staggered, regional Kigali phase-down schedules; and scrutiny of counterfactual and stockpile-sourcing claims.

Policy pathway: Both pathways sit beside the Kigali Amendment (173 of 198 parties ratified)⁴⁹ to capture legacy refrigerant that regulation doesn’t yet reach. ODS gases are not Paris Agreement gases, so they are ineligible for Article 6 without reform. Carbon finance instead closes the funding gap for its proper

capture, transport, and destruction, potentially maturing into municipal, take-back/extended producer responsibility (EPR) or commercial refrigerant-management systems.

Support most needed from buyers today

Multiyear offtake agreements that de-risk investments in MRV, chain of custody, and destruction facilities, plus tolerance for MRV still being field-tested.

CASE STUDY

Rice Methane Mitigation: A Frontier in Dispersed Emissions Mitigation

Rice is produced at a large scale: it is a major cereal crop for almost half of the global population,⁵⁰ cultivated across more than 165 million hectares of land with upwards of 144 million farms concentrated in Monsoon Asia.⁵¹ Rice cultivation is the source of 8 to 11 percent of global methane emissions.⁵²

Rice is traditionally grown in continually flooded paddies. Flooding helps suppress weeds but creates anoxic (oxygen-free) soil conditions that generate significant amounts of methane as organic matter decomposes.⁵³ Mitigation activities primarily focus on reducing the duration of flooding through practices such as alternate wetting and drying (AWD) and direct seeding into dry soil. Projects can also include other climate- and soil-friendly practices such as biochar amendments and fertilizer adjustments (affecting nitrous oxide emissions) as well as composting rice straw instead of reapplying it directly to the paddy (further reducing methane) or burning it (avoiding black carbon).

Early Clean Development Mechanism (CDM) methodologies tried to address this source but were found to be flawed; in 2024, Verra invalidated 4.5 million credits using these protocols.⁵⁴ Since then, the methodology landscape has been substantially rebuilt on stronger foundations, and rice methane is now reemerging in the VCM as a rapidly expanding category.

Why it meets our criteria

Scalability: The opportunity is massive. Sustainable rice practices carry mitigation potential of up to 48 percent of baseline emissions.⁵⁵ AWD alone can reduce methane by 30 to 70 percent and water use by 30 percent without reducing yields;⁵⁶ direct seeding has shown reductions of up to 90 percent in controlled studies;⁵⁷ biochar amendments have decreased methane by roughly 40 percent in early studies;⁵⁸ and combined AWD plus direct seeding has also demonstrated reductions up to 90 percent.⁵⁹ These practices do not require a major infrastructure overhaul, supporting rapid replication once methodology and MRV barriers are addressed. Constraints to scaling include the logistical difficulty of verifying practice adoption across thousands of smallholder plots, and the open question of whether satellite-enabled MRV systems can close that gap at cost.

Nearly all the 1.2 million unretired credits currently in this pathway are on legacy CDM methodologies, warranting caution.⁶⁰ However, the future is bright: several registries have developed or are in the process of developing new and improved methodologies, while project developers are active across Ghana, India, Indonesia, Latin America, the United States, and Vietnam. Gold Standard, whose rice methane methodology recently received CCP approval,⁶¹ forecasts approximately 3.2 million credits in this pathway over the next five years.⁶²

Value: Newer credits are currently \$15 to \$25 per metric ton of CO₂e.⁶³ Most irrigation management practices require minimal infrastructure changes, keeping both project and credit costs at a low starting point. Measurement and monitoring costs vary, however, and further research is needed to improve the reliability, availability, and cost of models and satellite-based tools to reduce reliance on analog approaches such as logbooks and farmer attestations. Forward offtake deals remain rare but

are gaining momentum, reflecting growing interest from corporate buyers. For example, Amazon signed a forward purchase agreement for nearly 700,000 credits from The Good Rice Alliance in April 2026.⁶⁴

Quality: The new generation of methodologies represents a meaningful shift toward higher-quality credits, though they remain in the early stages and have not yet been tested at scale across multiple crediting cycles. Rice methane projects also enhance quality and durability by offering multiple benefits: a new revenue stream for farmers, reduced pressure on scarce water resources, and minimal reversibility risk, which together have contributed to strong early farmer adoption.⁶⁵ Stakeholder concerns include whether current methodologies adequately account for nitrous oxide rebound from field drainage and whether AWD adoption already occurring without carbon finance could compromise additionality going forward.

Policy pathway: Proposed policies on rice methane appear promising, with groundwork laid by semi-governmental research bodies such as the International Rice Research Institute in partnership with national research institutions.⁶⁶ Government

adoption is under way in several markets, including Vietnam's Ministry of Agriculture, which has been working on AWD since 2011,⁶⁷ and the Philippines, which has pursued AWD across all national irrigation systems to adapt to increased water scarcity.⁶⁸ This policy's water savings double as a climate adaptation measure in regions facing more unpredictable irrigation supply, giving governments an additional rationale for adoption independent of carbon benefit. Carbon finance supports the transition by funding incentives to farmers to change practices, improving MRV science and best practices, and helping demonstrate to farmers and governments that these changes do not reduce yield.

Support most needed from buyers today

Forward offtake commitments enable the development and deployment of rigorous MRV. Buyers can extend impact by prioritizing projects that avoid additional superpollutants, such as those reducing fertilizer use and biomass burning.

CASE STUDY

Anaerobic Digesters: Established Technology, Uneven Additionality

Anaerobic digesters capture methane produced when organic waste, including municipal wastewater sludge, livestock manure, and other agricultural residues, decomposes in oxygen-free environments.⁶⁹ The captured biogas can generate electricity or heat, be used as cooking fuel, upgraded to renewable natural gas (RNG) for pipeline injection or vehicle fuel, or flared (and therefore converted to CO₂, which has a lower GWP). While crediting for digesters is primarily based on avoided or mitigated methane emissions, digesters can also reduce nitrous oxide and black carbon emissions with significant co-benefits.

Why it meets our criteria

Scalability: Digesters can address methane emissions from several large and dispersed waste streams. Manure management alone accounts for 1.3 percent of U.S. annual emissions.⁷⁰ The VCM pathway is mature, with multiple methodologies across Gold

Standard, Verra, and CAR and more than 27 million unretired credits currently on the market across hundreds of projects.⁷¹ The underlying technology is also mature and highly replicable, with digesters operating worldwide across household, agricultural, wastewater, and industrial applications with well-established connections to carbon finance. Industrial-scale digesters are particularly replicable and bankable because they can generate multiple revenue streams from the same waste sources, including energy, RNG, and digestate fertilizer.⁷²

Value: Wastewater digester projects are among the lowest-priced superpollutant credit categories, reported at an average of \$3.21 per ton CO₂e in 2026.⁷³ Agricultural and manure digester credits are priced slightly higher at an average of \$9.63 per ton CO₂e.⁷⁴ Digesters do have high up-front costs and incur costs from ongoing maintenance. A recent World Resources Institute (WRI) report found manure digesters can cost around \$500 a cow annually on U.S. dairy farms.⁷⁵ However, in addition to carbon finance, industrial-scale projects can partially offset these costs through revenues generated from the sale of energy, RNG, and digestate fertilizer.

Quality: Quality of projects varies substantially by project scale and waste stream. Household-scale digesters are highly additional and produce clean cooking fuel and organic fertilizer.⁷⁶ Industrial-scale digesters address concentrated methane sources and often generate highly measurable emissions reductions while also reducing local environmental nuisances such as odor, and can produce energy and fertilizer. Additionality may be a weak point for large-scale industrial projects, particularly where co-product revenue and existing policy incentives

(e.g., California's Low Carbon Fuel Standard - LCFS) can substitute for carbon finance as the primary factor in project viability. Measurement and verification rigor should be reviewed closely across all projects, but especially at the household scale where monitoring infrastructure is limited and costly to do well.

Policy pathway: Further policy support for industrial-scale digesters is plausible but may be more likely driven by energy generation,⁷⁷ waste management,⁷⁸ fertilizer production,⁷⁹ and local air quality improvements. Household-scale digesters may attract further support through clean development funds and national incentive programs.⁸⁰ Carbon projects can support these policies by reducing costs, raising awareness and improving technology and measurement.

Support most needed from buyers today

Buyers can purchase digester credits on the spot market. To ensure the best investment, they should prioritize credits with clear social or environmental benefits and strong evidence of additionality and robust MRV. Buyers should deprioritize credits generated under methodologies that ICVCM has rejected, including CDM methodologies AMS-I.E. and AMS-I.I (as of August 2026).⁸¹ Digesters may also offer a strong inseting opportunity for companies with significant Scope 3 emissions from livestock or agricultural waste residues in their supply chains; or where they can potentially purchase energy and/or fertilizers as commodities.

CASE STUDY

Landfill Gas Capture, Destruction, and Utilization: Mature but Regulation-Exposed

Landfills are the third-largest source of anthropogenic methane globally, generating roughly 799 million tons of CO₂e per year.⁸² Methane forms as organic waste decomposes anaerobically within landfills. Credit projects install gas collection then either flare methane or route it for electricity generation, direct thermal use, or upgrading to renewable natural gas (RNG).⁸³

Landfill gas (LFG) capture, destruction, and utilization is one of the CDM's original mainstay categories, with credits issued since the early 2000s. It was also one of the ICVCM's first two categories with CCP-approved methodologies, covering roughly 15 million credits.⁸⁴ The category now has a mature methodology landscape across ACR, CAR, Gold Standard, and Verra, with others in development. Gas collection is now widely mandated at larger sites in developed countries through policies such as the EU Landfill Directive and U.S. Clean Air Act New Source Performance Standard rules.⁸⁵ Where these regulations do not apply, however, landfill gas capture projects offer significant potential for superpollutant mitigation. New approaches to landfill gas management, including biocovers and enhanced well control, may also provide opportunities to mitigate additional methane emissions at sites

where conventional collection projects are otherwise nonadditional or uneconomic.

Why it meets our criteria

Scalability: Landfills account for roughly 8 percent of global methane emissions.⁸⁶ Sixty to 90 percent of emissions at average landfills could be mitigated through gas collection technology—such as wells, header pipes, and flares or utilization equipment—that is readily commercially available and retrofittable.⁸⁷ Legacy CDM and VCS issuance is large and mature, spanning thousands of projects over two decades. The ICVCM's initial CCP-approved portion alone totals approximately 15 million credits.⁸⁸ More than 40 million credits are currently available in the market out of nearly 80 million issued.

Value: Credits are priced near the low end of the carbon market, averaging about \$4.60 per ton CO₂e in 2026 for CCP-labeled supply.⁸⁹ Projects that generate a second revenue stream by selling captured gas for electricity, direct use, or RNG can substantially offset up-front project costs and improve project economics, though they need to be careful to avoid double counting of the environmental attributes sold.

Quality: Landfill projects perform well on several quality indicators: methane destruction is immediate, highly permanent, and readily verifiable, and projects can generate multiple benefits for the environment and local communities. The main risk has become additionality, as both market and policy incentives make landfill gas capture with beneficial use more financially attractive without carbon credits.⁹⁰ Larger landfill gas-to-electricity projects (more than 10 Megawatt electrical (MWe)) remain excluded from CCP approval pending further review.⁹¹

Novel approaches to mitigate landfill gas such as biocovers and enhanced gas extraction may avoid these additionality risks but will need to develop robust MRV and counterfactuals for high-integrity crediting.

Policy pathway: Landfill gas management is already regulated in many jurisdictions. The remaining opportunity is therefore concentrated in jurisdictions and sites where capture is not yet required. At the same time, the sector is being tested for a new policy pathway: Article 6.4 compliance markets. Landfill gas was the first project type approved under the Paris Agreement Crediting Mechanism, with a crediting baseline that declines faster for flare-only projects than for methane-to-energy projects, creating an explicit incentive to shift toward utilization.⁹²

Support most needed from buyers today

Spot purchasers should prioritize CCP-approved credits from projects in developing countries and in smaller and/or unregulated landfills. Buyers should

also favor beneficial-use projects (energy/RNG) over pure flaring. Continued scrutiny of legacy credits from large, already-regulated landfills can help distinguish genuinely additional projects and reward well-managed operations.

Forward purchasing and investments in newly developed landfills in developing countries can unlock complementary financing from multilateral development banks and governments while delivering major public health benefits from otherwise unmanaged waste. Waste-sector interventions further upstream, including organic waste diversion, composting, and anaerobic digestion, should complement landfill gas capture. Further, forward-looking buyers should be on the lookout for opportunities to invest in or support novel landfill gas credit types that show potential against these criteria.

CASE STUDY

Plugging Orphaned Oil and Gas Wells: High Potential, but Currently Constrained by Measurement and Additionality Concerns

Unplugged and unproductive oil and gas wells without a solvent operator are considered “orphaned.” As these wells sit, methane can leak from the degrading well casing and surface infrastructure.⁹³ In the United States, individual states are responsible for the eventual plugging of these wells.⁹⁴ However, the sheer number of these wells, limited numbers of plugging teams, and lack of public resources have left thousands of wells unplugged for years. Carbon credit projects measure methane emissions: before plugging, plug and cement the wellbore, and properly “abandon,” (that is, reclaim the site). Avoided emissions are estimated by projecting the leak rate forward, typically 20 years, based on the assumption that the well would otherwise have remained unplugged.⁹⁵

Orphaned well plugging is a new and potentially scalable pathway, but crediting approaches and MRV require further development. ACR published the world’s first dedicated methodology in 2023, though it was subsequently taken offline due to integrity concerns with measurement. Other registries such as Open Carbon Protocol, Climate Action Reserve, BCarbon, and CarbonPath have since stepped in,

each with different measurement protocols and projections.

Why it meets our criteria

Scalability: This mitigation measure has so far been concentrated in North America where the U.S. has an estimated 3.6 million abandoned wells, including orphaned and non-orphaned, emitting 7 million to more than 20 million metric tons CO₂e a year.⁹⁶ The Carbon Containment Lab estimates about 100 million MTCO₂e could be abated over 20 years by plugging currently documented orphaned wells.⁹⁷ Eight million credits have been issued under this pathway to date, with over 3 million of the unretired credits issued under ACR’s now inactive methodology.⁹⁸ While well plugging and abandonment (P&A) technology is mature, a few constraints currently dampen project activity: engineering and resource requirements vary from well to well and are hard to predict. The complexity of surface, mineral, and pore rights poses another challenge. Split ownership across private, state, federal, and tribal entities can create uncertainty around which entity gets credit for emissions reductions.

Value: At about \$20 a ton, prices are comparable to nature-based carbon removal credits.⁹⁹ One estimate puts the total 15-year market for documented orphaned wells at \$1 billion at \$20 a ton, rising to more than \$17 billion for all high-priority abandoned wells at \$100 a ton.¹⁰⁰ The cost of well plugging and pre- and post-plugging measurements can be high, ranging from thousands to hundreds of thousands of dollars a well.¹⁰¹ Well plugging and site remediation projects occasionally reach millions of dollars for a single well.

Quality: Plugging an orphaned well immediately stops methane emissions and benefits landowners and nearby communities by also stopping the co-emission of other toxic pollutants and returning well sites to other uses. Other environmental benefits include protecting the groundwater strata exposed to leaks in the well casing.

This pathway must overcome several quality risks, however. The first is overcrediting caused by unproven counterfactuals and emission baselines. Many methodologies require only a single pre-plugging measurement to support 20 to 50 years of crediting, but this approach captures only a snapshot of emissions because orphaned-well methane emissions can be unpredictable over time.¹⁰² Currently, a lack of consensus exists on which measurement or decline-curve approach most accurately reflects real-world leak behavior over a crediting period.¹⁰³ Further, permanence depends on the well plug remaining intact and the surrounding area being free from more drilling. Additionality is another concern: in certain cases, states may end up prioritizing plugging the same high-emitting wells that offer the best return on investment for carbon projects. Crediting terms should be limited by realistic timelines of state plugging programs. No methodology has yet applied for CCP assessment, so the category currently has no ICVCM validation.¹⁰⁴

Policy pathway: Lenient regulatory landscapes in most states allow many well operators to postpone or avoid their plugging obligations. As a result, a growing number of wells exist in a marginal or idle condition before becoming orphaned. The Carbon Containment Lab anticipates that U.S. policy reforms currently under way could temporarily lead

to an increase in orphaned wells as undercapitalized operators shed plugging liabilities.¹⁰⁵ Credit projects can contribute to the enactment and reform of these policies and absorb some of the orphaned backlog by creating an additional funding source for remediation, raising awareness about the environmental impact of orphaned wells, and generating practical experience with measurement, plugging, and leakage monitoring. Lessons from carbon-financed projects could also help governments develop better prioritization, measurement, and remediation practices for orphaned wells more broadly.

Support most needed from buyers today

This nascent pathway will require more buyer demand to grow into its next phase. Buyers can make a difference by not only supplying capital but also ensuring methodologies and projects meet high bars for additionality, measurement, and benefits being delivered to local communities. These goals can be achieved by supporting projects that complement state-funded plugging of prioritized wells and ensuring multistage state-of-the-art measurements are taken and credited appropriately.

Appendix Endnotes

- 1 Shine, K., Fuglestedt, J. S., Hailemariam, K., & Stuber, N. (2005). Alternatives to the Global Warming Potential for Comparing Climate Impacts of Emissions of Greenhouse Gases. *Climatic Change*, 68(3), 281-302. <https://doi.org/10.1007/s10584-005-1146-9>
- 2 GWP values are from Smith et al. (2021), IPCC AR6 WGI Chapter 7 Supplementary Material, Table 7.SM.7, as archived in the Chapter 7 GitHub data repository, unless otherwise specified. Chris Smith et al., “The Earth’s Energy Budget, Climate Feedbacks, and Climate Sensitivity: Supplementary Material,” in *Climate Change 2021: The Physical Science Basis*, ed. Valérie Masson-Delmotte et al. (Cambridge: Cambridge University Press, 2021), data archived at “metrics_supplement_cleaned.csv,” IPCC-WG1/Chapter-7, GitHub, accessed Aug. 12, 2026, https://github.com/IPCC-WG1/Chapter-7/blob/main/data_output/7sm/metrics_supplement_cleaned.csv
- 3 Effective radiative forcing (ERF) values are from NOAA’s Annual Greenhouse Gas Index (Butler & Montzka, 2024). James H. Butler and Stephen A. Montzka, “The NOAA Annual Greenhouse Gas Index (AGGI),” NOAA Global Monitoring Laboratory, accessed Aug. 12, 2026. <https://gml.noaa.gov/aggi/aggi.html>.
- 4 Black Carbon direct radiative forcing (2005-2014 mean vs 1750) not including secondary effects. From Smith et al. (2021), IPCC AR6 WGI Chapter 7 Supplementary Material. Smith et al., “Supplementary Material,” Table 7.SM.6.
- 5 Black carbon GWP/GTP values are from Samset, Lund & Aamaas (2023). Bjørn H. Samset, Marianne T. Lund, and Borgar Aamaas, *Climate Effects of Black Carbon Emissions: Updated GWP and GTP Values after the IPCC AR6, CICERO Report 2023:09* (Oslo: CICERO Center for International Climate Research, 2023), <https://pub.cicero.oslo.no/cicero-xmloi/handle/11250/3167190>.
- 6 Ozone radiative forcing methodology follows Myhre et al. (2013), IPCC AR5 WGI Chapter 8. Total ozone contribution (stratospheric + tropospheric, 0.47 W/m²) is taken from Smith et al. (2021), IPCC AR6 WGI Chapter 7. Gunnar Myhre et al., “Anthropogenic and Natural Radiative Forcing,” in *Climate Change 2013: The Physical Science Basis*, ed. Thomas F. Stocker et al. (Cambridge: Cambridge University Press, 2013), 659–740, <https://doi.org/10.1017/CBO9781107415324.018>. Smith et al., “Supplementary Material,” Table 7.SM.6.
- 7 Effective radiative forcing (ERF) values are from NOAA’s Annual Greenhouse Gas Index (Butler & Montzka, 2024). James H. Butler and Stephen A. Montzka, “The NOAA Annual Greenhouse Gas Index (AGGI),” NOAA Global Monitoring Laboratory, accessed Aug. 12, 2026. <https://gml.noaa.gov/aggi/aggi.html>. CFCs are ~95% of this value; the remainder is CCl₄, CH₃CCl₃ and halons (8 gases total). Declining as CFCs leave the atmosphere.
- 8 Effective radiative forcing (ERF) values are from NOAA’s Annual Greenhouse Gas Index (Butler & Montzka, 2024). James H. Butler and Stephen A. Montzka, “The NOAA Annual Greenhouse Gas Index (AGGI),” NOAA Global Monitoring Laboratory, accessed Aug. 12, 2026. <https://gml.noaa.gov/aggi/aggi.html>. HCFC: Effective radiative forcing of 1750-2024. (HCFC group: HCFC-22, -141b, -142b). From NOAA’s 2024 Annual Greenhouse Gas Index update. NOAA Global Monitoring Laboratory, “Annual Greenhouse Gas Index (AGGI),” updated Fall 2025, Table 2, “HCFCs” column, accessed Aug. 12, 2026, <https://gml.noaa.gov/aggi/aggi.html>.
- 9 Effective radiative forcing (ERF) values are from NOAA’s Annual Greenhouse Gas Index (Butler & Montzka, 2024). James H. Butler and Stephen A. Montzka, “The NOAA Annual Greenhouse Gas Index (AGGI),” NOAA Global Monitoring Laboratory, accessed Aug. 12, 2026. <https://gml.noaa.gov/aggi/aggi.html>. HFC: Effective radiative forcing from the HFC group, 1750–2024, is from NOAA’s 2024 Annual Greenhouse Gas Index (AGGI) update. The reported ‘HFC*’ group total (0.055 W/m²) includes SF₆, which NOAA states accounted for approximately 13 percent of the group’s forcing in 2024 (~0.007 W/m²); subtracting this yields an approximate pure-HFC forcing of 0.048 W/m². SF₆ is reported separately below to avoid double-counting; the 0.048 figure is therefore approximate. Ibid.
- 10 HFOs have ultra-short atmospheric lifetimes and very low abundances. Not included in AGGI or the AR6 halogenated aggregate.

- 11 PFCs fall within the IPCC AR6 aggregate for all halogenated gases (0.41 W/m², 1750-2019); the PFC share is small.
- 12 SF₆ forcing is estimated from the NOAA AGGI ‘HFC*’ group total, in which SF₆ accounted for approximately 13 percent of the group’s radiative forcing in 2024 (NOAA AGGI, Fig. 3). This estimated SF₆ share is subtracted from the HFC row above (note 8) and shown separately here to avoid double-counting. NOAA Global Monitoring Laboratory, “Annual Greenhouse Gas Index (AGGI),” Figure 3 caption.
- 13 NF₃ forcing is very small and falls within the AR6 halogenated aggregate.
- 14 Climate and Clean Air Coalition, “Tropospheric Ozone,” accessed September 4, 2026, <https://www.ccacoalition.org/short-lived-climate-pollutants/tropospheric-ozone>.
- 15 Environmental and Energy Study Institute, “Fact Sheet: Short-Lived Climate Pollutants: Why Are They Important?” (Washington, DC: EESI), <https://www.eesi.org/papers/view/fact-sheet-short-lived-climate-pollutants>.
- 16 Sophie Szopa et al., “Short-Lived Climate Forcers,” in *Climate Change 2021: The Physical Science Basis*, ed. V. Masson-Delmotte et al. (Cambridge: Cambridge University Press, 2021), chap. 6; U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2021*, chap. 1, “Introduction” (Washington, DC: EPA, 2023), Box 1-2. Climate and Clean Air Coalition, “Short-Lived Climate Pollutants,” accessed September 4, 2026, <https://www.ccacoalition.org/content/short-lived-climate-pollutants>.
- 17 Thornhill, G., Collins, W., Olivié, D., et al: Climate-driven chemistry and aerosol feedbacks in CMIP6 Earth system models, *Atmos. Chem. Phys.*, 21, 1105–1126, <https://doi.org/10.5194/acp-21-1105-2021>, 2021.
- 18 Smith, C., Z. R. J. Nicholls, K. Armour, W. Collins, P. Forster, M. Meinshausen, M. D. Palmer, and M. Watanabe, “The Earth’s Energy Budget, Climate Feedbacks, and Climate Sensitivity Supplementary Material,” 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*, ed. V. Masson-Delmotte et al. (Cambridge: Cambridge University Press, 2021), Table 7.SM.7, https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Chapter_07_Supplementary_Material.pdf.
- 19 “CDM Panel Calls for Investigation over Carbon Market Scandal,” Environmental Investigation Agency, July 2, 2010, <https://eia.org/press-releases/cdm-panel-calls-for-investigation-over-carbon-market-scandal/>.
- 20 “All Ratifications,” UN Environment Programme, Ozone Secretariat, as of August 10, 2026, <https://ozone.unep.org/all-ratifications>.
- 21 U.S. Environmental Protection Agency, “Frequent Questions on the Phasedown of Hydrofluorocarbons,” last modified August 5, 2026, <https://www.epa.gov/hfcs/frequent-questions-phasedown-hydrofluorocarbons>.
- 22 “F-Gas Legislation,” European Commission, Directorate-General for Climate Action, last updated May 22, 2025, https://climate.ec.europa.eu/areas-action/fluorinated-greenhouse-gases/f-gas-legislation_en.
- 23 “F-Gas Regulation,” European Fluorocarbons Technical Committee (EFCTC), last modified September 9, 2025, <https://www.fluorocarbons.org/regulation/eu-sector-specific-regulation/f-gas-regulation/>.
- 24 Climate and Clean Air Coalition (2024) Global Nitrous Oxide Assessment <https://wedocs.unep.org/items/fe972a7d-7aa2-4337-b27d-0cd857046eb9>
- 25 U.S. Environmental Protection Agency, “Global Mitigation of Non-CO₂ Greenhouse Gases: 2010–2030,” June 2013, https://www.epa.gov/sites/default/files/2016-06/documents/mac_report_2013-iv_industrial.pdf.
- 26 David R. Kanter, Jessica Wentz, and Eric Davidson, “Abating Industrial Nitrous Oxide Emissions in the United States: Legal, Economic and Scientific Dimensions,” *Climate Policy* (2026), published online April 29, 2026, <https://doi.org/10.1080/14693062.2026.2662997>.
- 27 Magdalena Jabłońska and Haythem Benamor, “Advances in Decomposition of N₂O from Nitric Acid Plants and Current Status over Selected Copper-Containing Catalysts,” *Catalysis Science & Technology* 16, no. 11 (2026): 3703–3719, <https://doi.org/10.1039/D6CY00137H>.

- 28 Lambert Schneider, Michael Lazarus, and Anja Kollmuss, “Industrial N₂O Projects Under the CDM: Adipic Acid—A Case of Carbon Leakage?,” Working Paper WP-US-1006 (Somerville, MA: Stockholm Environment Institute, October 9, 2010), https://carbonmarketwatch.org/wp-content/uploads/2010/10/CDM-Watch_Adipic-Acid-Study1.pdf.
- 29 Lambert Schneider and Martin Cames, “Options for Continuing GHG Abatement from CDM and JI Industrial Gas Projects” (Berlin: Öko-Institut, May 2014), 21, <https://www.nitricacidaction.org/wp-content/uploads/2017/04/Options-for-continuing-GHG-abatement-from-CDM-and-JI-industrial-gas-projects-en.pdf>.
- 30 UNEP Ozone Secretariat, “Controlling Industrial Emissions of Nitrous Oxide (N₂O) under the Montreal Protocol,” presentation at OEWG46, July 9, 2024, [https://ozone.unep.org/system/files/documents/N2O%20side%20event%20deck_FINAL%20\(clean\).pdf](https://ozone.unep.org/system/files/documents/N2O%20side%20event%20deck_FINAL%20(clean).pdf). Chemical & Engineering News, “Nitrous Oxide Packs a Dangerous Climate Punch,” updated July 15, 2021, <https://cen.acs.org/environment/climate-change/Nitrous-oxide-packs-dangerous-climate/99/i25>.
- 31 CDM Watch, “CDM Watch Submission to the European Commission on Design Aspects of Quality Restrictions on the Use of Credits from Industrial Gas Projects,” October 25, 2010, https://climate.ec.europa.eu/system/files/2016-11/cdm_watch_1_en.pdf.
- 32 ClearBlue Markets. *Vantage*, carbon intelligence platform, 10 Aug. 2026. www.clearbluemarkets.com
- 33 Climate Action Reserve (2026) China Adipic Acid Protocol. <https://climateactionreserve.org/how/protocols/industrial/china-adipic-acid/>
- 34 Climate Action Reserve (2026) Nitric Acid Protocol Public Webinar <https://climateactionreserve.org/event/nitric-acid-production-protocol-public-comment-webinar/>
- 35 Institute for Governance and Sustainable Development (IGSD) (2025) Action Plan for Controlling N₂O Emissions. <https://www.igsd.org/wp-content/uploads/2025/09/Action-Plan-for-Controlling-N2O-Emissions-Bilingual-Version.pdf>
- 36 Climate Action Reserve, “China Adipic Acid Production Protocol,” Version 1.0, adopted October 4, 2023, <https://climateactionreserve.org/how/protocols/industrial/china-adipic-acid/>.
- 37 International Climate Initiative, “The Nitric Acid Climate Action Group (NACAG),” March 17, 2021, https://www.international-climate-initiative.com/en/iki-media/news/the_nitric_acid_climate_action_group_nacag/.
- 38 Megan Lickley, et al, “Quantifying contributions of chlorofluorocarbon banks to emissions and impacts on the ozone layer and climate,” *Nature Communications*, 11, 1380 (2020), <https://doi.org/10.1038/s41467-020-15162-7>.
- 39 Tilden Chao, et al, “Recovery and Destruction of Hydrofluorocarbon Refrigerant Gases in Article 5 Countries Summary, Context, and Justification for Draft Methodology,” *Carbon Containment Lab*, (2023), <https://carboncontainmentlab.org/documents/yale-cc-lab-hfc-methodology-white-paper-may-2023-draft.pdf>
- 40 Carbon Containment Lab, “Aligning the Basel Convention and Montreal Protocol to Enable Life-Cycle Refrigerant Management and Environmentally Sound Management of Used and Waste Refrigerators, Cooling, and Heating Equipment,” Side Event Report, Basel Convention Conference of the Parties, 17th Meeting, Geneva, Switzerland, May 5, 2025, <https://carboncontainmentlab.org/documents/basel-convention-cop-2025-side-event-report-1749223116.pdf>.
- 41 “Lifecycle Refrigerant Management,” Projects, Carbon Containment Lab, accessed August 11, 2026, <https://carboncontainmentlab.org/projects/refrigerants>.
- 42 Carbon Containment Lab analysis of Pamela Quartson et al., *Voluntary Registry Offsets Database*, version 2026-06 (Berkeley Carbon Trading Project, University of California, Berkeley, 2026), gspp.berkeley.edu/berkeley-carbon-trading-project/offsets-database.
- 43 Recoolit, “Our Partnership with Google,” Recoolit (blog), May 8, 2025, <https://www.recoolit.com/post/google/>.
- 44 ClearBlue Markets. *Vantage*, carbon intelligence platform, 10 Aug. 2026, clearbluemarkets.com
- 45 “Open Carbon Protocol Approves HFC Destruction Methodology,” Quantum Commodity Intelligence, August 15,

- 2025, <https://www.qcintel.com/carbon/article/open-carbon-protocol-approves-hfc-destruction-methodology-46815.html>
- 46 “Registry,” Recoolit, accessed August 11, 2026, <https://registry.recoolit.com/buy>.
- 47 “Assessment Status,” Integrity Council for the Voluntary Carbon Market, last updated August 4, 2026, accessed August 11, 2026, <https://icvcm.org/assessment-status/>
- 48 Ibid.
- 49 “All Ratifications,” Ozone Secretariat, UN Environment Programme, last updated August 10, 2026, <https://ozone.unep.org/all-ratifications>.
- 50 Marte Nikolaisen, et al, “Modelling CH₄ Emission from Rice Ecosystem: A Comparison Between Existing Empirical Models,” *Frontiers in Agronomy* 4 (January 10, 2023): 1058649, <https://www.frontiersin.org/journals/agronomy/articles/10.3389/fagro.2022.1058649/full>.
- 51 Valerien O. Pede, et al, “Future of Rice in Asia: Perspectives and Opportunities, 2050,” International Rice Research Institute, MPRA Paper No. 123639(July 11, 2023), https://mpra.ub.uni-muenchen.de/123639/1/MPRA_paper_123639.pdf. https://mpra.ub.uni-muenchen.de/123639/1/MPRA_paper_123639.pdf.
- 52 Mukesh Kumar Mehla, et al, “Global methane emissions from rice paddies are now increasingly quantifiable,” *Commun Earth Environ* 7, 643 (August 8, 2026). <https://doi.org/10.1038/s43247-026-03902-4> <https://doi.org/10.1038/s43247-026-03902-4>
- 53 Leslie Guerra and Justin Freiberg, “Hidden in Plain Sight: An Overview of Rice Paddy Methane Mitigation,” Carbon Containment Lab (blog), June 9, 2025, <https://carboncontainmentlab.org/updates/posts/hidden-in-plain-sight-an-overview-of-rice-paddy-methane-mitigation>.
- 54 Jacqueline Krikorian, et al, “Technical Explainer: Carbon Credits for Improved Rice Cultivation,” RMI, July 30, 2025, <https://rmi.org/technical-explainer-carbon-credits-for-improved-rice-cultivation/>.
- 55 Tran Dang Xuan, et al, “Advances in Mitigating Methane Emissions from Rice Cultivation: Past, Present, and Future Strategies,” *Environmental Science and Pollution Research* 32, no. 34 (2025): 20232–20247, <https://link.springer.com/article/10.1007/s11356-025-36776-8> <https://doi.org/10.1007/s11356-025-36776-8>.
- 56 “GHG Mitigation in Rice: Alternate Wetting and Drying,” International Rice Research Institute, 2019, <https://ghgmitigation.irri.org/mitigation-technologies/alternate-wetting-and-drying>.
- 57 Yueyue Liu et al., “Direct-Seeded Rice Reduces Methane Emissions by Improving Root Physiological Characteristics Through Affecting the Water Status of Paddy Fields,” *Rhizosphere* 24 (December 2022): 100628, <https://doi.org/10.1016/j.rhisph.2022.100628>.
- 58 Qiong Nan et al., “Mitigating Methane Emission via Annual Biochar Amendment Pyrolyzed with Rice Straw from the Same Paddy Field,” *Science of The Total Environment* 746 (December 2020): 141351, <https://doi.org/10.1016/j.scitotenv.2020.141351>.
- 59 Tim Searchinger and Tapan K. Adhya, “Wetting and Drying: Reducing Greenhouse Gas Emissions and Saving Water from Rice Production,” World Resources Institute, December 16, 2014, <https://www.wri.org/research/wetting-and-drying-reducing-greenhouse-gas-emissions-and-saving-water-rice-production>.
- 60 Carbon Containment Lab analysis of Berkeley Carbon Trading Project Database
- 61 “Integrity Council Announces Assessment Decisions on Reforestation, Improved Forest Management (IFM) and Rice Cultivation Methodologies,” The Integrity Council for the Voluntary Carbon Market, February 5, 2026, <https://icvcm.org/integrity-council-announces-assessment-decisions-on-reforestation-improved-forest-management-ifm-and-rice-cultivation-methodologies/>.
- 62 Theodora Stankova, “Isometric, Gold Standard, and ACR Methodologies Gain CCP-Approved Status by ICVCM,” Carbon Herald, <https://carbonherald.com/isometric-gold-standard-and-acr-methodologies-gain-ccp-approved-status-by-icvcm/>.
- 63 Carbon Containment Lab, expert interviews with project developers

- 64 Sasha Ranevska, “Amazon Invests \$30M In India-Based Credits From The Good Rice Alliance,” Carbon Herald, April 23, 2026, <https://carbonherald.com/amazon-invests-30m-in-india-based-credits-from-the-good-rice-alliance/>.
- 65 “Alternate Wetting and Drying (AWD): The Tech Transforming Rice Cultivation for Climate Impact,” Blog, Sylvera, July 4, 2025, <https://www.sylvera.com/blog/alternate-wetting-and-drying-awd-tech-rice-cultivation-climate-impact>.
- 66 “Putting Alternative Wetting and Drying (AWD) on the Map, Globally and Nationally,” Climate Change, Agriculture and Food Security (CCAFS), 2011, <https://ccaafs.cgiar.org/outcomes/putting-alternate-wetting-and-drying-awd-map-globally-and-nationally>.
- 67 Ibid.
- 68 Bjoern Ole Sander et al., “Climate-Based Suitability Assessment for Alternate Wetting and Drying Water Management in the Philippines: A Novel Approach for Mapping Methane Mitigation Potential in Rice Production,” *Carbon Management* 8, no. 4 (2017): 331–342, <https://doi.org/10.1080/17583004.2017.1362945>.
- 69 “How Does Anaerobic Digestion Work?” U.S. Environmental Protection Agency, AgSTAR, last updated December 15, 2025, <https://www.epa.gov/agstar/how-does-anaerobic-digestion-work>.
- 70 EPA “Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2022,” United States Environmental Protection Agency, 2024, <https://www.epa.gov/system/files/documents/2024-02/us-ghginventory-2024-main-text.pdf>.
- 71 Carbon Containment Lab analysis of Pamela Quartson et al., Voluntary Registry Offsets Database, version 2026-06 (Berkeley Carbon Trading Project, University of California, Berkeley, 2026), <https://gspp.berkeley.edu/berkeley-carbon-trading-project/offsets-database>.
- 72 EPA, “Project Planning and Financing,” AgSTAR Program, accessed 11 Aug. 2026, <https://www.epa.gov/agstar/project-planning-and-financing>.
- 73 ClearBlue Markets. Vantage, carbon intelligence platform, 10 Aug. 2026, clearbluemarkets.com
- 74 Ibid. (clearblue)
- 75 Swati Hegde and Mike Badzmierowski, “Promising Technologies Need a Bigger Push to Cut Manure Emissions in the US,” World Resources Institute, August 6, 2025, <https://www.wri.org/technical-perspectives/us-manure-methane-mitigation-solutions>
- 76 CCAC Secretariat, “Biogas, a Climate and Clean Air Solution with Many Benefits,” Climate & Clean Air Coalition, March 7, 2022, <https://www.ccacoalition.org/news/biogas-climate-and-clean-air-solution-many-benefits>.
- 77 Muhammad Rizwan Haider et al., “Anaerobic Digestion for Bioenergy Production: Global Status, Environmental and Techno-Economic Implications, and Government Policies,” in *Bioresource Technology* 247 (2018): 1015–26, <https://doi.org/10.1016/j.biortech.2017.09.004>.
- 78 Andrew J. Satchwell et al, “Accelerating the Deployment of Anaerobic Digestion to Meet Zero Waste Goals,” *Environmental Science & Technology* 53, no. 19 (2019): 11078–86, <https://doi.org/10.1021/acs.est.8b04481>.
- 79 Christina van Midden et al., “The Impact of Anaerobic Digestate on Soil Life: A Review,” *Applied Soil Ecology* 191 (2023): 105066, <https://doi.org/10.1016/j.apsoil.2023.105066>.
- 80 Sunil Prasad Lohani et al, “Sustainability and Contribution of Household Biogas Plants to Energy Transition in Nepal,” *Scientific Reports* 15 (2025): article 24615, <https://doi.org/10.1038/s41598-025-24615-2>.
- 81 “Assessment Status,” Integrity Council for the Voluntary Carbon Market, accessed August 11, 2026, <https://icvcm.org/assessment-status/>.
- 82 Global Methane Initiative, “Landfill Methane: Reducing Emissions, Advancing Recovery and Use Opportunities,” September, 2011, https://www.globalmethane.org/documents/landfill_fs_eng.pdf.

- 83 Verra “Verra Publishes Revision to CDM Methodology for Landfill Gas,” Verra News, November 21, 2025, <https://verra.org/verra-publishes-revision-to-cdm-methodology-for-landfill-gas/>.
- 84 Integrity Council, “Integrity Council announces first high-integrity CCP-labelled carbon credits, as assessments continue,” Latest Posts, June 6, 2024, <https://icvcm.org/integrity-council-announces-first-high-integrity-ccp-labelled-carbon-credits-as-assessments-continue/>.
- 85 “Council Directive 1999/31/EC of 26 April 1999 on the Landfill of Waste, *Official Journal of the European Communities* L 182 (July 16, 1999), <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A31999L0031>. U.S. Environmental Protection Agency, “Standards of Performance for Municipal Solid Waste Landfills,” 40 C.F.R. Part 60, Subpart XXX, *Federal Register* 81, no. 166 (August 29, 2016): 59332, <https://www.federalregister.gov/documents/2016/08/29/2016-17687/standards-of-performance-for-municipal-solid-waste-landfills>.
- 86 Horacio Terraza and Hans Willumsen, “Guidance Note on Landfill Gas Capture and Utilization,” Technical Notes No. 108 Inter-American Development Bank, (2009), <https://publications.iadb.org/publications/english/document/Guidance-Note-on-Landfill-Gas-Capture-and-Utilization.pdf>.
- 87 “Benefits of Landfill Gas Energy Projects,” Landfill Methane Outreach Program, United States Environmental Protection Agency, accessed August 11, 2026, <https://www.epa.gov/lmop/benefits-landfill-gas-energy-projects>. “Basic Information about Landfill Gas,” Landfill Methane Outreach Program, United States Environmental Protection Agency, accessed August 11, 2026, <https://www.epa.gov/lmop/basic-information-about-landfill-gas>. Toby McIntosh, “GIJN Reporting Guide for Landfill Methane Emissions and Solutions,” Global Investigative Journalism Network, July 30, 2025, <https://gijn.org/resource/reporting-guide-landfill-methane-emissions-solutions/>.
- 88 Integrity Council, “Integrity Council announces first high-integrity CCP-labelled carbon credits, as assessments continue,” Latest Posts, June 6, 2024, <https://icvcm.org/integrity-council-announces-first-high-integrity-ccp-labelled-carbon-credits-as-assessments-continue/>.
- 89 ClearBlue Markets. *Vantage*, carbon intelligence platform, 10 Aug. 2026, clearbluemarkets.com
- 90 Linus Hiscox and Annie White, “Assessing the Quality of Landfill Gas Carbon Projects,” BeZero Carbon, August 17, 2022, <https://bezzerocarbon.com/insights/assessing-the-quality-of-landfill-gas-projects>.
- 91 “Integrity Council Announces First High-Integrity CCP-Labelled Carbon Credits, as Assessments Continue,” Integrity Council for the Voluntary Carbon Market, June 6, 2024, <https://icvcm.org/integrity-council-announces-first-high-integrity-ccp-labelled-carbon-credits-as-assessments-continue/>.
- 92 United Nations Climate Change, “UN Body Agrees First Methodology under Paris Agreement Carbon Market,” UN Climate Press Release, October 30, 2025, <https://unfccc.int/news/un-body-agrees-first-methodology-under-paris-agreement-carbon-market>.
- 93 Jade Boutot et al., “Documented Orphaned Oil and Gas Wells Across the United States,” *Environmental Science & Technology* 56, no. 20 (2022): 14228–36, <https://doi.org/10.1021/acs.est.2c03268>.
- 94 Ibid.
- 95 Wilkman, A., Smith, C., & Nikolova, E., “Technical Explainer: Orphaned Oil and Gas Well Carbon Credits,” RMI, 2026, <https://rmi.org/resources/technical-explainer-orphaned-oil-and-gas-well-carbon-credits/>
- 96 “Orphaned Oil & Gas Wells,” ACR, Accessed 2026, <https://acrcarbon.org/resources/orphaned-oil-and-gas-wells/>. Emily Follansbee et al, “Orphaned oil and gas well methane emission rates quantified using Gaussian plume inversions of ambient observations,” *Atmospheric Measurement Techniques*, 18, 4527–4542 (September 2025), <https://doi.org/10.5194/amt-18-4527-2025>
- 97 Assuming 100,000 wells emitting ~200 g/hr on average, using GWP-100
- 98 Wilkman, A., Smith, C., & Nikolova, E., “Technical Explainer: Orphaned Oil and Gas Well Carbon Credits,” RMI, 2026, <https://rmi.org/resources/technical-explainer-orphaned-oil-and-gas-well-carbon-credits/>. Carbon Containment Lab analysis of Voluntary Registry Offsets Database, Pamela Quartson et al., *Voluntary Registry Offsets Database*, version 2026-06 (Berkeley

Carbon Trading Project, University of California, Berkeley, 2026), <https://gspp.berkeley.edu/berkeley-carbon-trading-project/offsets-database>.

- 99 ClearBlue Markets. *Vantage*, carbon intelligence platform, 10 Aug. 2026, clearbluemarkets.com
- 100 “Plugging the Gap: How US Well Abandonment Could Become the Next Carbon Investment Frontier,” BRG, February 13, 2026, <https://www.thinkbrg.com/insights/publications/plugging-the-gap-how-us-well-abandonment-could-become-the-next-carbon-investment-frontier/>.
- 101 Wilkman, A., Smith, C., & Nikolova, E., “Technical Explainer: Orphaned Oil and Gas Well Carbon Credits,” RMI, 2026, <https://rmi.org/resources/technical-explainer-orphaned-oil-and-gas-well-carbon-credits/>
- 102 Matt Brasher, “Carbon Credits - Plugging Orphaned Oil & Gas Wells,” Brasher Petroleum Consulting, April 16, 2025, <https://www.brasherpetroleumconsulting.com/blog/Blog%20Post%20Title%20One-4c2ds>.
- 103 “Methane Mitigation of End-of-Life Oil and Gas Wells,” Carbon Containment Lab, accessed August 11, 2026, <https://carboncontainmentlab.org/projects/methane-mitigation-of-end-of-life-oil-and-gas-wells>.
- 104 “Assessment status,” accessed August 11, 2026, <https://icvcm.org/assessment-status/>
- 105 Mark Braly, “New Plugging and Abandonment Bonding Requirements: What Operators Need to Know,” BERIS International, April 16, 2026, <https://www.berisintl.com/new-plugging-and-abandonment-bonding-requirements-what-operators-need-to-know>.



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