Mitigating Landfill Methane

Key Strategies and Policy Levers to Drive Emissions Reductions

Memo / June 9, 2023

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Introduction

As organic waste decomposes in landfills, it generates methane — a super potent greenhouse gas with about 80 times the warming power of carbon dioxide emissions over 20 years. Human-driven methane emissions are responsible for nearly 45% of current net warming,[1] and atmospheric methane concentrations are rising at alarming rates.[2] The waste sector represents the third-largest human-driven methane source in the United States and globally.[3]

While some US landfills are required to control their methane in accordance with standards set by the Environmental Protection Agency (EPA), these standards are failing to deliver the methane reductions urgently needed this decade and beyond. Fortunately, there are a number of proven, often low-cost strategies to better:

- **Mitigate methane from waste in place through improved monitoring and control; and**
- **Prevent future methane generation through reduced organic waste disposal.[4]**

States, municipalities, and operators can start implementing these strategies today. At the same time, EPA should exercise its authority under the Clean Air Act to **incorporate the latest best practices into ambitious federal standards** that deliver landfill methane emissions reductions at scale. Stronger standards can help slow near-term warming, protect landfill-adjacent communities, and encourage landfilling alternatives that conserve and reuse resources.

In this memo, we provide an overview of landfill emissions today, available abatement strategies, and the benefits of acting now to reduce landfill methane. This is the first installment in RMI's ***Mitigating Landfill Methane Memo Series***, which will explore the technical approaches and policy levers that can achieve emissions reductions.

The Problem with Landfills

Landfill Methane Harms the Climate and Communities

Poorly managed landfills present an urgent threat to our climate, air quality, and public health. In the United States, municipal solid waste (MSW) landfills emit an estimated 3.7 million metric tons of methane, or about 295 million metric tons of carbon dioxide equivalent (MMT CO_2e) on a 20-year time horizon.[5] This is roughly equivalent to the annual emissions from driving 66 million gas-powered passenger cars or operating 79 coal-fired power plants.[6]

However, recent studies indicate landfill methane emissions may be considerably higher than modeled inventories, due to emissions from poorly operating gas collection systems or destruction devices and cover system leaks.[7] Senior personnel at EPA have publicly stated that current models may underestimate landfill methane emissions by a factor of two.[8] Aerial measurements have revealed large point source emissions at landfills across the country, with substantial under-reporting at some landfills.[9]

Beyond climate-warming methane, landfill gas contains hazardous air pollutants, precursors to ozone and particulate matter, odor nuisance compounds, and other dangerous gases that can impact air quality, human health, and quality of life.[10] Landfill-adjacent communities bear the brunt of these impacts. Per EPA's Environmental Justice Screening and Mapping Tool (EJScreen), 54% of landfills reporting to the Greenhouse Gas Reporting Program have communities within one mile of the landfill that exceed the national average for either percent people of color (40%) or percent low-income (30%).[11]

Root Cause: What Is Driving Landfill Methane Emissions?

Modern sanitary landfills receive and compact waste in layered cells, which generate methane as buried organic materials decompose. In the United States, more than half of landfilled materials are organic, and food waste is the single most common material landfilled in the country.[12] Methane production typically begins within the first year of disposal and can continue for 10 to 50 or more years.[13]

Some landfills in the United States are federally required to capture and control their emissions with a gas collection system, but even regulated landfills still have significant methane emissions due to ineffective gas capture and leaks. Recent field studies show real-world collection efficiency can be much lower than modeled assumptions and varies widely, from the low 20% range to above 90%.[14]

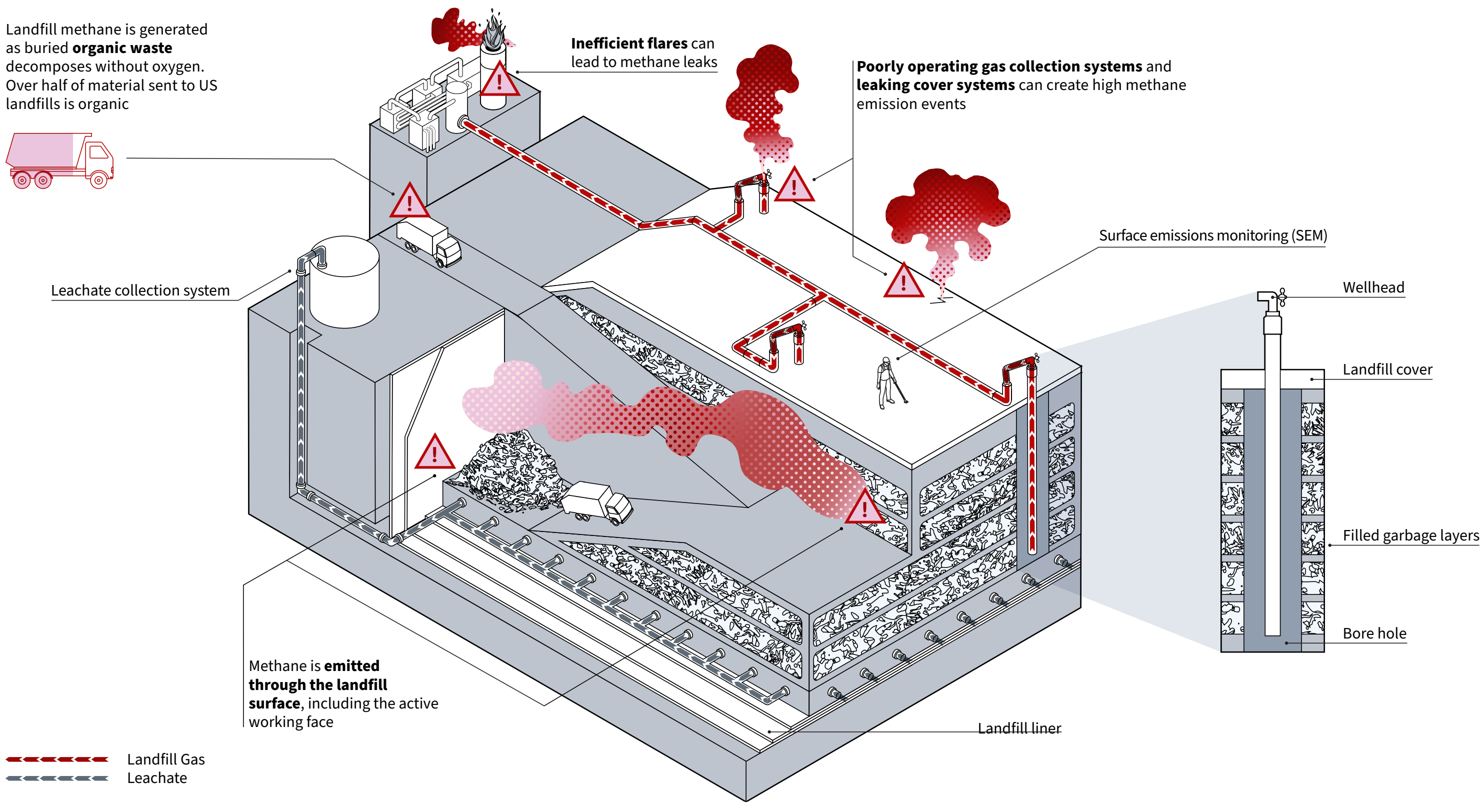
Landfill methane emissions are a function of several factors, including:

- Volume and composition of landfilled waste
- Characteristics of the landfill receiving waste (e.g., size, design, climate, pressure)
- Amount of methane oxidized (i.e., converted into less-potent CO_2) as it passes through the landfill cover
- Amount of methane captured with a gas collection system and either flared or used for energy[15]

Landfills emit methane diffusely through the landfill surface (***area source emissions***) and in more concentrated hot spots (***point source emissions***). Recent satellite and aircraft surveys with imaging spectrometers have observed strong point sources, or "super-emitter" activity, at landfills across the United States. For example, aerial campaigns conducted for the California Methane Survey found that landfills were the largest methane point source emitters in the state.[16] Furthermore, detectable point source emissions from landfills were larger than emissions from other sectors — often in the 100 to 1,000+ kg/hr range compared with oil and gas and agricultural methane emissions, which averaged in the 10 to 100+ kg/hr range.[17]

We illustrate the key drivers of landfill methane on the next page (Exhibit 1) — including the incoming organic waste responsible for methane generation and the operational issues and shortcomings in regulatory requirements that enable methane to escape. Key drivers relate to the **gas collection system** (e.g., installation delays, ineffective well spacing or tuning, system downtime due to flooded wells or damaged components), **landfill cover** (e.g., cracks and erosion, use of inappropriate cover materials, lag times between daily and intermediate cover and intermediate and final cover), **destruction** (e.g., inefficient flares), and **monitoring** (e.g., quarterly surface monitoring can miss methane leaks).[18] Each warning sign represents a mitigation opportunity.

Exhibit 1 Landfill Today: Key Components and Emissions Sources



Achieving Emissions Reductions: A Two-Pronged Approach

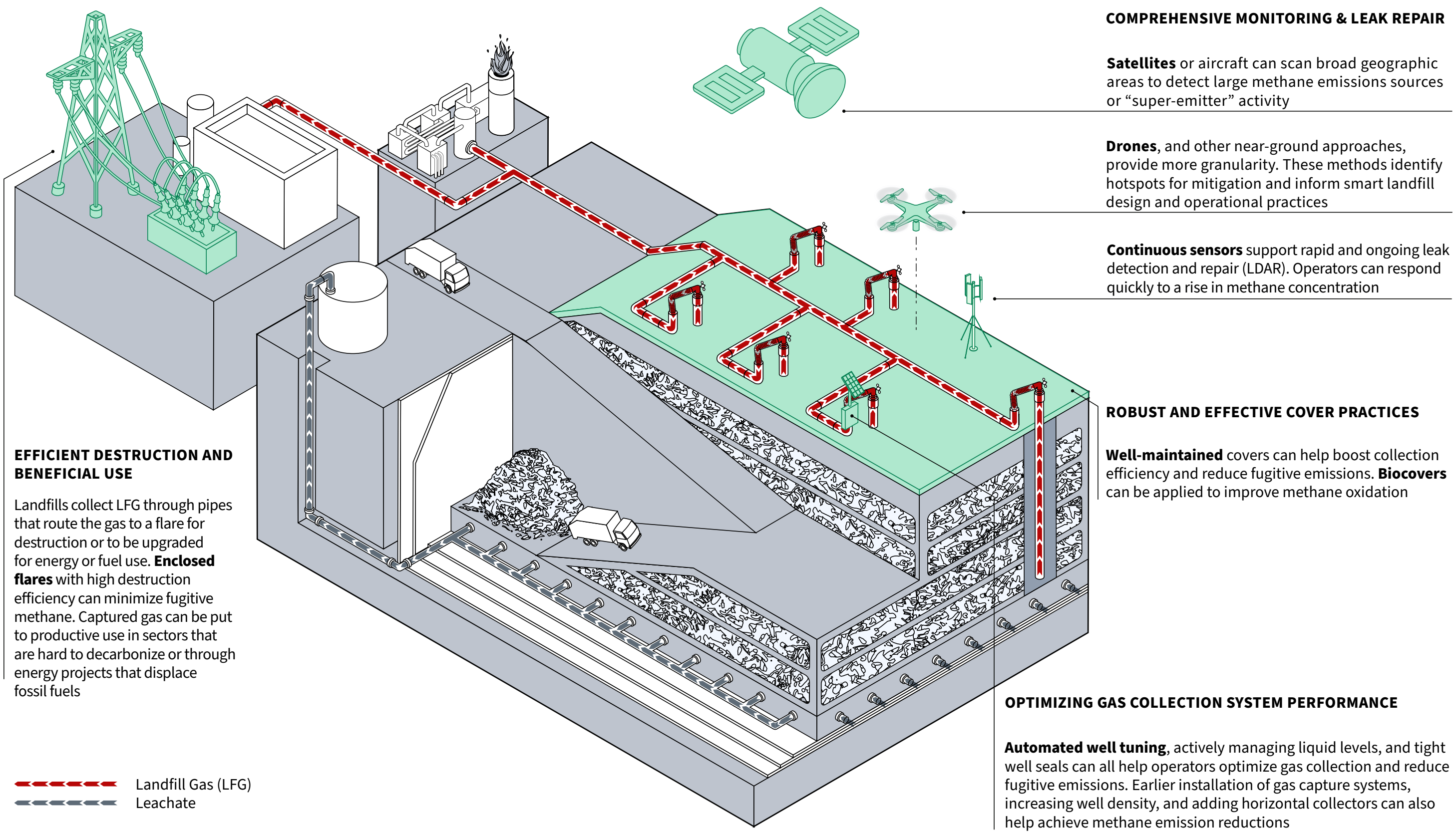
Organic waste landfilled in any one year is small compared with all the methane-generating waste already sitting in landfills today.[19] Addressing landfill methane, therefore, will require a two-pronged approach: (1) mitigating emissions from waste in place through improved monitoring and control while (2) preventing new methane generation through reduced organic waste disposal.

Mitigating Methane from Waste in Place through Improved Monitoring and Control

Improvements in monitoring, design, and operations can help control methane from organic waste already buried and decomposing in landfills today. These include: **comprehensive monitoring** to quickly detect and repair fugitive emissions, **robust gas collection system design and operations** to maximize gas capture, **effective cover materials and practices** to control surface methane, and **efficient destruction or beneficial use** of collected landfill gas. The figure on the next page (Exhibit 2) depicts a well-designed and managed landfill that maximizes gas collection while minimizing fugitive emissions — addressing the issues highlighted in Exhibit 1.

The California Air Resources Board estimates that a direct emissions reduction of 10% is achievable across the state's landfills by 2030, through increased monitoring, operational improvements, lower permeability covers, and advanced landfill gas collection systems.[20] The Maryland Department of Environment estimates a 25%–50% reduction in landfill gas emissions from proposed landfill regulation when fully implemented, as a result of increased monitoring and mitigation measures.[21]

Exhibit 2 Mitigating Methane through Improved Monitoring and Control



Landfill Methane: Key Problems and Solutions

	Problems (Exhibit 1)	Solutions (Exhibit 2)
Gas Collection and Control System	• Delays in GCCS installation and inadequate coverage • Design plan does not maximize collection system performance • Relatively infrequent wellhead tuning • Flooded wells or damaged components contribute to system downtime	• Early installation and expansion of GCCS • Robust GCCS design plan prioritizes active collection and optimizes well spacing, vertical and horizontal collection, and drainage to boost collection • Frequent/automated wellhead tuning to optimize vacuum • Frequent/continuous monitoring to avoid and address downtime
Landfill Cover	• Cracks or erosion in landfill cover • Use of inappropriate cover materials with limited oxidation capabilities • Lag times between daily and intermediate and final cover	• Frequent cover monitoring and maintenance • Use of cover materials that maximize methane oxidation, such as biocovers • Increased thickness/compaction of daily and intermediate cover • Early and ongoing installation of intermediate and final cover
Methane Destruction	• Inefficient flares	• Enclosed flares with minimum 99 percent destruction efficiency
Monitoring and Leak Repair	• Infrequent monitoring • Incomplete landfill coverage	• Comprehensive surface emissions monitoring and fugitive emissions monitoring • Fast and effective mitigation of detected leaks • Leverage advanced technologies (satellites, drones, continuous) to improve coverage and frequency

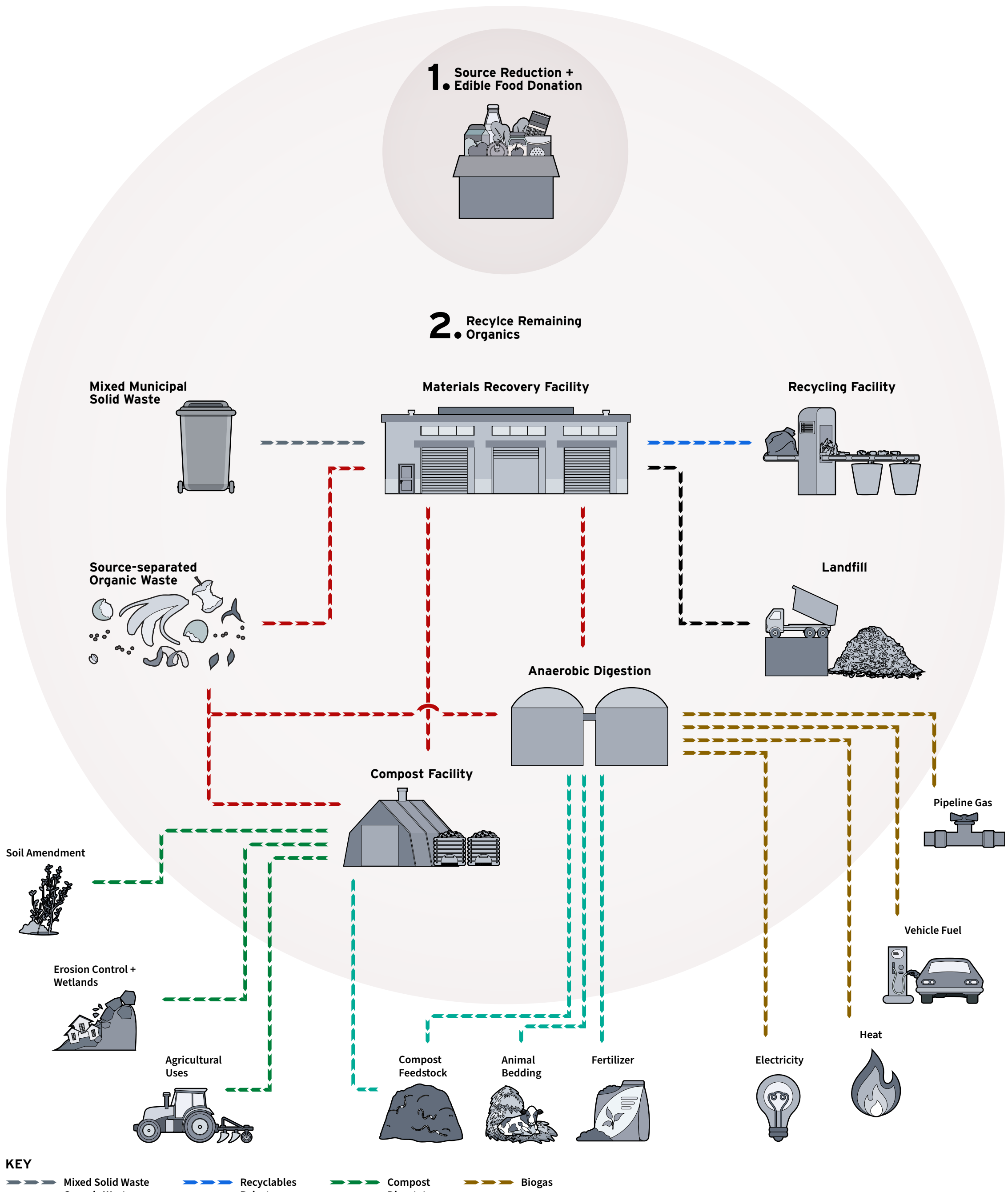
Note: This is not a comprehensive list; we show some of the factors that can lead to fugitive methane emissions, and the design and operational practices that can prevent or mitigate those emissions.

Preventing Methane Generation by Reducing Organic Waste Disposal

Reducing organic waste disposal at landfills prevents new methane generation. This strategy includes upstream efforts to **reduce and redistribute surplus**, and downstream efforts to **recycle the remaining organic waste.** Minimizing food waste on farms, improving inventory management, and donating excess edible food all help to keep organics out of the waste stream. The remaining organic waste can then be separated and processed into compost, biogas, or other beneficial end products. Diverting 75% of the food waste landfilled in one year in the United States to a composting facility or anaerobic digester would drive an 80%–90% emissions reduction over the waste's lifetime compared with landfilling, per EPA's WARM model.[22]

Exhibit 3[23] depicts various alternatives to landfilling organic waste. Successful organics diversion programs typically require a combination of policy support; behavioral change; investment in collection, processing, and recycling infrastructure; and end markets for products and commodities from diverted organics. The result is a more circular, efficient, and low-emissions waste management system.

Exhibit 3 Preventing Methane Generation by Reducing Organic Waste Disposal



Cross-cutting Benefits to Landfill Methane Action

The two-pronged approach of **improved monitoring and control** and **reducing organic waste disposal** will bring cross-cutting benefits, including:

- **Slowing Near-Term Warming:** Methane mitigation can rapidly reduce the rate of warming in the near term.[24] Research shows decarbonization focused on fossil fuel phaseout alone is insufficient to keep global warming below 1.5°C.[25] "Strong, rapid, and sustained" methane reductions — across sectors — are key to slow near-term warming and limit the risk of climate tipping points.[26]
- **Meeting Our Climate Commitments:** The United States has set several targets to reduce methane emissions as a signatory of the Global Methane Pledge (GMP) and at the 2023 North American Leader's Summit. Decisive action to control landfill emissions would help the United States meet its methane-specific and broader climate commitments; GMP-aligned methane reductions would contribute an estimated 8% to the 50%–52% overall emissions reductions the United States committed to at COP26.[27]
- **Protecting Landfill-Adjacent Communities:** Many of the technologies and practices that reduce landfill methane emissions also reduce emissions of volatile organic compounds, odors, and other local air pollutants, per EPA.[28] Stronger standards to capture and control landfill gas would therefore help address the air quality and odor issues facing communities near landfills. Strategies to prevent and divert organic waste also help reduce odors, minimize leachate generation and associated groundwater pollution, and prevent landfill expansion.[29]
- **Delivering Local Benefits:** Food waste prevention saves households money, while donation puts food on the table for families in need. Organics recycling can also create jobs; composting facilities typically employ more people per ton of waste than landfills do.[30] The end products of organic recycling carry additional benefits: biogas from diverted organics can be used to displace local fossil demand, and compost can improve soil health, sequester carbon, promote higher crop yields, and aid in reforestation and wetlands restoration.[31]

Change Levers

States, municipalities, and operators can take action today to reduce landfill methane emissions — and there are examples across the country of successful methane monitoring programs, innovative landfill design, and expanding organics recycling infrastructure and organics diversion programs.

While some strategies for improved landfill monitoring and control can carry incremental costs for operators, they can also generate returns over time; for example, improving gas capture rates can increase revenue for landfills selling their gas. Organics recycling projects, such as composting facilities and anaerobic digesters, typically have higher upfront costs than landfilling, but the revenue from valorized end products (e.g., compost, biogas, digestate) can make projects economically viable, and in some cases more profitable, than landfilling over time.[32]

Subnational policy can also drive landfill emissions reductions: through stronger state-level standards for landfill methane (e.g., California's Landfill Methane Regulation and Oregon's Landfill Gas Emissions Rules), local organics diversion ordinances (e.g., Austin, TX and Boulder, CO), compost procurement programs (e.g., Washington Organics Management Law), edible food donation requirements (e.g., California's SB1383), and by integrating waste management into broader climate plans (e.g., Climate Pollution Reduction Grants).

But federal policy support will be critical to scale methane abatement from a patchwork of forward-thinking jurisdictions and operators to a nationwide effort. Federal policy is vital to protect communities at risk in regions that are unlikely to act themselves.

EPA should develop stronger federal landfill standards. The agency is required to revisit its landfill emissions rules in 2024 and should exercise its authority under the Clean Air Act to develop ambitious standards that reflect the latest best practices in monitoring and controlling methane while encouraging organics diversion. At the same time, Congress should provide funding for subnational efforts to reduce food loss and waste and expand organics recycling. Together, these efforts can drive the emissions reductions urgently needed this decade while delivering the cross-cutting community benefits highlighted above.

Appendix: Background Information

Industry Backdrop

There are over 2,500 MSW landfills in the United States, about half of which are operational and accepting waste.[33] Landfills are owned by either public entities — cities, counties, regional authorities, state governments, or the federal government — or private companies — ranging from small businesses to businesses with billions in annual revenue. Privatization has increased over the years, and researchers estimate nearly half of all landfills are now privately owned.[34]

Landfills generate revenue primarily through tipping fees, a charge for waste disposal that averages over $50/ton nationally with wide geographic variance. Waste haulers typically pay the fee at the gate, but in most cases, collection and disposal costs are ultimately borne by waste generators through taxes. Some landfill operators also collect and monetize the landfill gas generated at the landfill. There are currently an estimated 532 operational landfill gas-to-energy projects in the US, the majority of which generate electricity. The remaining projects are direct-use or upgraded to pipeline-quality natural gas.[35] There are numerous federal and state-level incentives that support landfill energy projects, including the Renewable Fuel Standard, the Low Carbon Fuel Standard, and federal investment and production tax credits.

EPA's Landfill Methane Outreach Program (LMOP) has identified an additional 466 candidate landfills that could cost-effectively turn their methane into an energy resource.[36] While energy projects put captured gas to productive use, their emissions profile is highly dependent on site-specific management practices, gas collection efficiency, and end use. To ensure effective methane abatement, LFG projects should be subject to strong standards for leak detection and gas capture.

Regulatory Backdrop

Municipal solid waste landfills are subject to federal and state regulations governing landfill design and operations. EPA's Resource Conservation and Recovery Act (RCRA) and Clean Air Act (CAA) set minimum national standards, while delegating implementation to state and local governments.

Resource Conservation and Recovery Act: RCRA Subtitle D authorizes EPA to set national performance standards for all disposal facilities that accept municipal solid waste to manage the adverse effects on health and the environment. These standards include permitting requirements, location restrictions, operation and design criteria (including requirements for landfill liners, daily and final covers, leachate collection, and run-off controls), groundwater monitoring and corrective action requirements, closure and post-closure care, financial assurance criteria, and a prohibition on open dumping.

Clean Air Act: CAA Section 111 authorizes EPA to develop technology-based standards for specific categories of stationary sources. These include New Source Performance Standards (NSPS) for new, modified, and reconstructed sources and Emissions Guidelines (EG) for existing sources. Performance standards must reflect the emissions reductions achievable through the application of the "best system of emission reduction." In 1996, EPA classified landfills as a stationary source of air pollution posing a danger to public health and set the first NSPS and EG for landfills.[37] EPA is required to review and, if appropriate, revise the NSPS every eight years. EPA last updated the rules in 2016 with the next mandatory review coming in 2024.

NSPS/EG overview: When a landfill reaches the applicability threshold (design capacity of 2.5 million metric tons and 2.5 million cubic meters, ≥ 34 Mg/year in non-methane organic compound [NMOC] emissions, and surface methane ≥ 500 ppm), the landfill is required to monitor and control its emissions under the NSPS and EG.[38] Specifically, the landfill operator must:

- Install and operate a gas collection system within thirty months and expand the system to collect gas from all areas of the landfill where solid waste has been placed for a period of five years or more if active or two years or more if closed or at final grade.
- Route collected gas to a control system, either a flare or a treatment system that processes the collected gas for subsequent sale or beneficial use (e.g., for combustion, pipeline injection, vehicle fuel, or use in a chemical manufacturing process).

- Conduct Surface Emissions Monitoring (SEMs) quarterly: Operators must traverse the landfill at no more than 30-meter intervals to measure surface methane concentration with a gas analyzer. If the methane concentration exceeds 500 parts per million (ppm), the location must be marked and reported as an exceedance, and the landfill must take corrective action and re-monitor within ten days.
- Monitor wellhead performance monthly: Operators must measure temperature and pressure at each wellhead and take corrective action within five days if there is a temperature exceedance or negative pressure. Operators must also monitor and record oxygen and nitrogen levels at each wellhead monthly.

Landfills above the design capacity threshold but below the NMOC levels must submit an annual report to EPA certifying their NMOC emissions and re-calculate them each year. The 2016 rulemaking estimated 846 landfills would be subject to mandatory gas capture and control requirements by 2025.[39]

MSW landfills are also subject to National Emission Standards for Hazardous Air Pollutants (NESHAP) under CAA Section 112 to control, monitor, and report on HAPs, such as vinyl chloride, ethyl benzene, toluene, and benzene.

Greenhouse Gas Reporting Program: MSW landfills that generate methane at 25,000 metric tons of CO_2e per year or more are required to calculate and report their annual methane emissions to EPA's Greenhouse Gas Reporting Program (GHGRP), using first-order decay equations and gas collection data. The GHGRP covers 1,127 MSW landfills as of 2021. In May 2023, EPA proposed updates to the GHGRP to better account for large emissions events at landfills.

States are able to set more ambitious landfill methane standards through their implementation of federal plans. For example, landfill methane regulations in California and Oregon set more rigorous surface emissions monitoring requirements and lower thresholds for gas collection system installation.

States and municipalities have also taken the lead on legislation to divert organics from the landfill. Some laws directly target waste generators (e.g., New York State Food Donation and Food Scraps Recycling Law, Maryland Regulation on Food Waste Residuals, Vermont Universal Recycling Law), while others set state- or city-wide targets for organics diversion and require jurisdictions to develop compliance plans (e.g., California's SB 1383, Washington's HB 1799).

Climate Commitments

The United States has set several targets for methane reduction, including:

- Global Methane Pledge (GMP): Launched at COP26 in November 2021, the GMP targets at least 30% reduction in global methane emissions from 2020 levels by 2030. The United States joined the pledge, alongside 150 countries, to take voluntary actions to reduce methane emissions across sources. Achieving the pledge would reduce warming by at least 0.2°C by 2050 while also preventing hundreds of thousands of premature deaths, asthma-related emergency room visits, and crop losses.
- North American Leaders Summit: The United States, Canada, and Mexico committed to reduce methane emissions from the solid waste and wastewater sector by at least 15% by 2030 from 2020 levels.
- The US Methane Action Plan: EPA continues to boost its voluntary landfill methane outreach program to achieve a national goal of 70% methane emissions capture for all landfills around the country. The United States has also set a national goal of reducing food loss and waste by 50% by 2030.

Endnotes

[1] Richard Ferris et al., *A Primer on Cutting Methane: The Best Strategy for Slowing Warming in the Decade to 2030*, Institute for Governance & Sustainable Development, February 5, 2023, https://www.igsd.org/wp-content/uploads/2022/09/IGSD-Methane-Primer_2022.pdf.

[2] "Greenhouse gases continued to increase rapidly in 2022," *National Oceanic and Atmospheric Administration,* April 5, 2023, https://www.noaa.gov/news-release/greenhouse-gases-continued-to-increase-rapidly-in-2022

[3] "Overview of Greenhouse Gases: Methane," U.S. Environmental Protection Agency, April 13, 2023, https://www.epa.gov/ghgemissions/overview-greenhouse-gases#methane.

[4] Docket No. EPA-HQ-OAR-2002-0047-0082, "Eastern Research Group, Inc Memorandum Re: Clean Air Act Section 112(d)(6) Technology Review for Municipal Solid Waste Landfills," U.S. Environmental Protection Agency, June 25, 2019, https://www.regulations.gov/document/EPA-HQ-OAR-2002-0047-0082; Docket No. EPA-HQ-OAR-2003-0215-0204, "Comment submitted by Peter Zalzal et al., Environmental Defense Fund," U.S. Environmental Protection Agency, October 28, 2015, https://www.regulations.gov/comment/EPA-HQ-OAR-2003-0215-0204; Alex Badgett and Anelia Milbrandt, "Food waste disposal and utilization in the United States: A spatial cost benefit analysis," *Journal of Cleaner Production*, Volume 314 (September 2021) https://doi.org/10.1016/j.jclepro.2021.128057.

[5] *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2021.* U.S. Environmental Protection Agency, 2023. https://www.epa.gov/ghgemissions/draft-inventory-us-greenhouse-gas-emissions-and-sinks-1990-2021.

[6] "Greenhouse Gas Equivalencies Calculator," U.S. Environmental Protection Agency, May 30, 2023, https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator#results.

[7] Docket No. EPA-HQ-OAR-2019-0424, "Revisions and Confidentiality Determinations for Data Elements Under the Greenhouse Gas Reporting Rule," U.S. Environmental Protection Agency, May 22, 2023. https://www.federalregister.gov/documents/2023/05/22/2023-10047/revisions-and-confidentiality-determinations-for-data-elements-under-the-greenhouse-gas-reporting

[8] James Bruggers et al., "Your Trash Is Emitting Methane In The Landfill. Here's Why It Matters For The Climate," *NPR*, July 13, 2021, https://www.npr.org/2021/07/13/1012218119/epa-struggles-to-track-methane-from-landfills-heres-why-it-matters-for-the-clima.

[9] "Carbon Mapper Data Portal," *Carbon Mapper*, May 2023, https://data.carbonmapper.org/; Ebun Ayandele et al., Key Strategies for Mitigating Methane Emissions from Municipal Solid Waste, RMI, 2022, https://rmi.org/insight/mitigating-methane-emissions-from-municipal-solid-waste

[10] Zhenhan Duan, Charlotte Scheutz, and Peter Kjeldsen, "Trace gas emissions from municipal solid waste landfills: A review," Waste Management, Volume 119 (January 2021): 39-62, https://pubmed.ncbi.nlm.nih.gov/33039980/

[11] Preet Bains et al., Trashing the Climate: Methane from Municipal Landfills, Environmental Integrity Project, May 2023, https://environmentalintegrity.org/wp-content/uploads/2023/05/Trashing-the-Climate-report-5.18.23.pdf

[12] "Facts and Figures and Materials, Waste and Recycling: National Overview," *U.S. Environmental Protection Agency*, December 3, 2022, https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/national-overview-facts-and-figures-materials.

[13] *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2021.* U.S. Environmental Protection Agency, 2023. https://www.epa.gov/ghgemissions/draft-inventory-us-greenhouse-gas-emissions-and-sinks-1990-2021.

[14] James Hanson and Nazil Yesiller, *Estimation and Comparison of Methane, Nitrous Oxide, and Trace Volatile Organic Compound Emissions and Gas Collection System Efficiencies in California Landfills Final Report,* Prepared for: The California Air Resources Board and The California Department of Resources Recycling and Recovery, March 25, 2020, https://ww2.arb.ca.gov/resources/documents/landfill-gas-research; Morton A. Barlaz, Jeff P. Chanton, and Roger B. Green, "Controls on Landfill Gas Collection Efficiency: Instantaneous and Lifetime Performance," *Journal of the Air and Waste Management Association*, Vol 59, Iss 12. (2009), https://doi.org/10.3155/1047-3289.59.12.1399.

[15] *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2021.* U.S. Environmental Protection Agency, 2023. https://www.epa.gov/ghgemissions/draft-inventory-us-greenhouse-gas-emissions-and-sinks-1990-2021.

[16] Riley Duren, Andrew Thorpe, and Ian McCubbin, *The California Methane Survey: Final Project Report*, Prepared for: The California Energy Commission and The California Air Resources Board, July 2020, https://www.energy.ca.gov/sites/default/files/2021-05/CEC-500-2020-047.pdf

[17] Dr. Jason Schroeder, Landfill Methane Research Workshop: Methane Remote Sensing for Leak Identification and Mitigation, *The California Air Resources Board*, December 5, 2022, https://ww2.arb.ca.gov/sites/default/files/2022-12/Methane%20Remote%20Sensing.pdf.

[18] Eduardo P. Olaguer et al., "Landfill Emissions of Methane Inferred from Unmanned Aerial Vehicle and Mobile Ground Measurements," Atmosphere, Vol 13, Iss 6 (2022): 983. https://doi.org/10.3390/atmos13060983; Daniel H. Cusworth et al., "Using remote sensing to detect, validate, and quantify methane emissions from California solid waste operations," *Environmental Research Letters*, 15 (2020): 054012, https://iopscience.iop.org/article/10.1088/1748-9326/ab7b99/pdf; James Hanson and Nazil Yesiller, *Estimation and Comparison of Methane, Nitrous Oxide, and Trace Volatile Organic Compound Emissions and Gas Collection System Efficiencies in California Landfills: Final Report*, Prepared for: The California Air Resources Board and The California Department of Resources

Recycling and Recovery, March 25, 2020, https://ww2.arb.ca.gov/resources/documents/landfill-gas-research; *Preliminary Concepts for Potential Improvements to Landfill Methane Regulation*, The California Air Resource Board, May 18, 2023, https://ww2.arb.ca.gov/sites/default/files/2023-05/LMR-workshop_05-18-2023.pdf.

[19] *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2021.* U.S. Environmental Protection Agency, 2023. https://www.epa.gov/ghgemissions/draft-inventory-us-greenhouse-gas-emissions-and-sinks-1990-2021.

[20] *2022 Scoping Plan for Achieving Carbon Neutrality*, California Air Resources Board, December, 2022 https://ww2.arb.ca.gov/our-work/programs/ab-32-climate-change-scoping-plan/2022-scoping-plan-documents.

[21] *COMAR 26.11.42: Control of Methane Emissions from Municipal Solid Waste (MSW) Landfills*, Maryland Department of the Environment, October 24, 2022, https://mde.maryland.gov/programs/workwithmde/Documents/AQCAC/2022MeetingMaterials/Control%20of%20Methane%20from%20MSW%20Landfills%20-%20October%20AQCAC_final%20PDF.pdf.

[22] "Waste Reduction Model (WARM) Version 15," Environmental Protection Agency, September 2022, https://www.epa.gov/warm/versions-waste-reduction-model-warm#15.

[23] Based on Figure 4-1 from *Downstream Management of Organic Waste in the United States: Strategies for Methane Mitigation*, U.S. Environmental Protection Agency, January 2022, https://www.epa.gov/system/files/documents/2022-01/organic_waste_management_january2022.pdf

[24] *Global Methane Assessment: Benefits and Costs of Mitigating Methane Emissions,* Climate and Clean Air Coalition and United Nations Environment Programme, 2021, https://www.ccacoalition.org/en/resources/global-methane-assessment-full-report.

[25] Richard Ferris et al., *A Primer on Cutting Methane: The Best Strategy for Slowing Warming in the Decade to 2030,* Institute for Governance & Sustainable Development, February 5, 2023, https://www.igsd.org/wp-content/uploads/2022/09/IGSD-Methane-Primer_2022.pdf.

[26] *Synthesis Report of the IPCC Sixth Assessment Report (AR6)*, Intergovernmental Panel on Climate Change, 2023,, https://www.ipcc.ch/report/ar6/syr/downloads/report/IPCC_AR6_SYR_LongerReport.pdf; Richard Ferris et al., *A Primer on Cutting Methane: The Best Strategy for Slowing Warming in the Decade to 2030*, Institute for Governance & Sustainable Development, February 5, 2023, https://www.igsd.org/wp-content/uploads/2022/09/IGSD-Methane-Primer_2022.pdf.

[27] Alicia Zhao et al., *An "All-In" Pathway To 2030: U.S. Methane Emissions Reduction Potential,* America Is All In and Center for Global Sustainability, University of Maryland, August 2022, https://cgs.umd.edu/sites/default/files/2022-08/All-In%20to%202030_Methane.pdf.

[28] "Landfill Methane Outreach Program (LMOP): Benefits of Landfill Gas Energy Projects," U.S. Environmental Protection Agency, April 21, 2023, https://www.epa.gov/lmop/benefits-landfill-gas-energy-projects.

[29] *Downstream Management of Organic Waste in the United States: Strategies for Methane Mitigation,* U.S. Environmental Protection Agency, January 2022, https://www.epa.gov/system/files/documents/2022-01/organic_waste_management_january2022.pdf.

[30] John Ribeiro-Broomhead and Neil Tangri, *Zero Waste and Economic Recovery: The Job Creation Potential of Zero Waste Solutions*, Global Alliance for Incinerator Alternatives, 2021, https://zerowasteworld.org/zerowastejobs/.

[31] "Reducing the Impact of Wasted Food by Feeding the Soil and Composting," U.S. Environmental Protection Agency, May 2023 https://www.epa.gov/sustainable-management-food/reducing-impact-wasted-food-feeding-soil-and-composting.

[32] Alex Badgett and Anelia Milbrandt, "Food waste disposal and utilization in the United States: A spatial cost benefit analysis," *Journal of Cleaner Production*, Volume 314 (September 2021) https://doi.org/10.1016/j.jclepro.2021.128057.

[33] *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2021 (Annex 3-14).* U.S. Environmental Protection Agency, 2023. https://www.epa.gov/ghgemissions/draft-inventory-us-greenhouse-gas-emissions-and-sinks-1990-2021.

[34] Arlene Karidis, "Why Some Landfills are Becoming Privatized, While Others Remain Public," *Waste360*, September 2018 https://www.waste360.com/landfill-operations/why-some-landfills-are-becoming-privatized-while-others-remain-public

[35] *LMOP Landfill and Project Database,* U.S. Environmental Protection Agency, May 2023, https://www.epa.gov/lmop/lmop-landfill-and-project-database.

[36] *LMOP Landfill and Project Database,* U.S. Environmental Protection Agency, May 2023, https://www.epa.gov/lmop/lmop-landfill-and-project-database.

[37] Linda Tsang, *EPA's Methane Regulations: Legal Overview,* Congressional Research Service, January 2018, https://sgp.fas.org/crs/misc/R44615.pdf.

[38] *Final Updates to Performance Standards for New, Modified, and Reconstructed Landfills, and Updates to Emission Guidelines For Existing Landfills: Fact Sheet,* U.S. Environmental Protection Agency, 2016, https://www.epa.gov/sites/default/files/2016-09/documents/landfills-final-nsps-eg-factsheet.pdf.

[39] *Final Updates to Performance Standards for New, Modified, and Reconstructed Landfills, and Updates to Emission Guidelines For Existing Landfills: Fact Sheet,* U.S. Environmental Protection Agency, 2016, https://www.epa.gov/sites/default/files/2016-09/documents/landfills-final-nsps-eg-factsheet.pdf.