Key Strategies for Mitigating Methane Emissions from Municipal Solid Waste

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About RMI

RMI is an independent nonprofit founded in 1982 that transforms global energy systems through market-driven solutions to align with a 1.5°C future and secure a clean, prosperous, zero-carbon future for all. We work in the world's most critical geographies and engage businesses, policymakers, communities, and NGOs to identify and scale energy system interventions that will cut greenhouse gas emissions at least 50 percent by 2030. RMI has offices in Basalt and Boulder, Colorado; New York City; Oakland, California; Washington, D.C.; and Beijing.

About Carbon Mapper

Carbon Mapper is a non-profit organization focused on facilitating timely action to mitigate greenhouse gas emissions. Its mission is to fill gaps in the emerging global ecosystem of methane and CO_2 monitoring systems by delivering data at facility scale that is precise, timely, and accessible to empower science-based decision making and action. The organization is leading the development of the Carbon Mapper constellation of satellites supported by a public-private partnership composed of Planet, NASA's Jet Propulsion Lab, the California Air Resources Board, the University of Arizona, Arizona State University, and RMI, with funding from High Tide Foundation, Bloomberg Philanthropies, The Grantham Foundation, and other philanthropic donors. Learn more at **carbonmapper.org** and follow us on Twitter **@carbonmapper**.

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The Integrated Global Greenhouse Gas Information System (IG3IS) is an initiative of the UN World Meteorological Organization working to document and promote the use of best-practice, scientific methods to enhance the capacity of nations, states, cities, and industries to target significant greenhouse gas (GHG) emission reduction opportunities and track progress towards their reduction goals. IG3IS methods combine and analyze data from atmospheric measurements and socioeconomic activity for more accurate and consistent GHG emissions estimates at scales needed to inform and manage climate action. Since gaining approval of its Science Implementation Plan in June 2019, IG3IS has supported new projects to better inform and enable emission reduction of nations, cities, and industries, and has won endorsement for the use of its framework and methods by international organizations such as the UNFCC, the IPCC, and the Committee on Earth Observing Satellites. Learn more at **ig3is.wmo.int**.

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Glossary

- **Anaerobic digestion:** A process in which microorganisms decompose organic material in the absence of oxygen. The process produces biogas, more commonly referred to as landfill gas when it occurs naturally in landfills.
- **Area source:** The total integrated methane emissions from all sources at a landfill.
- **Bottom-up:** A term describing emissions estimates derived from models.
- **Compressive force technologies:** Technologies that utilize compressive force to extract organics (mainly food waste, as a slurry or a cake) from source-separated organics or mixed waste.
- **Decisive decade:** The decade from 2020 to 2030, during which significant action needs to be taken to mitigate the most severe consequences of climate change.
- **Greenhouse gas (GHG):** A gas that absorbs infrared radiation and traps heat in the atmosphere, gradually increasing the temperature of the Earth's surface. Common GHGs include carbon dioxide, methane, nitrous oxide, and fluorinated gases.
- **Full area coverage:** A measurement technology with spatial sensitivity encompassing the full area of a landfill.
- **Landfill cover:** A surface covering used to minimize odors, decrease fire hazards, deter scavenging and disease-carrying vectors (e.g., flies, mosquitoes, rodents), confine waste, and protect public health. The different types of landfill covers include daily covers, intermediate covers, alternative covers, and final covers.
    - **Daily cover** is a type of landfill cover made of earthen materials that is used overnight during active stages of landfill usage.
    - **Intermediate cover** or **interim cover** is a type of landfill cover that is used temporarily when an area of the landfill that has received waste will be inactive for 180 days and cannot accept any solid waste during that period.
    - **Alternative cover** includes **alternative daily cover (ADC)** and **alternative intermediate cover (AIC),** and these terms refer to the use of non-earthen (non-soil) materials as landfill cover. The type of material allowed as an ADC or AIC depends on the jurisdiction, but can include compost, shredded tires, construction and demolition waste, and ash.
    - **Final cover** is a type of landfill cover that is more permanent and is implemented when the landfill (or a part of the landfill) has reached its capacity and can no longer accept waste.

- **Landfill gas (LFG):** A by-product of the decomposition of organic materials in landfills. Typically, LFG has a composition of approximately 50% methane, 50% CO_2, and a small amount of non-methane organic compounds.

- **LandGEM:** A GHG emissions estimation tool developed by the US Environmental Protection Agency (EPA) to approximate landfill emissions, including total landfill gas, methane, CO_2, non-methane organic compounds, and individual air pollutants from municipal solid waste landfills.

- **Leachate:** The liquid that percolates through waste in landfills or dump sites and is generated as a result of decomposition of organic waste or from external sources such as rainwater.

- **Local coverage:** Measurement technology whose spatial sensitivity is restricted to emissions sources at certain discrete points or subregions at a landfill.

- **Managed land disposal sites:** Facilities that are designed, operated, and monitored to ensure regulatory compliance and protect public health and safety.

  - **Sanitary landfills:** Managed land disposal sites with regulatory oversight and environmental control systems such as liners to collect leachate for treatment, and landfill covers to control odors and rodents; many also have systems for gas collection and use or destruction through flaring.

  - **Processed waste landfills:** A subset of sanitary landfills that accept only residuals from processed waste — waste that has been treated or had recyclables and organic materials removed — as mandated by policy.

- **Materials recovery facility (MRF):** A facility that is designed to accept single-stream recyclables or mixed waste and sort out certain materials such as recyclable materials or organics. This process can be performed by hand or with machinery, and the methods depend on the composition of the single-stream recyclables or mixed waste and the materials to be recovered. The facility may additionally compact, repackage, or otherwise process this sorted waste for transport.

- **Mechanical biological treatment (MBT) plant:** A waste processing facility that combines mechanical sorting to recover recyclables and food waste with biological treatment processes such as composting and anaerobic digestion. The main difference between MRFs and MBT plants is that the former typically do not recover food waste.

- **Methane emissions:** Methane released into the atmosphere.

- **Methane generation:** The total methane produced from the anaerobic decomposition of organic waste in landfills. This includes methane captured by LFG collection systems, methane emissions that are released into the atmosphere, and any residual emissions that are neither captured nor released into the atmosphere.

- **Municipal solid waste (MSW):** Nonhazardous trash, garbage, refuse, or solid waste discarded by households as well as commercial, institutional, and industrial establishments.

- **Point source:** Discrete emissions hot spot at a landfill (e.g., a leak in a gas capture system).

- **Putrescible waste:** Solid waste that contains organic matter that can rapidly decompose.

- **Short-lived climate pollutant:** A pollutant that persists for a short time (compared with CO_2, which can persist for hundreds of years), but which typically has a disproportionately high impact on global warming, despite its short life. Examples of short-lived climate pollutants include methane, black carbon, tropospheric ozone, and hydrofluorocarbons.

- **Top-down:** A term describing emissions estimates derived by measuring atmospheric concentrations of methane.

- **Unmanaged land disposal sites:** Unmanaged sites can be either open dump sites or controlled dump sites. These sites are breeding grounds for pathogens that pose public health and safety risks.

  - **Open dump sites:** Land disposal sites where solid waste is uncompacted, uncovered, and unmanaged.

  - **Controlled dump sites:** Land disposal sites where the disposed-of solid waste is compacted and has daily covers but typically does not have other environmental control systems such as liners, leachate collection and treatment, or gas collection and flare systems. These sites are sometimes referred to as basic landfills.

- **Wastewater treatment plant (WWTP):** A facility that removes pollutants from and stabilizes sewage, runoff, and other forms of wastewater, so that it can return to a natural water system such as an aquifer. The WWTP removes from the water any contaminated effluent that cannot be stabilized or treated and disposes of it.

Executive Summary

Methane has been responsible for roughly 30% of global warming since preindustrial times, and it has 84–86 times the global warming impact of carbon dioxide on a 20-year time horizon.[1] Meanwhile, global observations indicate that the atmospheric growth rate of methane is accelerating.[2] Dramatic reductions in methane emissions during the decisive decade of the 2020s will be critical to achieving urgent climate goals. Achieving the Global Methane Pledge — a commitment to reduce global methane emissions by at least 30% from 2020 levels by 2030 — would eliminate over 0.2°C of warming by mid-century.[3]

Today, the waste sector accounts for 18% of global anthropogenic (human-caused) methane emissions. It is one of the single largest sources of methane emissions to the atmosphere, just behind the oil and gas industry and enteric fermentation (livestock digestion process), which contribute 24% and 27%, respectively. Municipal solid waste (MSW) alone is responsible for 11% of these emissions.[4] The world generates 2 billion metric tons of MSW per year, a number that is expected to increase by 70% by 2050 as a result of a growing population.[5] This increase in waste generation has the potential to drive a proportionate increase in landfill gas (LFG), which is primarily methane and carbon dioxide (CO_2) — the two greatest contributors to global warming.

Efforts to limit global warming to 1.5°C must include the waste sector. A recent study shows that it is technically feasible to reduce methane emissions from solid waste by 80% based on a projected 2030 baseline.[6] Ambitious targets to cut methane emissions such as the Global Methane Pledge will depend not only on reducing methane emissions from the oil and gas sector and livestock — the two largest methane sources — but also on promoting the cost-effectiveness and broad implementation of methane abatement strategies in the waste sector.

This report highlights the most effective strategies to mitigate methane emissions from MSW, as it is a significant source of methane emissions and has substantial emissions reduction potential both in the near term and over a longer time frame.

These strategies are described below, along with key enabling factors to help them succeed and maximize methane abatement, such as capital investments, policy and financial incentives, community engagement, educational awareness, technical support for policymakers, and available end markets, among other considerations.

Exhibit ES1 Key MSW Methane Mitigation Strategies

PRE-LAND DISPOSAL SITES

1 Food Waste Prevention

Prevent food loss and waste along the entire supply chain.

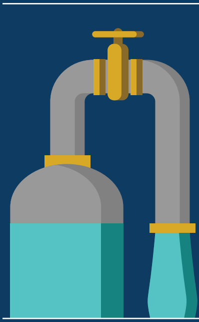
2 Organic Waste Diversion

Divert and process organic waste via source separation and organics recovery technologies to manage and convert diverted organics into beneficial products or commodities.

LAND DISPOSAL SITES

3 Dump Site Rehabilitation*

Upgrade dump sites to well-managed sanitary landfills with gas capture systems, improving public health and safety.

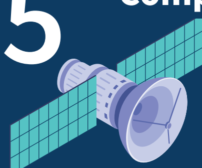


4 Landfill Design and Operation

Optimize the design and operation of landfills to enhance gas capture systems and minimize the release of methane to the atmosphere. This is the most effective strategy to mitigate methane emissions from previously landfilled and/or nondiverted waste.

ALL SITES

5 Comprehensive Emissions Monitoring and Quantification



Monitor and quantify emissions across landfills and organics processing facilities to pinpoint emissions sources, enable timely mitigation solutions, and validate implemented abatement strategies.

*This strategy is applicable mostly in developing countries.

This report also describes improvements in landfill design and operations as essential tools in mitigating methane emissions. It details how landfill operators can use comprehensive monitoring to inform actionable emissions reduction strategies and improve greenhouse gas (GHG) inventories.

Recommended management practices for designing and operating landfills, detailed in Section 4, include strategies aimed at the early stages of design as well as ongoing operations and maintenance. These measures help guide the development of a comprehensive methane abatement strategy at individual landfills; the optimal suite of technology solutions will vary by landfill.

Comprehensive emissions monitoring and quantification, as discussed in Section 5, is essential to identifying, attributing, and addressing leaks at landfills and dump sites, ensuring that organics processing facilities are effectively minimizing methane emissions, and, ultimately, validating implemented abatement strategies. This is important, as initial studies from airborne remote sensing surveys revealed that, for example, just 32 of California's 436 landfills and composting facilities account for approximately 16% of the state's total methane inventory.[7] The surveys also suggest discrepancies between modeled and measured emissions estimates across the United States, underscoring the need to validate current bottom-up inventory estimates.

Efforts to understand, monitor, and manage methane emissions from the waste sector present a near-term opportunity to mitigate, and change the trajectory of, global warming. This study recommends strategies to realize significant reductions in MSW methane emissions and highlights areas for prioritized action by various stakeholders such as operators, regulators, policymakers, and civil society during the decisive decade. This report represents an initial step in creating a roadmap for MSW methane abatement and deploying an effective methane monitoring and analytic framework to enable actionable emissions reductions for landfill owners and operators.

1. Reducing Waste-Sector Methane Is Critical to Mitigating Climate Change

Methane emissions have a high global warming potential compared with CO_2 and must be sharply reduced in this decisive decade to limit global warming to 1.5°C. The role of methane in driving global warming, the waste sector's contribution to methane emissions, and the continued growth in waste generation are why mitigating methane in the waste sector is critical.

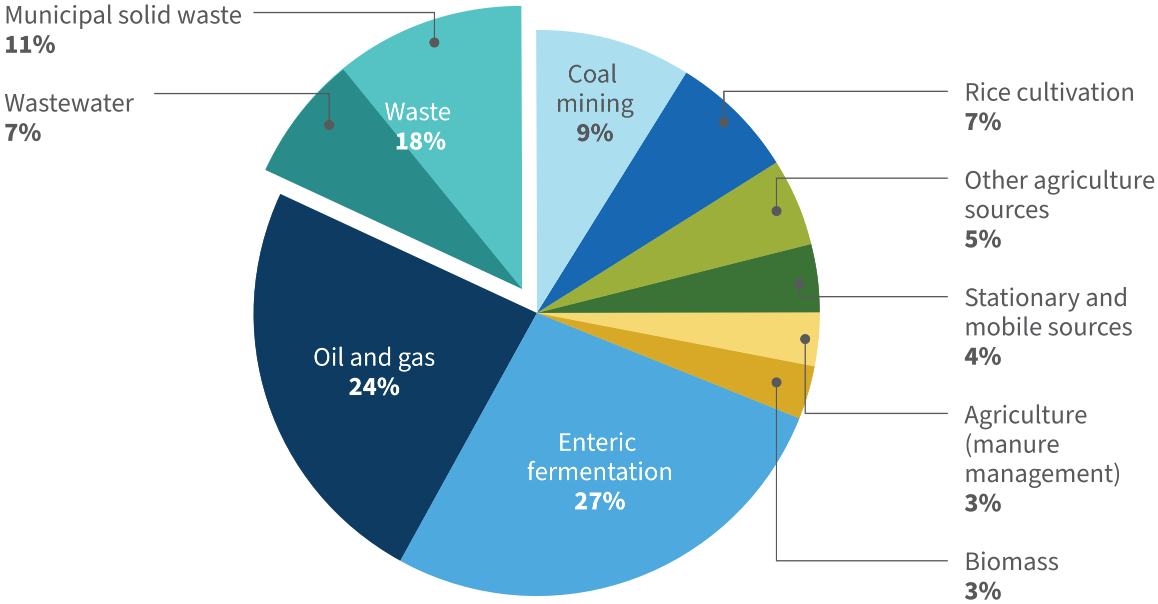
Methane is a short-lived but incredibly potent GHG. After CO_2, methane is the largest contributor to GHG emissions, having accounted for roughly 30% of global warming since preindustrial times.[8] It has a disproportionately high impact on global warming, causing 84–86 times the warming impact of CO_2 on a 20-year time horizon.[9] Current estimates of the relative warming impact of various GHGs are commonly based on a 100-year time horizon, but this significantly underestimates the contribution of short-lived climate pollutants such as methane to overall GHG emissions and undermines the urgency of reducing these short-lived pollutants. Additionally, global observations indicate that the atmospheric concentration of methane is accelerating rapidly.[10]

The waste sector is among the top methane contributors globally and must be addressed now. Methane is produced when organic materials decompose under anaerobic conditions typical in landfills. The waste sector — solid waste and wastewater — is responsible for 18% of global anthropogenic methane emissions, with municipal solid waste (MSW) contributing 11% to the total emissions, as shown in Exhibit 1.[11] In 2020, global human-caused methane emissions from MSW alone had the same warming impact as approximately 4.4 billion metric tons of CO_2,[i] which is equivalent to the annual emissions from about 950 million gasoline passenger vehicles.[12] Limiting methane emissions from waste over the decisive decade is critical to limiting global warming to 1.5°C. Achieving the Global Methane Pledge alone — which aims to reduce global methane emissions by at least 30% of 2020 levels by 2030 — would eliminate over 0.2°C of warming by 2050.[13]

Population growth is fueling higher MSW generation and methane emissions. Methane emissions from MSW are accelerating due to global population growth and economic development, which results in increased consumption and waste generation. Globally, the total MSW generated annually is estimated at 2 billion metric tons and is expected to increase by 70% by 2050.[14] Per capita waste generation in low- and middle-income countries is projected to increase by an estimated 40% or more by 2050, while high-income countries are expected to increase per capita waste generated by 20%.[15] As more waste is generated, more organic waste (e.g., food waste, yard waste, paper, cardboard) is sent to landfills and dump sites, where it decomposes and generates LFG, which is primarily methane and CO_2. Methane emissions are expected to increase during the decisive decade — with the largest contribution from the waste sector, driven by population and income growth in regions with poor waste management systems.[16]

i This estimate assumes a 20-year methane global warming potential of 86.

Exhibit 1 Global Anthropogenic Methane Emissions by Source, 2020



Source: Global Methane Initiative, "Global Methane Emissions and Mitigation Opportunities," **https://www.globalmethane.org/documents/gmi-mitigation-factsheet.pdf**

The composition of MSW is a main driver of its methane generation potential. MSW composition is often determined by cultural context and waste management practices. However, across countries and regions, organic material remains a significant fraction of disposed-of waste. Organic waste accounts for 64%–68% of the MSW generated in low-income, middle-income, and high-income countries; food and green waste contribute the largest share.[17,ii] As organic waste decomposes in anaerobic conditions, it generates methane, which can be captured or released as emissions. The volume and type of organic waste, moisture content, gas capture effectiveness, landfill cover type, regulatory oversight, and monitoring and quantification practices, among other factors, ultimately affect how much methane is emitted from land disposal sites. Robust waste management programs that promote waste prevention and diversion can reduce the amount of disposed decomposable waste. At the same time, effective gas capture and faster leak detection and repair can minimize methane emissions from decomposed waste. If solid waste and methane management practices do not improve dramatically to limit decomposable organic material at land disposal sites and effectively capture LFG from nondiverted organic waste, the combination of the status quo and a growing population will continue to drive massive MSW methane emissions, despite modest waste management efficiency gains.[18]

There is significant untapped potential for limiting global MSW methane emissions by the end of the decade. Recent efforts to reduce methane emissions have focused on the oil and gas sector, enabling abatement efforts and cost-effective mitigation options. Now, societies must seize similar opportunities in the waste sector. A 2021 study showed that implementing all technically feasible methane abatement strategies could reduce methane emissions from landfills and dump sites by 80% (from business-as-usual emissions) by 2030.[19] Giving similar attention to the waste sector could enable cost-effective implementation of these technology options and maximize methane abatement from solid waste. MSW methane represents a significant untapped opportunity to limit anthropogenic methane emissions by 2030, and now is the time to act.

ii Total organic material includes food and green waste, paper and cardboard, rubber and leather, and wood.

2. Aligning around Key Waste Management Concepts

Around the globe, countries are at different stages of waste management. In many developing countries, it is common to see dump sites in the open with few or no systems to protect public health and safety. In more developed countries, disposed-of waste is typically concealed using mechanisms to protect public health. Further, what is considered MSW may vary across countries and regulatory frameworks. Below we define MSW for the purposes of this report and describe various MSW disposal sites.

Solid Waste Taxonomy and Classification of Land Disposal Sites

The term *MSW* commonly refers to nonhazardous trash, garbage, refuse, or solid waste and includes various items discarded by households as well as commercial, institutional, and industrial establishments. The term *solid waste* can be misleading as it includes materials that are not physically solid. MSW includes all putrescible and non-putrescible solid, semisolid, and liquid wastes. These include packaging; food; grass clippings; furniture; ashes; industrial wastes; construction and demolition wastes; vehicles and parts; home and industrial appliances; dewatered, treated, or chemically fixed sewage sludge; manure; animal solid and semisolid wastes; and other solid, semisolid, or liquid wastes. This waste is sent to land disposal sites (LDS), which can be either managed or unmanaged.

Unmanaged land disposal sites: These sites can be either open dump sites or controlled dump sites. These sites are breeding grounds for pathogens that pose public health and safety risks. Because these dump sites are unmanaged and typically have limited or no regulatory oversight, it is common to find hazardous waste in them, along with other waste materials not typically found in managed disposal facilities.

- **Open dump sites:** LDS where solid waste is uncompacted, uncovered, and unmanaged. These unmanaged land disposal sites are often found in developing countries. In some cases, the disposed-of waste is burned in open fires, releasing pollutants into the atmosphere such as carbon monoxide, dioxins, volatile organic compounds, and black carbon, which are detrimental to human health when inhaled.

- **Controlled dump sites:** LDS where the disposed-of waste is compacted and has daily covers but typically does not have other environmental control systems such as liners, leachate collection and treatment, or gas collection and flare systems. Controlled dump sites are considered a slight improvement over open dump sites and are sometimes referred to as basic landfills.

Managed land disposal sites: Facilities that are designed, operated, and monitored to ensure regulatory compliance and protect public health and safety. For the purpose of this report, *managed land disposal sites* refers to MSW landfills, which are further subdivided into sanitary landfills and processed waste landfills. MSW landfills do not accept hazardous waste, radioactive waste, or untreated medical waste.

- **Sanitary landfills:** Managed LDS with regulatory oversight and environmental control systems such as liners to collect leachate for treatment, which prevents groundwater contamination, and landfill cover to control odors, rodents, and other animals; many also have systems for gas collection and use or destruction through flaring. Sanitary landfills are most commonly seen in developed countries and are sometimes referred to as engineered landfills.[20]

- **Processed waste landfills:** A subset of sanitary landfills that accept only residuals from processed waste — waste that has been treated or had recyclables and organic materials removed — as mandated by policy.[21] The processing of solid waste minimizes the biological methane generation potential of the residual waste. Processed waste landfills exist in Japan, Singapore, Europe, and possibly other countries.[22]

The scope of this report is managing methane emissions from managed and unmanaged land disposal sites. We examine and recommend strategies for reducing methane generation by diverting organic materials from landfills and dump sites, do a deep dive into mitigation solutions after waste has been disposed of at LDS, and discuss approaches for emissions monitoring and quantification. Although we explore organics processing as an approach to reducing methane emissions from LDS, this report does not examine strategies to mitigate emissions from organics processing facilities, which suggests an opportunity for future study.

Processed Waste Landfill: Semakau Landfill in Singapore

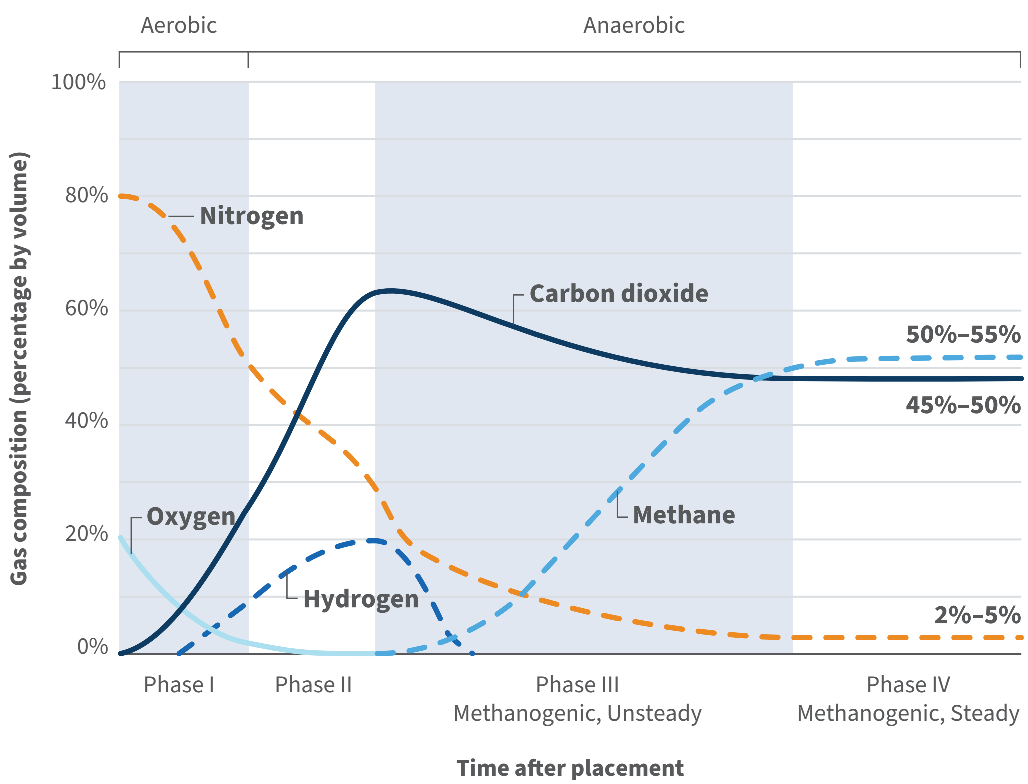
Singapore is an island-city state with an urban collection rate for MSW estimated at over 90%.[23] Paper, plastic, glass, and metal are all collected in the same bin (this is known as single-stream recycling) and sent to a materials recovery facility (MRF) for sorting, after which the materials are sent to recycling facilities for processing. Once the recyclables have been sent onward, the remaining waste is sent to a waste-to-energy (WTE) facility for incineration, reducing the solid waste volume by about 90%. This slows the speed at which the landfill reaches capacity and helps to conserve land. The heat from the incineration is captured to power a steam turbine that generates electricity, and the ash residue and residual waste that cannot be incinerated are disposed of at Semakau landfill — the country's only landfill.[24]

Methane Generation in Land Disposal Sites

Landfills are dynamic systems in which methane generation depends on a variety of factors, such as type and composition of waste, age of waste, waste-in-place, moisture content, and meteorological elements. Once methane is generated, the amount that escapes into the atmosphere depends on additional factors such as the type of landfill cover, effectiveness of gas capture systems, monitoring and quantification practices, and regulatory oversight. Understanding and considering the dynamic nature of landfills is critical when designing a strategy to maximize methane abatement.

LFG is a natural by-product of the microbial decomposition of organic material such as food, paper, yard waste, sewage sludge, and wood in waste streams under anaerobic conditions (i.e., in the absence of oxygen). When MSW is first placed in a landfill, the organics portion of the waste undergoes an aerobic (i.e., in the presence of oxygen) decomposition stage, which generates mostly CO_2 and a small amount of methane. Anaerobic conditions are typically established within less than a year, and methane-producing microbes begin decomposing the organic waste materials and generating methane.[25] Microbial decomposition of the organic waste occurs in four phases, as illustrated in Exhibit 2, but the timing can vary widely.

Exhibit 2 **Production Phases of Landfill Gas**

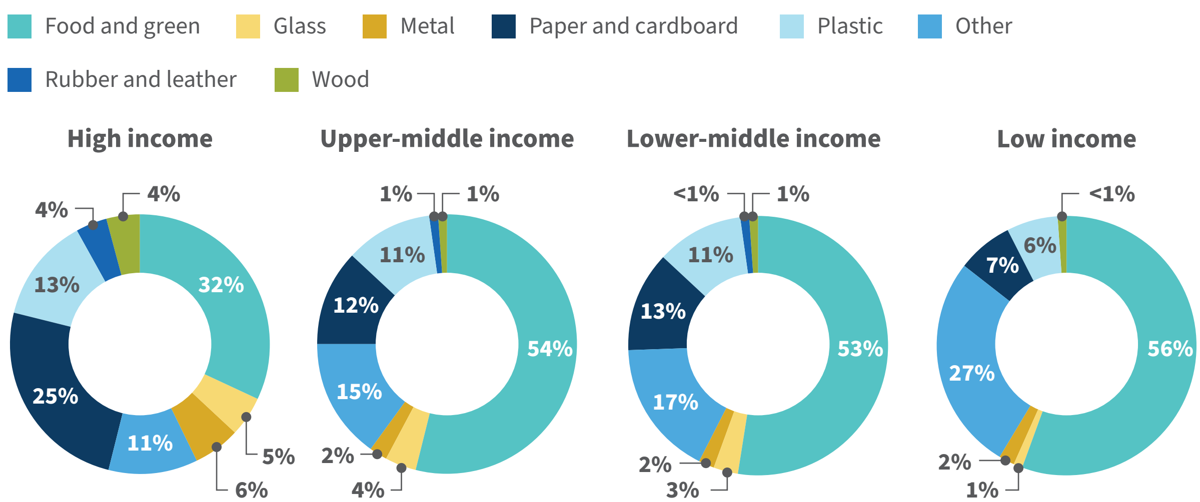


Source: "Basic Information about Landfill Gas," US EPA, n.d., accessed June 1, 2022, **https://www.epa.gov/lmop/basic-information-about-landfill-gas**

After waste placement, the composition of LFG changes with each phase, and landfilled waste may undergo several phases of decomposition at once in different parts of the landfill. The total duration of each phase varies with landfill conditions such as when and where waste is disposed of, type of waste, moisture content, weather, and other factors. Depending on these factors, the phases shown in Exhibit 2 can occur at different times for various parts of the landfill. Upon reaching equilibrium (Phase IV), LFG composition is roughly 50% methane and 50% CO_2, with trace amounts of other gases.[26] After waste is disposed of, LFG is produced at a stable rate for about 20 years in the equilibrium phase, although LFG will continue to be emitted for 50 years or more after the waste is disposed of at the landfill.[27] LFG generation may last longer depending on the conditions at the landfill, such as how long waste disposal occurs.

Similarly, the composition of waste streams is dynamic, and it often depends on factors such as waste management practices, regulations, behavioral patterns, cultural context, and income level. Exhibit 3 illustrates the variation in global MSW composition based on gross national income levels.[iii] It is important to note that food and green waste is the largest component of the waste stream regardless of income level, representing a significant mitigation opportunity to eliminate organics and methane generation from landfills. And although the composition of food and green waste is lower in high-income countries, the total organic waste composition (food and green, paper and cardboard, rubber and leather, and wood) remains relatively the same across all income levels.

Exhibit 3 Global Municipal Solid Waste Composition by Income Level



Note: Pie chart values may not sum to 100% due to rounding.

Source: Silpa Kaza, Lisa C. Yao, Perinaz Bhada-Tata, and Frank Van Woerden, *What a Waste 2.0: A Global Snapshot of Solid Waste Management to 2050*, World Bank, 2018, **https://doi.org/10.1596/978-1-4648-1329-0**

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iii Income level refers to the following gross national incomes per capita in US dollars. Low income: $1,025 or less; lower-middle income: $1,026–$4,035; upper-middle income: $4,036–$12,475; high income: $12,476 or more.

Changes in waste composition can affect how quickly methane generation begins in the unsteady anaerobic methanogenic phase. Several other factors, including those described in Exhibit 4, can affect the methane generation rate. In order to maximize the methane abatement potential at any LDS, it is critical to consider these factors when designing a methane reduction strategy.

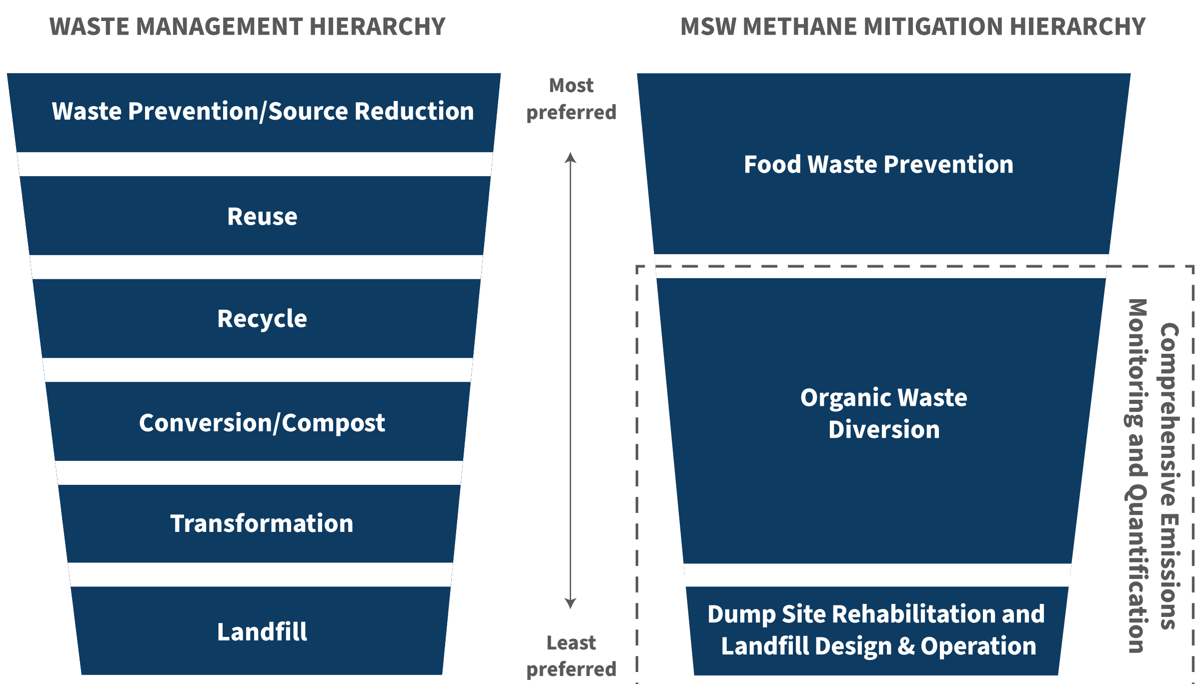
Exhibit 4 Factors Affecting Landfill Gas Generation

Factor	Description
Waste composition	The biological methane potential of the disposed-of waste depends on the composition. An organic material has biological methane generation potential; an inorganic material does not generate methane. Further, the type of organic waste affects the rate at which waste decays and produces methane. For example, food waste, yard waste, and paper decompose more quickly than leather, textile, and wood.
Age of waste	Age influences how much anaerobic decomposition of organic matter has occurred. Typically, more recently discarded waste will produce more landfill gas than older waste.
Waste-in-place	The total tonnage of landfilled organic waste affects the volume of landfill gas that can be generated. Higher tonnage of organic material will generate more LFG.
Meteorological conditions	Rainfall, temperature, barometric pressure, and other atmospheric factors that influence the rate of decomposition can either speed up or slow down LFG generation and/or release of emissions. For example, a wet climate can lead to greater moisture infiltration into landfills, resulting in more rapid decomposition and methane generation.
Type of landfill cover	The cover type (daily, intermediate, or final) affects the level of moisture infiltration and applied vacuum to the LFG collection system.

3. Overview of Municipal Solid Waste Management Strategies to Reduce Methane Emissions

To reduce methane emissions from MSW, stakeholders need to consider not just landfills, but the full waste management system. Today, a typical approach to managing waste relies on using landfills and open dumps with minimal consideration and implementation of other waste management alternatives. A widely accepted and preferred paradigm for managing solid waste is an integrated waste management system, which utilizes a holistic approach and a tiered set of alternatives. In this paradigm (see left side of Exhibit 5), the best option is waste prevention, followed in order of preference by reuse, recycling, conversion/composting, transformation/waste-to-energy, and finally disposal at landfills. Although this approach reduces reliance on landfills, they continue to play an important role for the residual waste that cannot be handled through alternative approaches. Because methane emissions are produced only from the organics portion of waste at land disposal sites, we focus on organic waste in applying this waste management paradigm to address methane emissions (see right side of Exhibit 5).

Exhibit 5 **Comparing Waste and MSW Methane Management Paradigms**



Source: Adapted from "Comparative Greenhouse Gas Emissions Analysis of Alternative Scenarios for Waste Treatment and/or Disposal," County of Los Angeles Department of Public Works, 2016, **https://pw.lacounty.gov/epd/SoCalConversion/PDFS/CT_Comparative_GHG_Analysis_Feb_2016_Complete.pdf**

Decision support tools such as EPA's waste reduction model (WARM) and municipal solid waste decision support tool (MSW DST) help stakeholders evaluate the economic and environmental impacts of solid waste management strategies and facilitate the implementation of integrated waste management approaches.[28]

Programs designed to avoid food waste in particular are an optimal approach, as they prevent much of the organic waste altogether. These "pre-land disposal sites" (pre-LDS) approaches may include crafting policies intended to promote behavioral changes, partnering with local food banks, addressing supply chain challenges in developing countries, and making changes to corporate business models, as discussed below.

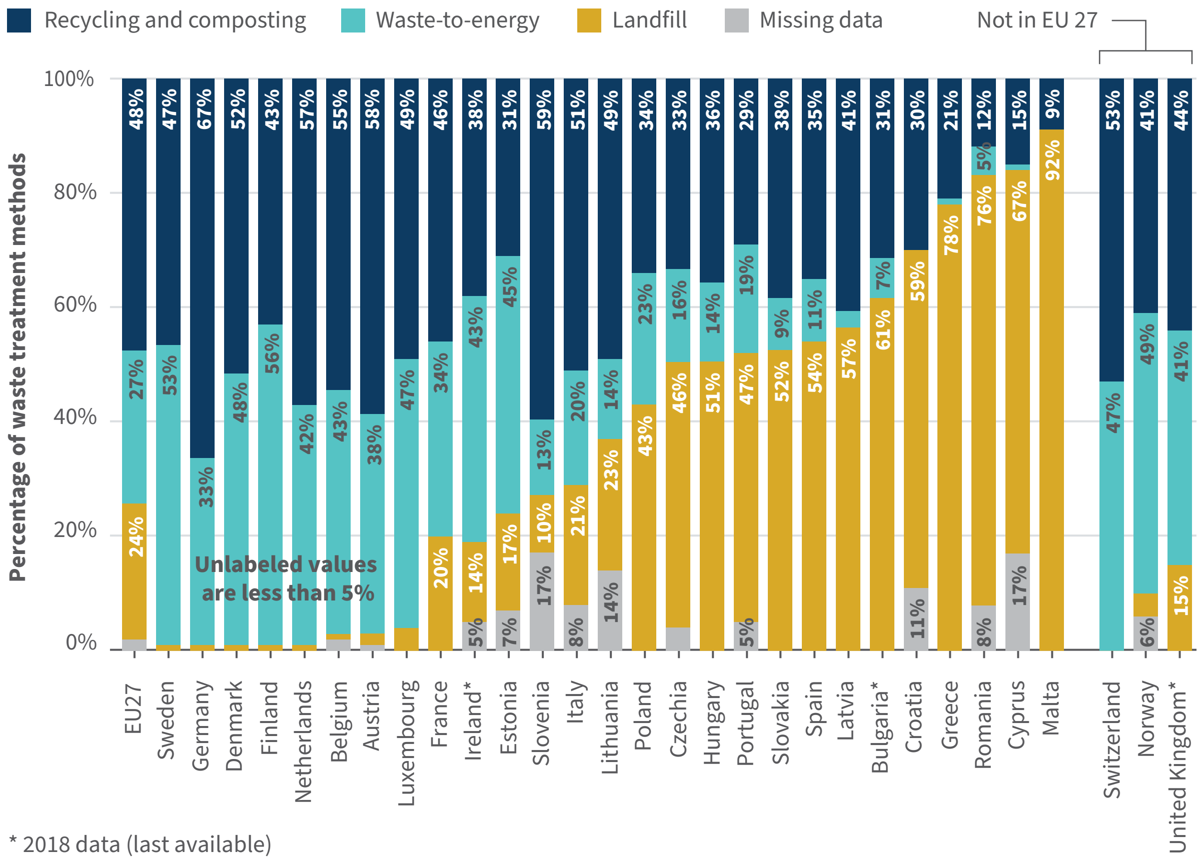
Once organic waste is destined for disposal, keeping it out of land disposal sites altogether is preferable to relying on capturing the methane generated from landfilled organic material. Although a substantial quantity of methane can be captured at the landfill, as discussed below, it is essentially impossible to capture all the methane formed from decomposed organic waste. In contrast, it should be easier to capture a larger proportion of methane generated from organic material processed under controlled conditions outside landfills. Two main approaches to avoiding methane formation by diverting organic material from landfills and dump sites are (1) consumer or household-based source separation programs, and (2) automated sorting and compressive force technologies to separate organic materials from a mixed waste stream.

Finally, for the portion of organic waste that has already been placed in landfills and dump sites or cannot be diverted, i.e., at land disposal sites, methane emissions can be mitigated by upgrading dump sites and implementing design and operational improvements at landfills. These measures can enhance the effectiveness of gas capture systems and minimize the release of methane to the atmosphere.

A major consideration in designing policies for reducing methane emissions from MSW is the variation across countries in factors such as regulatory frameworks, financial considerations, societal behaviors regarding waste, and waste management practices. The degree of recycling and composting varies widely across countries, as does the use of landfills, waste-to-energy facilities, and other alternatives for handling the remaining waste. In Europe, for example, Germany, Slovenia, Austria, the Netherlands, Belgium, Switzerland, Denmark, and Italy recycle and compost more than half of their generated MSW (Exhibit 6), while some others achieve substantially lower levels.[29] The diverse sets of challenges and variations across countries lead to non-uniform mitigation solutions around the globe.

Nevertheless, there are some methane abatement strategies that could be widely employed around the world. For example, a relevant approach for both developed and developing countries is tackling methane emissions pre-LDS through waste prevention and organics diversion to limit the decomposable waste that ends up at land disposal sites. The strategies for abating methane emissions at LDS may differ.

Exhibit 6 MSW Management in Europe in 2019



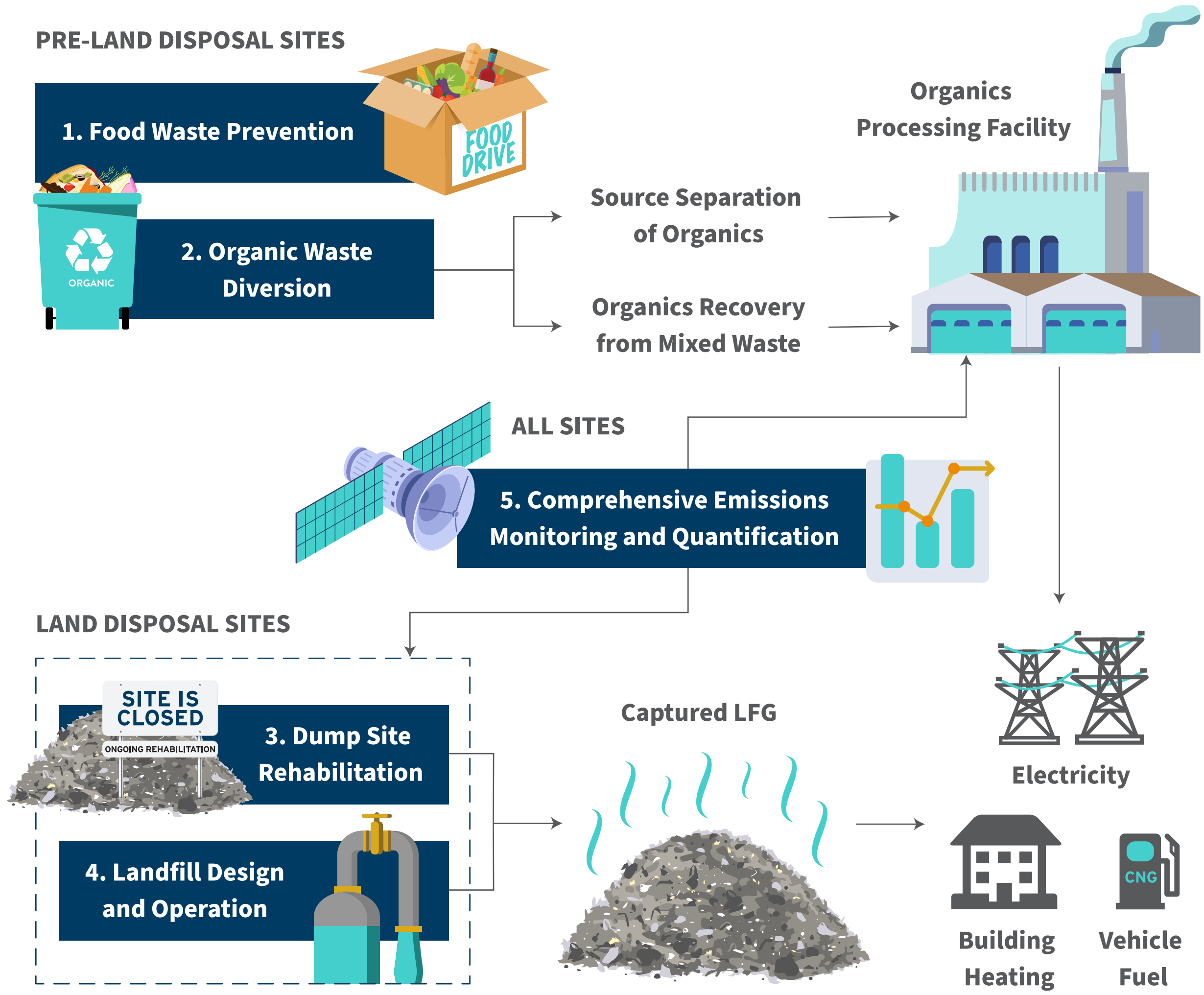
* 2018 data (last available)

Source: "CEWEP: The Confederation of European Waste-to-Energy Plants," n.d, accessed June 1, 2022, **https://www.cewep.eu/municipal-waste-treatment-2019/**

For developing economies, the biggest opportunity to reduce methane emissions from non-diverted organic waste will involve rehabilitating dump sites to sanitary landfills with gas capture systems. In developed countries, mitigating methane emissions will focus more on incorporating innovative design and operational measures at existing sanitary landfills, including adding gas capture systems to landfills that do not yet have them. All these actions can be underpinned by comprehensive emissions monitoring and quantification as a foundation to measure emissions, prioritize actions, and track progress. These abatement strategies are summarized in Exhibit 7.

It is important to underscore that community engagement and support are necessary to ensure the success of many of these strategies. Such engagement is also essential for strategies that rely on individual or community actions, such as household separation programs for yard waste, food waste, or other organic waste. Communities care deeply about odor, noise, truck traffic, and pollution, and waste management solutions can affect all of these issues. Community opposition can delay or derail major new waste management facilities. Many communities with waste-handling facilities are also overburdened with other sources of industrial pollution, as well as economic disadvantages.

Exhibit 7 **Methane Emissions Reduction Strategies**



It is therefore critical to integrate community views and considerations into decisions about waste management. One way to bring communities into the decision-making process is through educational outreach and community involvement programs. These programs can help communities and individuals develop a deeper understanding of the environmental, health, and safety concerns; inform communities about available waste and methane management options; and encourage people's participation in the decision-making process. They can also encourage individuals to participate in household-based programs or make other changes in their own habits. Better awareness and direct involvement can also build community support for new projects or upgrades that tackle methane emissions.

The remainder of this section provides more detail on, and highlights important considerations for, managing methane emissions pre-LDS and at LDS, as well as for monitoring and measuring emissions.

Managing Methane Emissions Pre-Land Disposal Sites

Organics diversion is the process of minimizing putrescible food and other organic waste sent to land disposal sites. Preventing organic waste from entering landfills and dump sites is the optimal solution for mitigating MSW methane emissions. Approaches to organics diversion include food waste prevention, source separation of organics (SSO), and organics recovery from mixed waste. For each of these approaches, we discuss factors to consider for effectively leveraging organics diversion as a methane abatement strategy.

Food Waste Prevention

Food waste is a global problem that affects food security, hampers environmental sustainability, and represents significant economic losses along the supply chain. The Food and Agriculture Organization of the United Nations estimates that 931 million metric tons of food waste was generated in 2019, which is equivalent to approximately 17% of the food produced for human consumption globally.[30] As recyclables such as metals, paper, cardboard, wood, and plastic are, to varying degrees, being recovered for their commodity value, food waste is left as one of the largest components of the waste stream.

Food waste also decomposes far more rapidly than other types of organic waste, producing methane more quickly after it is placed in a landfill. Finally, an estimated 8%–10% of global GHG emissions (both CO_2 and non-CO_2) are associated with food waste, including the release of methane emissions after disposal.[31] Thus, reducing food waste not only ultimately reduces methane emissions at land disposal sites, but can also lead to more efficient food production across the food supply chain, further reducing GHG emissions and economic losses.

Key Factors to Consider

Developed Countries: In developed countries, food waste largely occurs in households, catering, and retail. Drivers of food waste include aversions to selling or buying imperfect foods (cosmetic standards), low consumer prices, adherence to best-before dates, and fear of litigation, which results in setting use-by dates earlier than needed.[32]

Changing the way people purchase and manage food at the household, grocery, retail, and even corporate levels is critical to food waste reduction. Individual behavioral changes such as better food planning, preparation, preservation, and storage can help minimize food waste at the household level. Large food retailers such as grocery stores can also do more to better align their inventories with consumer demand and develop strategies to utilize imperfect or surplus produce. They also have an opportunity to educate consumers on waste reduction strategies as well as product labels and “best by” dates, which are often misinterpreted as expiration dates, and to develop easy-to-understand product labels. Corporations could also evolve their business models to incorporate food waste reduction initiatives as part of their environmental, social, and governance targets and goals.

Developing Countries: A significant amount of food waste in developing countries is due to production, storage, and distribution challenges between farm and plate.[33] Further, a recent U.N. study showed that household per capita food waste in upper-middle-income and lower-middle-income countries is largely similar to that of high-income countries, suggesting significant food waste occurs at the household level in developing countries as well.[34] Efforts focused on improving the cold chain management of perishable foods, improved packaging, and increasing available outlets for bulk sale are critical to reducing food waste in developing countries. Power outage solutions for refrigeration would help reduce food waste at the household level in developing countries. Additionally, efforts to influence and sustain behavioral changes (described above) will reduce household food waste.

Case Study: Voluntary Food Waste Prevention Program in the United Kingdom

Efforts to prevent food waste in the United Kingdom (UK) have been made primarily through voluntary initiatives such as the Courtauld Commitment (CC), led by the Waste and Resources Action Programme (WRAP) and funded by both the UK government and the food sector.[35] As part of its food waste targets, the CC aims to achieve U.N. Sustainable Development Goal (SDG) 12.3 — to reduce per capita food waste across manufacturing, retail, hospitality and food service, and households by half by 2030 from 2007 levels.[36] To facilitate this goal, WRAP also developed the Food Waste Reduction Roadmap (FWRR), which lays out milestones and encourages major food retailers, manufacturers, and food service companies to adopt the *target, measure, and act* approach. This approach involves setting a target, measuring food waste and reduction progress, and implementing actions that reduce food waste at households and businesses.[37]

In addition to these initiatives, WRAP develops targeted educational campaigns such as the Love Food Hate Waste (LFHW) program, aimed at households, and the Guardians of Grub program, aimed at the hospitality and food sectors. The LFHW campaign educates citizens on the appropriate refrigeration temperatures for foods and provides other resources on the program's website, including a portion planner and the A–Z of food storage.[38] The Guardians of Grub also provides resources such as a business case presentation — to make the case for food waste reduction to critical staff; a food tracking calculator — to estimate the cost of food waste and potential savings; and educational posters.[39] By leveraging a team of specialists and using social media and other channels, WRAP designs and measures the effectiveness of behavior change interventions.[40]

Co-op is one of the UK's largest food retailers (it has over 2,500 stores), is a signatory to the CC, and is committed to the FWRR, which adopts the target, measure, and act principles. Co-op set a target to halve food waste by 2030 compared with 2015 levels.[41] Central to Co-op's strategy is the food and drink waste hierarchy, which prioritizes waste reduction, followed by recycling, and then energy recovery, before considering landfill disposal.

The food retailer also follows the UK food surplus and waste measurement and reporting guidelines. This enables setting a comprehensive baseline, reporting data accurately, and understanding food waste drivers. Lastly, having set targets and measured food waste levels, in line with the FWRR framework, the retailer acts by taking steps to reduce food waste. Co-op implemented measures such as improving its forecasting, generating weekly key performance indicator reports for store teams, managing store surplus via food share partnerships, engaging with suppliers to deploy technical interventions that reduce food waste and extend shelf life, and leveraging LFHW campaigns to engage customers on reducing food waste. Co-op also has a working group that meets quarterly to share insights, manage issues, and align on interventions for the organization.

Through Co-op's food share program, over 1,100 of its stores have established food share partnerships with 800 local community groups; they have donated almost 3 million food products and reduced backhaul costs (i.e., costs paid to a carrier to transport freight during its return trip). Since 2015, Co-op has recorded a 30% reduction in food waste.[42] The success of WRAP initiatives can be seen across the UK food sector and in the progress made by signatories such as Co-op. As of 2019, over 50% of the UK's food and drink sector had adopted the FWRR target, measure, and act approach, saving over £100 million worth of food.[43]

Enabling Levers

- National commitment to SDG 12.3 to halve food waste
- Voluntary frameworks and food waste reduction roadmap
- Funding support from UK government
- National food waste measurement and reporting guidelines
- Targeted educational campaigns/resources and working groups
- Adopting food and drink material hierarchy

Organic Waste Diversion

Following food waste reduction efforts, the best option for mitigating MSW methane emissions is to keep organic waste out of landfills and dump sites, either through separating organic waste materials at the point of generation (i.e., the source) or by recovering the organic materials after they have been mixed with other waste types and sent for disposal. This section discusses SSO, technology options for separating organics from mixed waste, and processing of recovered organics for conversion into beneficial products or commodities.

Source Separation of Organics

Source separation can be more burdensome for households because it requires finding space for separate collection receptacles and organics must be put in a separate bin, rather than a single garbage can. Source separation is also generally more expensive for communities because it requires additional separate collection efforts, with the concurrent increases in truck traffic, diesel pollution, traffic congestion, and road wear and tear. Analogous to efforts to improve recycling rates in recent years, government entities, food-service industries, and communities should focus on separating food and other organics at the source. Successful source separation of organics may require financial or other incentive programs, sustained educational awareness programs to encourage positive behavioral changes, and/or mandatory participation ordinances.

Key Factors to Consider

Cost of SSO Programs: Organics diversion is more costly than traditional mixed waste collection and processing. The higher cost is driven by elements such as less-efficient collection (e.g., multiple waste streams and smaller volumes of the waste streams at each location), space constraints, enhanced sanitation protocols, additional labor, and equipment purchase and maintenance. Additional or higher costs on residents and communities can disincentivize organics diversion and be particularly burdensome in lower-income communities. Incentivizing source separation through subsidies or other funding mechanisms could help promote source separation.

Behavioral Patterns: Community concerns about uncleanliness, odor, and rodent/pest infestations can hinder the adoption of SSO programs. SSO also requires households and businesses to become more intentional in how they discard waste. Continued educational campaigns and awareness programs about different waste types and their effective disposal can help address these issues. Beyond the "how," educating those who generate waste on the "why" is important in sustaining positive behavioral changes and building community support for such programs.

Enabling Regulations: Organics diversion requires mechanisms to either incentivize or require the participation of households and businesses. One approach is to mandate source separation, either across the board or only for entities (e.g., schools, hospitals, correctional facilities) and businesses that generate large volumes of organic waste. For example, restaurants that meet a minimum threshold set by regulations (e.g., a certain seating capacity or amount of waste generated) could be required to participate in food waste source separation programs, and restaurants below that threshold could participate voluntarily. Mandatory source separation is increasingly common across Europe; it is enabled by the Waste Framework Directive, which requires all European Union (EU) Member States to collect biodegradable waste separately from mixed waste streams by December 31, 2023.[44]

Case Study: Source Separation of Food and Yard Waste in Portland, Oregon

The City of Portland, Oregon, implemented a highly effective SSO program that has reduced landfilled residential garbage rates by 30%–40% over the past decade (see Exhibit 8). A commercial composting ordinance set to take effect in 2023 will expand the program's impact.

Portland initiated a curbside residential compost collection pilot program in 2010, in which 2,000 residents sent food scraps and yard waste to a central compost processing facility. The pilot program delivered a 33% reduction in landfill-bound garbage and an 87% satisfaction rate among participants.[45] After seeing the success of the pilot program and wanting to increase the incentives for participation, the City implemented mandatory weekly compost and recycling pickups, while reducing garbage pickup to every two weeks. During the first year of this citywide program, Portland saw a 37% reduction in landfilled residential garbage.[46] A long-term study of waste disposal trends in Portland shows that rates of compost, recycling, and garbage disposal have been sustained, with the exception of an increase in all forms of waste (particularly organics) at the onset of the COVID-19 pandemic.[47]

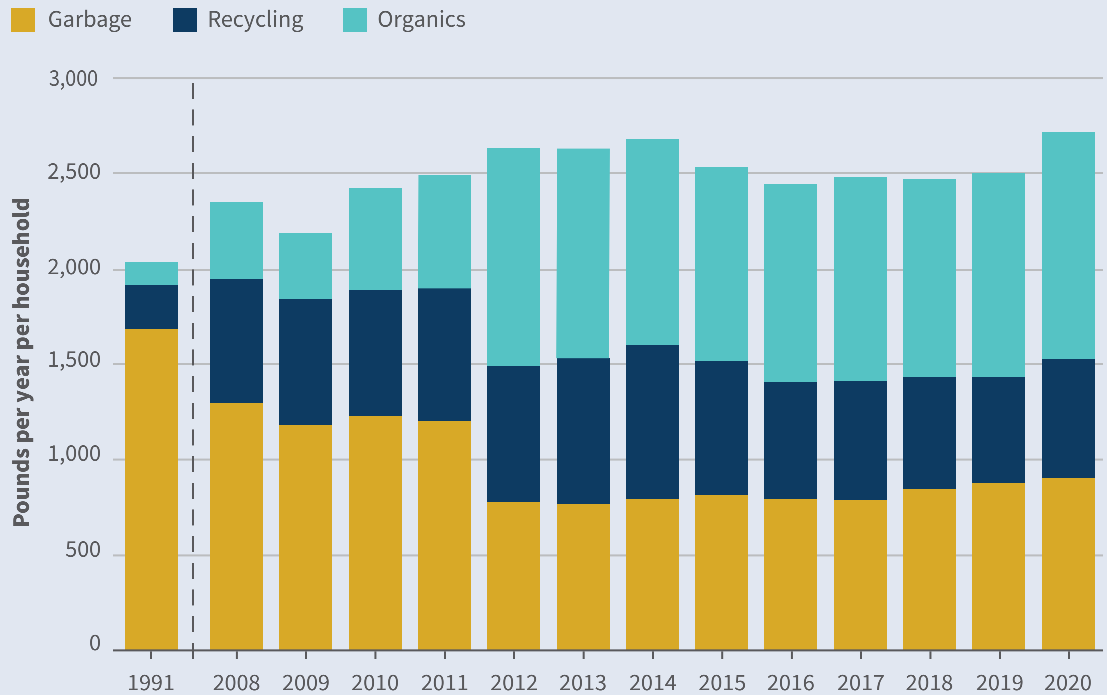
The Portland Metro Council passed an additional requirement for composting at commercial food businesses to take effect in 2023–24. Commercial businesses generate about half of all organic waste in Portland, and the commercial sector has a much lower organics diversion rate, because much of the diversion is voluntary.[48] With the new code requirement, large food businesses in the Portland metro area will be required to separate food scraps from garbage beginning in March 2023, with a tiered code requirement that will affect smaller food businesses in 2023 and 2024. This policy is set to affect grocery stores, restaurants, food and beverage manufacturers, and any businesses with onsite cafeterias, restaurants, or food preparation (e.g., hospitals, schools).[49]

The success of the residential program relied on several factors. The City of Portland and the greater metropolitan area provided multiple resources for residents, including free home composting bins, educational resources, and a garbage and recycling hotline where residents could receive immediate answers about whether particular waste should be composted, recycled, or landfilled. Scheduling food waste collections more frequently than garbage collections also incentivizes source separation, as food waste is more likely to cause unwanted odors when it sits for extended periods. Portland also has several economic penalties in place for noncompliance.[50] Finally, the use of a pilot program for residential compost allowed the government to test out the program before committing to citywide implementation.

Enabling Levers

- Pilot program with participant feedback
- Food waste collection weekly and garbage collection every two weeks
- Free composting bins
- Accessible educational resources for residents
- Enforcement and penalties for noncompliance

Exhibit 8 Annual Garbage, Recycling, and Organics (Food and Yard Waste) Collected per Household in Portland, Oregon



Source: City of Portland, Oregon, Bureau of Planning and Sustainability, "Residential Curbside Collection Service Rate Study," 2021, **https://www.portland.gov/sites/default/files/2021/swr-rate-study-fy-2021-22.pdf**

Organics Recovery from Mixed Waste

A complementary or alternative approach to source separation programs is to recover organic waste — such as paper, cardboard, wood, yard waste, and food waste — from mixed waste before it is placed in a landfill. This can be achieved via automated sorting at MRFs. The facilities utilize unit processes such as magnets, eddy current separators, screens, air density separators, optical sorting, and manual sorting to recover recyclables. The technology does not rely on households' and businesses' ability or commitment to sort materials, so it can more reliably divert a higher percentage of organic materials. Automated sorting technologies that recover recyclables for their commodity value (e.g., paper, plastic, metal) are common in developed countries. Using automated sorting to recover food waste is particularly widespread in Europe, typically seen in mechanical biological treatment (MBT) facilities.

For most MRFs, where automated sorting does not recover food waste, a nascent compressive force technology can be used to supplement automated sorting to extract mainly food waste from SSO and mixed waste streams for conversion into a high-yield biogas feedstock ideal for anaerobic digestion. Vendors claim these technologies can extract up to 95% of the food waste from source-separated food waste collection programs, as they often contain contaminants such as plastic bags and other non–food waste materials.[51] Compressive force technologies have not been widely adopted, although they can be found in Europe, the United States, Singapore, India, and possibly other countries.

With either source separation or technology-based organics recovery, the diverted organic matter is sent to processing facilities, where it can be converted to biogas, compost, biochar, heat, steam, fertilizers, or other valuable resources. Segregating organics from mixed waste using technology as an alternative or supplement to source separation will increase the success rate of organics diversion.

Key Factors to Consider

Up-Front Costs: The capital cost of developing an MRF or purchasing a compressive force technology may discourage adoption. The capital cost of an MRF, as shown in Exhibit 10, ranges from $25,000 to $55,000 per ton per day of processing capacity. Covering this expense can be challenging, especially for smaller landfill owners/operators. In addition, funding for waste management projects is highly limited in many emerging economies, which have competing funding priorities such as poverty eradication, electricity, and education. Where the economic viability of such technologies has yet to be proven, high interest rates may exacerbate the barriers to securing financing.

Technical and Economic Viability, and Commercial Availability: Successful implementation of mixed waste processing relies on the commercial viability and availability of technologies that recover organic waste from MSW streams. Specifically, it will require developing and/or upgrading MRFs to also recover food waste or using a separate compressive force technology. Although these technologies are commercially available, broader adoption of technology could be facilitated by conducting assessments to verify their technical effectiveness — particularly for nascent technologies — and economic viability. Upon verification, regulatory incentives can be a useful mechanism to promote adoption of organics recovery technologies, which could be critical in achieving high organics diversion rates.

Case Study: Organics Recovery at a Municipal Solid Waste Treatment Facility in India

In India, source separation of waste is not common, posing a challenge to isolating organic waste. Compressive force technologies are one option for recovering organics from mixed waste. One type of compressive force technology is an organics extrusion press, which separates mixed waste into organic and inorganic fractions. At a mixed MSW treatment facility in Goa, India, a high-pressure press recovers up to 95% of food waste with <1% contamination.[52]

The mixed MSW stream undergoes pre-processing to remove recyclables, inert waste, and other materials to optimize the feedstock before it is fed to an organics extrusion press. The separated organic fraction is fed into an anaerobic digester, where it is converted to biogas and the digestate is used as compost, while the nondegradable and nonrecyclable inorganic fraction is converted to refuse-derived fuel.[53] Exhibit 9 shows the extracted organic fraction from mixed MSW using an organics extrusion press like the one utilized in Goa.

The 100-metric-ton-per-day treatment facility recycles 5%–8% of its waste, converts 20% of its waste into compost, and generates up to 1 megawatt-hour per 100 metric tons of waste.[54] Only 10%–15% of the total waste received at the treatment facility is ultimately sent to landfills.[55] By deploying an organics extrusion press at a mixed MSW treatment facility, this project demonstrates an alternative organics recovery approach to SSO programs.

Several factors enabled the technology's success in Goa. India's 2016 Solid Waste Management Policy requires mixed waste to be separated into organic and inorganic fractions, enabling the technology to play a vital role in meeting this policy.[56] Before the project was initiated, a delegation of Goa government officials visited Europe to study modern waste treatment facilities, allowing for a broad survey of potential technologies that could be used at the Goa facility.[57] Since completion, the project has been evaluated for compliance with India's Solid Waste Management Policy, and educational and research institutions undertake regular performance and environmental impact assessments to ensure public accountability.[58]

Enabling Levers

- Strong national goals and policies
- Modern waste treatment education for government officials
- Policy compliance evaluation
- Technical review and environmental impact assessments performed by trusted research institutions

Exhibit 9 Extraction of Wet Organic Fraction from Mixed MSW Using Organics Extrusion Press

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Source: Anaergia, "Organics Extrusion Press," 2017, **https://www.biogasworld.com/wp-content/uploads/2018/02/ComBroch_OREX_v4.pdf**

Organics Processing

In addition to segregating organics via source separation or mixed waste processing, successful methane mitigation through organic waste diversion will depend on having available options for processing the diverted organic waste without emitting methane. Possible end destinations for organic waste include anaerobic digestion, composting, gasification, and waste-to-energy (WTE) facilities. Insufficient or overly expensive processing capacity will hinder efforts to divert organics from landfills and dump sites. Building this infrastructure will require significant capital investments. Further studies evaluating the additional processing capacity and scale-up costs required would facilitate investment and other incentive programs needed to develop these facilities. Below, we describe a range of organics processing technologies as well as key factors that should be considered to enable the success of this mitigation strategy.

Conversion Technologies: These technologies include non-combustion processes such as anaerobic digestion, composting, gasification, and other types of processes that convert solid waste into beneficial products.

- **Anaerobic Digestion:** A biological process that involves the breakdown of biodegradable organic materials by microorganisms in the absence of oxygen, which occurs naturally in landfills. The biogas that would otherwise be generated in landfills can be produced in a controlled environment using anaerobic digesters (i.e., enclosed tanks where the breakdown of organic matter occurs). The feedstock, such as food waste, animal manure, fats, oils, grease, and sewage sludge, is converted into biogas, which can be recovered to generate electricity and heat or upgraded to natural gas by removing CO_2 and other trace gases.[59] Biogas is composed of approximately 50%–70% methane and 30%–40% CO_2, with the remainder made of other trace gases.[60]

- **Composting:** Composting involves the decomposition of organic waste by microorganisms in the presence of oxygen; the compost is subsequently used as a soil amendment or fertilizer.[61]

- **Gasification:** A non-combustion process that converts feedstock such as organic material or fossil-based material under high heat and limited oxygen into synthesis gas (also known as syngas), which is primarily carbon monoxide and hydrogen.[62] Viable organic feedstock includes crop residue, animal waste, and organic municipal solid waste.[63] Syngas is a valuable intermediate product that can be used to manufacture ammonia, methanol, or fertilizer, or be used as a fuel for steam or electricity generation.[64] Gasification of waste is not a widespread approach except in Japan, where only 10% of household waste is sent to landfills — and only after undergoing incineration or gasification.[65]

WTE: Solid waste is incinerated, and heat recovered from the combustion process is used to generate electricity or steam or is used directly for heating.[66] Incineration reduces the volume and weight of the material, thereby reducing the residual waste sent to landfills. The processed waste — ash residue or unconverted waste — can be disposed of in landfills or utilized (e.g., ash residue can be used in road construction).[67] This technology largely eliminates any potential for methane generation from the landfilled residual waste by removing decomposable organic material. WTE is a controversial technology in many areas, however, in large part due to concerns about emissions of toxic air pollutants and associated impacts on public health, especially in nearby communities.

Key Factors to Consider

High Up-Front Costs: Many projects that use these technologies are capital intensive, which can pose a significant barrier to development. The capital cost of a composting facility, depending on the type, ranges between $45,000 and $140,000 per metric ton per day of processing capacity. An anaerobic digestion facility ranges between $120,000 and $190,000 per metric ton per day of processing capacity. The cost of these facilities and other facility types is highlighted in Exhibit 10.

Governments can help offset the cost of organics diversion and processing projects through a variety of financial mechanisms, including direct loans or loan supports, tax incentives, and grants. They can also add fees to tipping fees (which are paid to the landfill owner or operator to dispose of waste at a landfill) to incentivize alternatives and raise funds for these programs. These fees should be designed such that they create a financial incentive to improve diversion practices. It is important, however, to ensure that any additional fees do not create an undue economic burden on disadvantaged communities. Further, mechanisms should be in place to ensure that these funds are used as intended and not employed for other purposes.

Exhibit 10 Installed Capital Cost Estimates for Waste Management Facilities

Facility Description	Feedstock or Facility Type	Installed Capital Cost ($ per Metric Ton per Day of Capacity)
Materials Recovery Facility	Source-Separated Recyclables or Mixed Waste	$25,000–$55,000
Anaerobic Digestion (AD) Facility	Digestible Organics	$120,000–$190,000
Composting Facility	Covered Aerated Static Pile	$45,000–$60,000
Composting Facility	Batch/Continuous In-Vessel	$85,000–$140,000
WTE/Incineration Facility	Mixed Waste	$325,000–$375,000
Gasification Facility	Processed Mixed Waste	$350,000–$400,000
Fully Integrated MRF with Conversion Technologies	MRF, AD, Composting, Thermal, Ash Recovery	$450,000–$475,000

Note: The above US national average cost estimates, in 2021 US$, are based on a facility with a processing capacity of 1,000 metric tons per day.

Source: Expert compilation based on confidential data collected by E. Tseng and Associates

Leveraging Existing Infrastructure: Before developing new infrastructure, project developers should consider existing infrastructure that could be leveraged to maximize processing capacity and improve project economics. For example, existing anaerobic digesters at WWTPs can be retrofitted to accept diverted organic waste. A 2019 study assessing California's capacity to process landfill-bound food waste found that at least 3.1 million wet metric tons of projected food waste in 2030 could be co-digested at existing municipal WWTPs if the capacity of key processes were expanded to match excess capacity at the anaerobic digesters.[68] This study showed that maximizing co-digestion in the state could generate up to $393 million in annual revenue, result in a net positive investment, and help meet 60% of the state's goal to reduce landfill emissions by 4 million metric tons of carbon dioxide equivalent in 2030.[69] Although the project economics at individual facilities will vary depending on numerous factors, it is important to consider existing capacity when assessing the economic viability of new projects.

Available End Markets: For organics processing to scale, projects must consider end-user demand and capacity for generated products and commodities such as biogas-based natural gas, compost, fertilizers, steam, and electricity. The absence of robust end-use markets can threaten the financial viability of organics processing infrastructure. Activating and sustaining markets for reduced emissions products or commodities is central to the success of mitigating methane via organics diversion. Use of certification programs to verify reduced emissions can also drive demand from end-users and corporations that have net-zero carbon commitments or that are aiming to reduce their Scope 2 and 3 emissions. Government-led efforts can help support end-market development by building and supporting demand through investments, off-taker guarantees, incentives, and other enabling policies.

Competition for Organic Waste: At many sanitary landfills, LFG is being captured for beneficial use in LFG-to-energy projects, which may involve significant investments that require several years to recover. Policies to divert organic waste may therefore receive pushback from some landfill operators if they threaten current business models.

Environmental, Health, and Community Concerns: Many communities as well as environmental and environmental justice advocates strongly oppose the use of WTE technologies due to concerns about public health impacts from the emissions (including air toxics, particulate matter, nitrogen oxides, sulfur dioxides, and acid gases), climate impacts, and effects on waste reduction efforts. WTE facilities are often sited in areas that are already suffering disproportionate pollution impacts on the most vulnerable populations — communities of color, low-income communities, and marginalized communities. WTE facilities may also incentivize waste generation and undercut waste prevention or recycling programs because they need feedstock to remain commercially viable.

More broadly, organics processing and other waste management facilities can raise a variety of community concerns related to new or expanded industrial development. These include noise, odor, air pollution, increased truck traffic, undesirable land uses crowding out other uses, and others. Broader adoption of any of these technologies will require carefully considering and addressing or avoiding adverse environmental and health impacts on surrounding communities.

Case Study: Production of Automotive Fuel, Fertilizers, and Electricity from Food Waste in Vera Park, Sweden

Nordvästra Skånes Renhållning AB (NSR), a waste management business in Sweden, produces 80 gigawatt-hours of biogas and 145,000 metric tons of fertilizer-grade digestate annually by treating organic materials in household waste.[70]

NSR is jointly owned by six municipalities in Sweden, and its goal is creating a long-term sustainable and cyclical society. NSR's Vera Park facility, shown in Exhibit 11, digests 160,000 metric tons of food waste annually, or approximately 12% of all food waste in Sweden.[71] Food waste is source-separated at the household level and then sent to the Vera Park facility. The organic waste fraction is pretreated at the facility, producing an appropriate feedstock/substrate for the biogas plant. Food waste from households, groceries, and restaurants, along with manure, are co-digested in the biogas plant, and the biogas product is upgraded to automotive fuel or injected into the natural gas grid. The digestate (by-product from the biogas production) is used as fertilizer and transported to farmers' storage tanks. With over 20 years of operation, this facility showcases a long-term, successful case of biogas production from the digestion of food waste.

The success of the Vera Park facility is enabled by the Swedish government's strong waste-sector goals and its adherence to the EU's waste and circular economy plans. The Swedish government is targeting a 20% reduction in food waste by 2025 (from 2020 levels) and a 50% organics separation rate.[72] Other goals in Sweden have targeted at least a 50% organics separation rate with 40% treated for energy recovery. Additionally, a landfill tax and bans on putting combustible waste and organic waste into landfills have further incentivized good behavior and a strong waste diversion program. The government also employed a robust educational program on waste sorting to further enable source separation and make facilities such as Vera Park more effective. Strong waste-sector goals and policies enable innovative waste processing businesses such as NSR and its Vera Park facility.

Exhibit 11

Vera Park Facility Showing the Blending Tank (on the Left) and the Digester and Post-Digester Tanks (on the Right)

Source: IEA Bioenergy Task 37, "More Than 10 Years Production of Fossil Free Automotive Fuel and Certified Digestate from Food Waste: Vera Park in Helsingborg, Sweden," International Energy Agency, 2014, **http://task37.ieabioenergy.com/case-stories.html**

Enabling Levers

- Strong national and EU waste-sector goals
- Landfill tax
- Ban on organic waste in landfills
- Educational programs to promote effective source separation

Managing Methane Emissions at Land Disposal Sites

Rehabilitation of Dump Sites to Sanitary Landfills with Gas Capture Systems

Although intercepting all organic material before it reaches the landfill will avoid methane emissions from waste generated in the future, organics diversion is unlikely to prevent all organic waste from entering land disposal sites. Further, it will not prevent methane generated from waste previously buried at landfills and dump sites. In developing countries, where regulatory oversight of the waste sector can be limited and open dumps are often the norm, a lack of methane capture systems means methane emissions are released directly into the atmosphere.

Open dump sites also pose significant health and safety risks such as fire hazards, waste landslides, and toxic leachate contamination of groundwater and surrounding surface water. An example of such unmanaged LDS is Bantar Gebang, which is pictured in Exhibit 12. Bantar Gebang is the largest open dump site in Indonesia and commonly referred to as “the Mountain” owing to the magnitude of the waste pile.[73] Heavy rainfall in Indonesia presents significant challenges with landfill leachate, a stew of highly toxic chemicals that can leak into groundwater or flow into nearby bodies of water, threatening human health and aquatic life in nearby rivers. These dump sites can also take a significant toll on human safety as a result of open scavenging in unhealthy conditions and waste landslides. In 2005, the Leuwigajah dump site — a separate open dump site in Bandung, Indonesia — recorded the second-deadliest waste landslide in history, burying 71 houses and killing 143 people.[74]

Exhibit 12 **Bantar Gebang Open Dump Site in Indonesia**

Source: Kartika Sari Henry, Wikimedia Commons, **https://commons.wikimedia.org/wiki/File:Mountain_of_garbage_in_Bantar_Gebang_with_some_excavator.jpg**

Upgrading these dump sites to sanitary landfills fitted with gas capture systems, liners, landfill covers, and other control systems that optimize methane abatement not only significantly decreases the release of methane emissions, but also improves the health and safety of the local community living near the dump site. EPA assumes that LFG collection systems capture 75% of the methane generated at an active sanitary landfill.[75] Although there is substantial uncertainty about whether these levels are being achieved in practice, rehabilitating dump sites to sanitary landfills with gas capture systems can still significantly decrease methane emissions.

The recovered LFG can be utilized in LFG energy projects to generate electricity; be used directly as fuel for industrial boilers, dryers, or cement kilns; or be upgraded to pipeline-quality natural gas. However, the high cost of dump site rehabilitation and the lack of financing and incentives for these projects are significant barriers to advancing methane management in developing countries.

Key Factors to Consider

High Up-Front Cost: Developing countries often lack the funds to build comprehensive waste management systems. Improving access to affordable capital and supporting the understanding of available funding mechanisms can help fund expensive capital projects such as rehabilitation of open dump sites. Development finance institutions can play a critical role in low- and middle-income countries by providing more favorable financing terms than commercial and investment banks. Project developers can further de-risk investments to unlock finance by exploring currency hedging and local currency loans to prevent loss from currency devaluation. Government agencies and financial institutions can also organize investment trainings to educate landfill owners and operators on available financing options. Additionally, generating offsets for carbon markets could serve as a funding mechanism.

Lack of Regulatory Frameworks and Oversight: Most developing countries lack comprehensive regulatory frameworks for solid waste management. Sanitary landfills commonly seen in developed countries are designed to meet minimum regulatory requirements (e.g., requirements for daily cover, liners, leachate collection, and LFG collection for use or destruction) that are enforced. Absent similar mandates and oversight in developing countries, dump site rehabilitation will occur only infrequently and voluntarily.

Limited or Unavailable Data: Better waste and emissions data could facilitate upgrading dump sites to sanitary landfills with methane capture systems, particularly when resources are constrained. Given limited financial and technical resources in developing countries, waste and/or emissions data can help prioritize methane mitigation efforts, deploy the limited resources, and optimize methane emissions reduction. As developing countries build their regulatory frameworks, they should also consider incorporating data collection mechanisms to address these gaps. Regulators could require waste disposal facilities to periodically perform methane surveys and report their GHG emissions. This is unlikely, however, without substantial support from governments, philanthropy, and development organizations. Such support could take the form of providing funding and technical assistance to local companies to perform emissions monitoring as well as provide training on estimation methodologies.

Need to Build Local Capacity: Due to limited technical and financial resources in emerging economies, the upgrading of dump sites and development of methane mitigation projects often rely on experts in developed countries where these solutions are already implemented. Involving local communities in solution development and decision-making, investing in technical development programs, and hiring local companies, among other activities, can help secure buy-in, create economic opportunities, and ensure a project's long-term success.

Sensitivity to Local Cultural Context: Closely linked to developing local capacity is understanding local cultural context — governance structure, behavioral patterns, and socioeconomic factors — when developing or implementing methane mitigation solutions. These mitigation strategies need to consider social, cultural, and economic factors such as the impacts on waste pickers, who depend on informal waste collection for their livelihoods. Further, relying on local expertise (technical and nontechnical) can help embed methane management solutions into the communities where they are being developed, enhancing the long-term success of these solutions.

Case Study: Rehabilitation of Europe's Largest Open Dump Site to a Sanitary Landfill

The Vinča dump site near the Republic of Serbia capital city of Belgrade is Europe's largest unmanaged open dump site, but an ongoing project is converting it to a sanitary landfill. The Vinča site absorbs 600 truckloads of trash every day, including 1,500 metric tons of household waste and 3,000 metric tons of construction waste.[76] The site is quickly running out of space, and until recently, was completely uncovered and releasing methane into the atmosphere. Further, fires due to uncontrolled methane emissions at Vinča have caused significant air quality problems in Belgrade.[77]

In October 2019, construction workers began to enclose the Vinča dump site and upgrade it to meet modern sanitary landfill standards, including a cover, a leachate collection system, and an LFG capture system. The overall project is much more expansive, including construction of a new sanitary landfill, an LFG-to-electricity plant, a WTE facility, and a construction and demolition waste recycling center.[78] As of spring 2022, the Vinča dump site has been closed, and progress is well under way for the rest of the project, which is expected to be completed by 2023.[79]

This project was made possible through a public–private partnership between the City of Belgrade and the Beo Čista Energija (BCE) consortium, which includes SUEZ (a French utility), Itochu (a Japanese conglomerate), and Marguerite (a Luxembourg-based fund).[80] The consortium was formed to develop this integrated waste management project, and will recoup its investment through a 25-year waste disposal and treatment contract with the City of Belgrade. BCE also secured financial support from the International Finance Corporation (IFC), the European Bank for Reconstruction and Development (EBRD), and the Development Bank of Austria (OeEB). The project cost approximately €370 million, underscoring how lack of funding could be a significant barrier to undertaking similar dump site rehabilitation projects in emerging economies.[81]

Thus far, several key elements have facilitated the rehabilitation of the Vinča dump site. The formation of the public–private partnership and BCE's 25-year agreement with the City of Belgrade made this project more financially attractive and viable. This project will also bring Serbia one step closer to meeting the EU's strict environmental regulations, which, once met, will allow the nation to join the EU.[82] These elements, coupled with the Vinča dump site being the largest unmanaged dump site in Europe, helped attract investment from the IFC, the EBRD, and the OeEB, whose financial investments made the project possible. The investors also hired Arup, an international sustainable development and engineering firm, to perform independent environmental audits in order to ensure that their investments would result in the GHG emissions and pollution reductions promised by the project.[83] LFG energy facilities will generate additional energy for the city of Belgrade. Finally, the physical tolls that the Vinča dump site has taken on air quality and pollution in the Danube River — the second-longest river in Europe — motivated the government to act, as this pollution brought increased international attention to the dump site.[84]

Enabling Levers

- Public–private partnership that ensures technical capacity and attracts funding
- Financial investment from development banks
- Independent environmental audits
- Incentive to join the EU

Design and Operational Strategies at the Landfill

The final opportunity for emissions mitigation occurs at the landfill. Although the ultimate goal is to divert organic materials away from land disposal sites, these materials will continue to be major sources of methane for decades to come, both from organic materials already in place at landfills and from organic waste that will continue to be sent to landfills despite diversion efforts. Because most organic waste generated today is sent to landfills and dump sites, improving landfill design and daily operations to optimize LFG capture is critical in mitigating emissions from non-diverted organic waste.

The term *design strategies* refers to a menu of mitigation options intended to maximize LFG collection efficiency that are incorporated into the facility during the initial permitting and construction stage, and during development of additional disposal cells as more waste is sent to landfills. The term *operational strategies* describes measures to optimize landfill operations for methane mitigation, including monitoring to identify sources and causes of LFG emissions, minimize the migration of excessive surface emissions, improve the effectiveness of gas capture systems, and convert the captured LFG to beneficial end products. Because landfills represent a crucial near-term opportunity for methane emissions reductions, we explore these design and operational strategies in more detail in Section 4.

Key Factors to Consider

Holistic System Design: Landfills are dynamic and complex systems, and each site is unique. As a result, the optimal set of solutions will differ to a degree among individual landfills, although some basic elements, such as a cover and LFG collection wells, are necessary to effectively capture methane at any landfill. Thus, the proposed solutions in Section 4 are not prescribed off-the-shelf strategies, but rather, they should serve as a toolbox of available options for designing an effective methane abatement strategy for each landfill. A whole-systems approach to design and operations should be undertaken to ensure that interactions within the system do not conflict with each other to result in a negative outcome.

Lack of Complete, Precise, and Timely Emissions Data: To mitigate landfill methane, operators must be able to rapidly identify, quantify, and pinpoint high emissions (from leaking equipment and process errors); take action to mitigate those emissions; and assess the effectiveness of the mitigation measures. Achieving rapid leak detection and repair (LDAR) requires consistent monitoring of methane emissions at landfills. Enabling flexible regulatory frameworks for monitoring that establish standards on sample frequency, detection limits, and spatial coverage for high-emissions events can incentivize advanced technologies that fill existing gaps. Such advanced monitoring technologies could facilitate more timely leak detection, as well as inform operators of the effectiveness of various mitigation solutions at the landfill.

Permitting Delays: Proposals for new landfills and other waste management facilities and upgrades to existing facilities often trigger complex permitting processes that can add months, and in some cases years, to projects, increasing costs and disincentivizing developers from making important design or operational updates that would significantly address methane emissions. However, some of these permitting delays are due to important community or other environmental and safety concerns that need time to be comprehensively addressed. Permitting reforms focused on facilitating approvals of pollution reduction projects, alongside enhanced community engagement efforts, could potentially speed the permitting process for beneficial projects while addressing community concerns.

Regulatory Capacity and Enhanced Coordination: Although the design and operational strategies discussed in Section 4 are critical to mitigating methane at the landfill, these measures are unlikely to be adopted voluntarily. Regulatory requirements are necessary to maximize methane reduction opportunities that fully deploy the optimal mitigation measures at the landfill, and successful regulation requires adequate regulatory capacity. In many countries, environmental regulators have limited legal authority as well as limited financial and human resources, technical capacities, and/or enforcement capabilities, any of which can hinder effective regulations.

Although these constraints are often more severe in developing countries, they are by no means confined to those countries. Such limitations can lead to ineffective policies or mandates that address specific concerns in isolation, but that fail to adequately consider whole-systems interactions and may result in unintended consequences or less-optimal methane management solutions. Successful implementation of these strategies depends on building and maintaining adequate regulatory capacity. Another regulatory-related constraint is a lack of coordination between overlapping jurisdictions, in which a waste facility is subject to oversight by multiple regulatory entities. This can lead to complications or delays in project implementation. Interagency coordination can help alleviate these issues, but overlapping jurisdictions remain a challenge.

Managing Methane Emissions Pre-LDS and at LDS

Comprehensive Emissions Monitoring and Quantification

A wide variety of new advanced technologies for monitoring and quantifying methane emissions can help operators design methane abatement strategies at landfills and dump sites and evaluate whether those strategies are achieving the desired impact. These technologies range from handheld sensors that detect emissions at close range, to optical imaging cameras that can scan an area from the ground, to sampling from aircraft and drones, to satellite imagery. Each technology has different sensitivities, ranges, detection thresholds, costs, and other considerations.

For developed countries with landfills where methane capture technology is installed, comprehensive monitoring can facilitate rapid methane leak repairs by enabling faster leak detection, quantification, and source attribution. Airborne campaigns in California have shown a disproportionate amount of methane emissions localized to a small fraction of sources.[85] Follow-on airborne surveys of landfills are being conducted across the United States and are being planned for other jurisdictions to determine the degree to which the findings are representative outside California. Meanwhile, this initial insight suggests an opportunity to minimize methane emissions across developed countries in the near term. In addition, monitoring technologies with advanced mobility (e.g., robots, airborne instruments) can access active working faces of landfill operations that are typically not monitored owing to health and safety concerns. They can also more easily capture anomalous events such as leaks, which are generally not represented in GHG inventory models.

In developing countries, improved monitoring and quantification can serve two purposes. First, given resource constraints in these nations, monitoring technologies can help prioritize the landfills and open dump sites with the biggest near-term opportunities for methane reduction. Second, as in developed countries, improved monitoring and quantification can facilitate rapid leak detection and repair at formerly open dump sites that have undergone rehabilitation to sanitary landfills with gas capture systems; frequent monitoring has proven to be necessary at such facilities.

Additionally, the data and insights generated can improve current GHG inventories that rely on bottom-up models, which are often inaccurate in the estimation of facility-level emissions. Today, estimating landfill methane emissions relies on default values in GHG inventory models that may not accurately reflect the variability of methane generation at the facility level. These models also do not account for the methane generation impact of site topographic features such as cracks, faulty covers, or ongoing construction. The default values in these models could be overestimating methane emissions at well-managed landfills with higher capture efficiencies, while underestimating emissions in poorly managed landfills.

No single measurement technology can fully characterize landfill emissions, given their complexity. In most cases, a tiered system of monitoring technologies with variable temporal and spatial coverage — including some combination of ground-based surveys, fence-line monitoring, aircraft, drones, and satellites — will provide frequent data and insights. These results will in turn enable key actors to improve emissions visibility, attribute methane emissions to their sources, and prioritize areas of intervention, thereby empowering landfill operators to rapidly address the root cause.

Section 5 explores how leveraging top-down and bottom-up estimation approaches alongside new monitoring technologies can help address some of these challenges. A joint modeling and measurement framework could fill knowledge gaps, reduce uncertainty and bias in GHG emissions estimates, and improve regulatory frameworks for emissions accounting.

Key Factors to Consider

Optimize Observing System Completeness: The ultimate mitigation potential enabled by any monitoring system is constrained by the observing system completeness (i.e., the percentage of total emissions from a given population of emissions sources that can be detected by the system). Observing system completeness is a function of spatial coverage, sampling frequency, and detection limit.[86] Additionally, accurate quantification of landfill methane emissions depends on both the attributes of the observing system and variability in emissions, weather, and other factors that translate to measurement uncertainty. Persistent, high-frequency monitoring by aircraft is relatively expensive and can be impractical to implement in many jurisdictions.

Emerging methane-sensitive satellites offer the potential to provide cost-effective and timely operational monitoring for the majority of the world's MSW landfills, organics processing facilities, and unmanaged dump sites. Limitations in individual technologies underscore the need for regulatory frameworks that promote a comprehensive suite of monitoring technologies, such as pairing remote sensing technologies with traditional technologies to create flexible and cost-effective monitoring frameworks that maximize emissions detection.

Leveraging Performance-Based Regulations: Regulatory environments that leverage performance-based regulations may allow for more flexibility in adopting innovative methane monitoring technologies as they are geared toward ultimate end-point emissions reductions and less focused on individual practices adopted by operators. Although challenges still exist with performance-based standards and regulations (e.g., measurement sampling frequency, calibration), outcome-based regulations can foster technology innovations, enhance emissions monitoring and quantification, and improve GHG accounting practices.

Shifting Methane Emissions to Organics Processing Facilities: We outline several methane abatement strategies in Section 3, one of which requires diverted organic materials to be converted to other beneficial end products. However, care should be taken to ensure that curbing methane emissions at land disposal sites does not result in simply shifting methane emissions to organics processing facilities. Poor operations or malfunctions can result in methane emissions at composting and digestion facilities. Therefore, frequent monitoring and reporting should also be conducted at these facilities to ensure that the diversion of organics does not result in methane emissions at composting, anaerobic digestion, or other organics processing facilities.

Case Study: Emissions Monitoring and Quantification Combined with Design and Operational Improvements at Sunshine Canyon Landfill, California

In 2016, the Airborne Visible InfraRed Imaging Spectrometer — Next Generation (AVIRIS-NG) instrument flew over Sunshine Canyon Landfill in Los Angeles County, California, where it geolocated and quantified methane plumes in excess of 1,000 kilograms per hour (kg/h) (Exhibit 13) emanating from the landfill's intermediate cover slopes.[87] These findings were shared with the Sunshine Canyon Landfill Local Enforcement Agency (SCL LEA) and the landfill operator.

The history of Sunshine Canyon Landfill included a significant number of community odor complaints starting in 2009. The increase in odor complaints was the result of an ineffective LFG collection system due to insufficient vertical gas wells and lack of horizontal collectors.

In 2010, in an attempt to reduce odor, the regulator ordered the operator to institute a nonstandard practice that required a minimum of 9 inches of compacted daily soil cover to be installed without peeling back the cover at the start of the work day (CUP 00-194-5, Amendment 45.N–2). This resulted in perched leachate that did not drain to the bottom of the leachate collection system and flooded the LFG collection wells. The rationale for the standard practice of removing the daily cover is to preserve usable airspace, reduce cover soil cost, and improve fluid flow through waste lifts.[88] Because the standard peel-back was no longer being performed, the methane generated was not efficiently captured by the flooded LFG wells, leading to pressure buildup within the landfill and persistent gas blowouts.

Odor complaints following the implementation of the daily soil cover without peel-back led to an abatement order in 2016 by South Coast Air Quality Management District, with mitigation measures recommended by the SCL LEA that involved a holistic assessment of the landfill's operations, resulting in the utilization of an alternative daily cover (ADC) and the discontinuation of the compacted soil cover without peel-back.

Between March and December 2017, the recommended remediation measures were installed on intermediate slopes, including ClosureTurf (an impermeable polyethylene plastic layer with an additional artificial grass layer on top), Posi-Shell (a cement, bentonite, and fiber spray mix), and enhanced vegetative cover. LFG collection pipes were placed above the existing intermediate cover and below the geomembrane to capture gas under the ClosureTurf. Additionally, both horizontal and vertical wells were installed to capture LFG throughout the landfill. These remedial measures enabled the landfill operator to increase the vacuum to the LFG collection system in the affected areas.

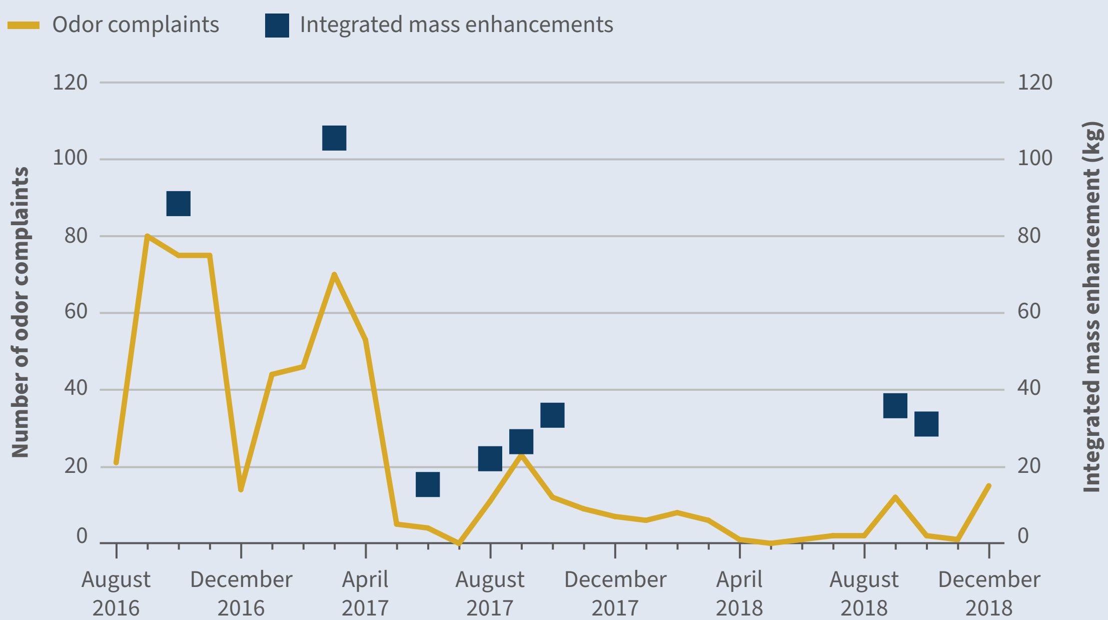
The implementation of the 2016 abatement order resulted in approximately a 55%–60% reduction in methane emissions, as corroborated by follow-up AVIRIS-NG flights and records of the LFG collection volumes. During those follow-up flights in 2017, scientists observed that the methane emissions were substantially reduced. These quantified reductions also correlated closely with reductions in community odor complaints (Exhibit 13). This example shows how independent observations can be used to guide and validate management practices aimed at reducing emissions. However, even after emissions reductions are verified, sustained monitoring is needed to ensure long-term reduced emissions.

Enabling Levers

- Comprehensive emissions monitoring and quantification
- Close coordination between the observational system operator, landfill operator, and SCL LEA
- Regulatory environment focused on addressing community complaints
- Holistic design of mitigation measures

Exhibit 13 **Methane Plumes Imaged at Sunshine Canyon Landfill**

Before infrastructure improvements | **After infrastructure improvements**



Source: Daniel H. Cusworth, Riley M. Duren, Andrew K. Thorpe, Eugene Tseng, David Thompson, Abhinav Guha, Sally Newman, Kelsey T. Foster, and Charles E. Miller, "Using Remote Sensing to Detect, Validate, and Quantify Methane Emissions from California Solid Waste Operations," *Environmental Research Letters* 15 (5): 054012, 2020, **https://doi.org/10.1088/1748-9326/ab7b99**

4. Recommended Management Practices for Designing and Operating Landfills to Mitigate Methane

In Section 3, we described a whole-systems approach to mitigating MSW methane emissions involving pre-LDS solutions (e.g., food waste prevention, organics diversion and processing) and solutions at LDS (e.g., dump site rehabilitation, landfill design and operations), both facilitated by comprehensive emissions monitoring to ensure the effectiveness of solutions.

In this section, we do a deep dive into the design and operation of landfills as a methane abatement strategy. These management practices are geared toward landfill owners and operators, engineering consulting firms, and landfill design experts. The optimal solution or combination of solutions for minimizing methane emissions will vary across landfills. The measures described below are not prescribed turnkey solutions; rather, they should be seen as a toolbox of options for designing an effective methane abatement strategy for individual landfills. We recommend a case-by-case assessment of each landfill to determine the most suitable mitigation solutions. The optimal methane abatement strategy should consider a holistic approach such that various mitigation measures complement one another.

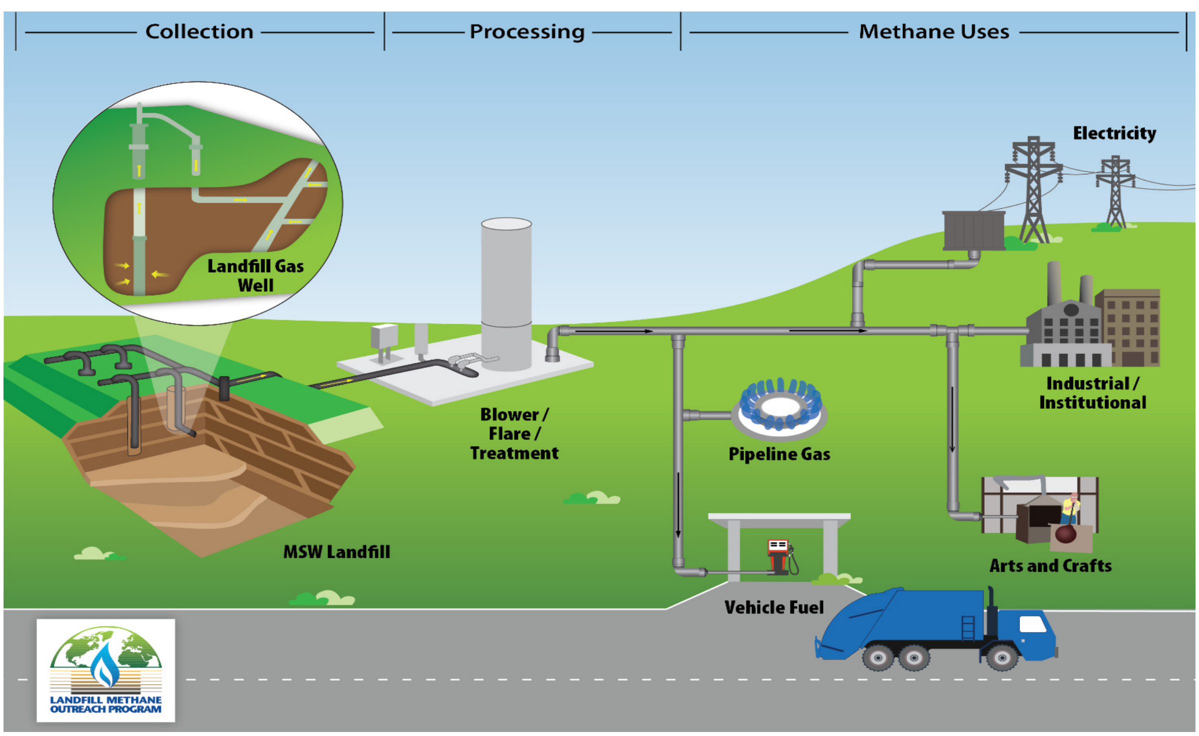
A sanitary landfill in San Jose, California.

To mitigate methane emissions at LDS, landfills should be designed to include, and maximize the effectiveness of, gas capture systems. LFG capture systems collect the LFG through vertical and horizontal pipes buried in an MSW landfill (Exhibit 14). The captured LFG is then processed and treated for use or destroyed in a flare. Design considerations for optimizing gas collection systems include the types of gas wells, the timing of installation, the spacing between wells, and leachate drainage. Exhibit 15 (next page) presents a menu of mitigation options that can be incorporated into the design of landfills before the operating cell (an area of land actively receiving solid waste) is constructed, to optimize LFG collection efficiency.

The day-to-day operation of a landfill is equally critical to managing LFG emissions. Many aspects of landfill maintenance, or, more broadly, the sustainability goals of the landfill owner/operator, may affect the amount of methane emissions released to the atmosphere. Important considerations include type and thickness of landfill cover, waste compaction, frequency of emissions monitoring, LDAR, personnel training, and emissions reduction targets. Exhibit 16 (on page 48) describes operational measures for managing LFG emissions on an ongoing basis, whereas Exhibit 17 (on page 49) outlines mitigation strategies focusing on landfill covers. These covers are installed to minimize odors, reduce the risk of fires, deter scavenging and pests, confine waste, and protect public health. Lastly, Exhibit 18 (on page 50) offers suggestions for enhanced methane monitoring.

Although many of these measures can be costly, which can be particularly challenging for developing countries where funding is limited, some fundamental methane mitigation measures can be implemented at reasonable cost. These measures include installing daily landfill covers, installing final covers on closed land disposal facilities, implementing basic LFG collection and flare systems, and conducting more frequent monitoring with lower-cost emissions monitoring technologies.

Exhibit 14 **Schematic of a Landfill Gas Collection System**



Source: "Basic Information about Landfill Gas," US EPA, n.d., accessed June 1, 2022, **https://www.epa.gov/lmop/basic-information-about-landfill-gas**

Exhibit 15 Recommended Management Practices for Designing Landfills

Design Measure	Description
1. Utilize gabion cubes on bottom liner	LFG collection wells are prone to flooding by leachate, rendering them less effective at drawing out gas. Installing gabion cubes, or the equivalent, in the design of the LFG collection system and landfill liner system can enhance drainage of leachate and prevent that flooding. Caisson wells, or vertical gravel columns built from the bottom up, are also effective approaches. All vertical wells should be proactively linked to base-level leachate drainage systems. For disposal sites without liners, newly developed disposal cells should include liners with gabion cubes.
2. Optimize timing of horizontal LFG well installation at active landfills	Horizontal LFG collection pipes are useful for collecting gas in ongoing disposal operations before the final elevation of the landfill is reached. This is especially true when wells are connected to gabion cubes. It is recommended to install and connect the horizontal LFG collection pipes to gabion cubes as soon as the disposal lift reaches the top of the cube. Horizontal wells should be installed on at least every other lift. The piping system should be designed to allow for landfill settlement and shifting of disposal mass to maximize the effective life of horizontal LFG collectors.
3. Optimize timing of vertical LFG well installation at active landfills	Install and connect the vertical LFG wells in a timely manner while continually raising the wellhead as the disposed height of the waste increases during ongoing disposal operations. The time when the LFG well is installed depends on several factors, such as development of disposal cell, depth of disposal cell, type of waste, and amount of settlement.
4. Maintain vertical LFG wells by installing water pumps	When needed, use pumps to remove water (e.g., infiltration from rain or leachate from waste decomposition) in wells, as flooding may limit the effectiveness of LFG collection. For deeper LFG collection wells, installing pumps in series is recommended.
5. Ensure optimal spacing for vertical LFG collection wells	Optimize LFG well spacing with an approximate 30% overlap of radius of influence to maximize LFG collection coverage within the waste mass. Overlapping the radius of influence prevents buildup of LFG in an area with no vacuum pressure gradient. The rule of thumb for well spacing is one to three wells per acre, depending on performance.
6. Design and install LFG collection wells with a well boot seal	Landfill well casings and annuluses can be a significant source of surface gas leaks and air intrusion due to settlement of trash mass. Installing a boot minimizes the creation of a path of least resistance for the migration of LFG and maximizes effective vacuum pressure on the LFG collection system by preventing atmospheric air intake. Membrane boot seals on vertical wells should be reinstalled or upgraded after several lifts.
7. Utilize vacuum box when drilling vertical LFG collection wells	Use adequately sized vacuum boxes to ensure that LFG and odors are collected and not vented to the atmosphere during well drilling and construction activities. Without the use of vacuum boxes, methane is directly emitted into the atmosphere when drilling reaches into the disposed-of trash.
8. Design sequence of cell filling to minimize uncompacted slopes	Plan the sequencing of cells to minimize the amount of exposed sloped areas. Sloped surfaces are harder to compact than horizontal surfaces and thus tend to leak more emissions. Filling in new cells against sloped surfaces will help minimize methane leakage and allow for collection of LFG by using newly installed horizontal LFG collectors.
9. Utilize modular biofilter cells and activated charcoal for filtration of collected gas	Use biofilters and activated charcoal filtration for low-flow LFG volume and low methane content. Biofilters provide microbial oxidation of methane from landfills; activated charcoal helps remove volatile organic compounds from the landfill gas.

Exhibit 16 Recommended Management Practices for Operation and Maintenance of Landfills

Operational Measure	Description
1. Optimize efficiency of methane flares	Where methane flares are installed to thermally destroy methane, ensure the use of high-efficiency flares for methane destruction. Backup or supplemental LFG flaring systems should have redundancy capacity to capture and flare at least 100% of the total LFG generated in case of downtime of the LFG-to-energy system.
2. Utilize captured gas in LFG energy projects	Flaring of LFG methane releases CO_2 and can result in methane emissions due to incomplete combustion (methane slip) and malfunctions. Utilizing the captured LFG rather than flaring it will offset CO_2 emissions by replacing fossil-based fuels that would otherwise have been produced and used. Develop LFG energy projects or partner with off-takers to ensure a market for the captured LFG.
3. Optimize continual upgrade of gas collection system	LFG collection systems must be dynamically adapted and upgraded to meet changing conditions at the landfill. These systems should be designed in phases to match the potential increasing flow of methane, and have a backup routing of the gas flow, to properly allow for increases in the LFG generation rate. When a landfill is managed with effective leachate removal, the remaining drier material will produce less methane over time. However, if a landfill has higher moisture content, methane generation may be accelerated in the early stages. For landfills with a long projected disposal life, periodic upgrades of the gas collection system will be necessary. Additionally, automated dynamic tuning of the LFG collection system using real-time data and machine learning to optimize vacuum to the LFG collection well is recommended.
4. Minimize daily working face	Minimize the exposed surface area of the daily uncovered working face (i.e., where there is no daily cover) to impede the emissions of LFG from underlying trash to the surface and atmosphere.
5. Maintain a minimum surface grade to promote drainage	Minimize infiltration of water by maintaining a minimum drainage grade of surface areas of the landfill to prevent ponding. Water from infiltration will increase the moisture content and accelerate decomposition of organic materials. Consider the use of geosynthetic liners to manage stormwater runoff and drainage.
6. Periodically analyze composition of disposed-of waste	Understanding the changes in the waste stream enables more accurate prediction of the volume of LFG generated. The successful impact of recycling programs (i.e., decreasing levels of paper, plastic, and metal in landfills) results in a relatively higher weight percentage of food waste, thus increasing moisture content in the landfill. This information can be used to dynamically update modular LFG collection systems, as discussed above.
7. Understand local conditions and extraordinary events and their impact on landfill operations	Extraordinary events such as COVID-19 can significantly increase organic material in residential waste streams, while reducing those in commercial waste streams. Separate cells that take wastes with different percentages or types of organic content can flexibly react to these changes. Other extraordinary events, such as wildfires, can destroy a landfill's gas collection system. Understanding such context enables landfill operators to proactively manage methane emissions.
8. Create LFG travel pathways using construction and demolition waste	Stockpile construction and demolition wastes that are composed of a mix of larger granular materials (e.g., crushed concrete) and free of drywall to create LFG travel pathways. This will allow the flow of LFG toward vertical gas collection wells.

Exhibit 17 Recommended Management Practices for Implementing Landfill Covers (Daily, Intermediate, and Final)

Mitigation Measure	Description
1. Increase thickness of daily soil cover and intermediate soil cover	Apply thicker soil cover after disposal and peel back the applied soil cover before future disposal to minimize soil thickness and increase trash-to-trash contact. This promotes drainage of leachate to the bottom of the landfill and movement of LFG to the gas collection system. Monitor daily and intermediate covers for methane emissions to optimize cover performance.
2. Increase compaction of daily cover and intermediate soil cover	Maximize density of the applied soil cover to decrease permeability. This will allow for higher applied vacuum to the LFG collection system. The less permeable the cover, the less likely it is for LFG emissions to escape to the atmosphere. Increased compaction also allows for greater application of vacuum on the LFG collection system to capture more LFG without drawing oxygen into the landfill. Drawing oxygen into the landfill can cause an increased risk of subsurface oxidation events and fire hazards.
3. Optimize timing of the removal (peel-back) of in-place daily or intermediate soil cover	Peel back the soil cover when waste is being disposed of to minimize the time between removal of the in-place soil cover and the disposal operation.
4. Add vegetative layer to intermediate soil cover	Add a vegetative layer with organic soil content to the intermediate soil cover. Soil with organic content can be used as an intermediate cover because it supports vegetative growth, which has a biofiltration property that provides microbial oxidation of methane escaping to the surface.
5. Use of Posi-Shell on intermediate cover	Posi-Shell (a cement, bentonite, and fiber spray mix) enhances intermediate cover performance by lowering permeability and allowing greater vacuum to be applied without increasing the potential of oxygen intrusion. When combined with an effective LFG collection system and dynamic placement of horizontal and vertical collection wells, this enables better recovery of LFG from active cells.
6. Use of closure turf with surface gas collection system	Install a temporary impermeable plastic layer with a surface LFG collection system. The plastic layer allows for greater vacuum to be applied to the LFG collection wells. The surface gas collection system will capture surface emissions not captured by LFG collection wells.
7. Avoid green waste as ADC or AIC	Using green waste as an ADC or AIC eventually results in anaerobic decomposition and generates methane. As much as possible, use green waste as mulch, for erosion control, or for other applications that result in aerobic decomposition, reducing methane generation.
8. Install final cover on an ongoing basis	Install final cover on parts of the landfill that have already reached their final contours, as opposed to installing final cover only when the entire landfill has reached capacity and is no longer accepting waste for disposal. Final covers should be less permeable and more effective at preventing moisture infiltration into the disposed-of waste than temporary daily and intermediate covers.
9. Repair landfill cover damage on an ongoing basis to maintain cover integrity and performance	Damage or erosion to landfill covers can occur for a variety of reasons, such as rain, stormwater runoff, truck traffic, or animal activity. Monitoring paired with repair of landfill covers is essential. Close attention to episodic damages, such as erosion occurring after major rain events, is also essential.

Exhibit 18 Recommended Management Practices for Monitoring Methane Emissions and Landfill Conditions

Measure	Description
1. Install LFG perimeter monitoring wells	LFG perimeter monitoring wells monitor the LFG concentration at the property boundary and provide information on the effectiveness of the LFG collection system. Offsite migration of LFG indicates the need for upgrades, mitigation measures, and/or installation of additional collection wells.
2. Increase gas composition monitoring of LFG collection system	Regularly monitor oxygen levels at individual gas collection wells to balance vacuum levels and LFG collection performance. This effort aims to maximize gas capture and ensure that excess oxygen is not pulled into the landfill, which can cause subsurface oxidation events and fires.
3. Increase LDAR monitoring frequency of surface emissions	More frequent monitoring will identify point sources or broader surface area emissions from landfill covers and equipment. Point sources include rills, burrows, damaged wells, leaking pipe infrastructure, and inefficient flares. Surface area emissions may come from thinning covers or damaged equipment.
4. Build access benches on sloped faces during filling and closure	Building benches on landfill side slopes provides access for cover maintenance, installation of new LFG extraction wells, and emissions monitoring. Having access to all parts of the landfill for monitoring, maintenance, and repair improves detection of methane leaks.
5. Utilize audio/visual/ olfactory surveys	Basic observation surveys, particularly those using olfactory sensing, can rapidly identify methane sources. The nose is a very sensitive odor detector that can detect excessive LFG emissions. LFG odor is a proxy indicator for potential methane emissions sources, as methane and CO_2 emissions are carrier gases for odorous chemical compounds. Trained personnel can walk through landfills to detect sources of LFG odor, while looking for visual or audio clues to gas leakage.
6. Implement advanced methane detection technologies	New sensors utilizing infrared cameras or optical gas imaging to detect methane and volatile organic compounds are readily available and can observe the entire landfill. These tools can be handheld or tracked via robots to identify point source emissions. They may also be mounted on aerial drones or planes or satellites to provide access to more remote or dangerous areas.

5. Methane Monitoring and Quantification through Top-Down and Bottom-Up Methods

Consistent, comprehensive monitoring and quantification are critical to effectively managing methane emissions at landfills and dump sites. Reliable methane emissions monitoring and quantification are needed to inform effective management and enforcement, as well as more accurate GHG accounting at different scales from global to facility-level inventories. Quantification can include both bottom-up approaches (e.g., process-based models) and top-down approaches (e.g., atmospheric measurements). Many existing approaches can be unreliable, owing to factors such as overly simplistic models, poor site-level information being input into models, or infrequent atmospheric measurement sampling.

Advanced technologies, capable of attributing emissions to specific sources and revealing the variable sizes and durations of methane emissions, are necessary for prioritizing emissions reduction and determining the effectiveness of proposed solutions. In this section, we describe various monitoring approaches, inclusive of several evolving emissions detection technologies commonly utilized in the oil and gas industry, and their strengths and weaknesses, and we suggest opportunities to improve emissions quantification.

Bottom-Up Modeling

Bottom-up biogas generation models estimate methane emissions from waste deposited at landfills coupled with estimates of gas collection efficiency and methane oxidation. These models generally produce a single value for a specific landfill, often on an annual basis, and usually based on waste tonnage. In the United States, the most prominently used model is the Landfill Gas Emissions Model (LandGEM).[89] LandGEM is a first-order decay model, in which estimated methane emissions depend heavily on two parameters: methane generation potential and methane generation rate. *Methane generation potential* refers to the maximum amount of methane that can be produced for a mass of waste; *methane generation rate* refers to how quickly methane is generated from this mass of waste. Both methane generation potential and methane generation rate depend on waste composition. However, methane generation rate also depends on environmental factors (e.g., precipitation, temperature, local climate).

Default values for LandGEM model parameters are based on a survey of 40 landfills performed during the 1980s, although the model can be adapted to include site-specific parameter values. LandGEM also assumes by default a 75% recovery efficiency of generated methane.[90] This recovery efficiency has rarely been validated in field settings addressing all methane pathways (recovery, emissions, oxidation, lateral migration, and internal storage), and may vary significantly across landfills, depending on the utilization of best management practices for gas recovery.[91] Aside from LandGEM, other first-order kinetic decay models or first-order transport models are used for regional to global applications and may offer more options for parametric specifications (e.g., the IPCC Waste Model, Capturing Landfill Emissions for Energy Needs [CLEEN], and the California Landfill Methane Inventory Model [CalMIM]).[92]

The accuracy of kinetic decay models (e.g., LandGEM) or first-order transport models (e.g., CalMIM) for estimating emissions can be improved by using higher-quality inputs of site-specific parameters (e.g., waste-in-place, area coverage of different landfill faces, types of covers, depth of cover, presence of gas capture) to drive simulations. Accuracy can also be improved with rigorous calibrations against measurement campaigns and top-down observations. For example, in 2015, Kurt Spokas and colleagues used comprehensive CalRecycle landfill survey information (e.g., acreage of intermediate/daily cover, types of material used, thickness of cover) from 2012 to run CalMIM simulations that they compared against available field data for 10 landfills.[93] This integration resulted in better estimates when the simulations were compared against atmospheric observations, demonstrating the value models can provide when better data is used.

To improve modeled emissions estimates, landfill operators and local enforcement agencies may substitute site-specific information regarding waste composition and management for LandGEM default parameters. However, this approach is hard to generalize; it depends on information gathered and/or made available by landfill operators, and still largely fails to account for anomalous events. The resulting high levels of uncertainty in bottom-up modeling estimates underscore the need for more robust and reliable emissions estimates across solid waste facilities.

Top-Down Atmospheric Observations for Emissions Quantification or Leak Detection

Atmospheric measurements of methane concentrations can be used to detect emissions hot spots — helpful for guiding operations and remediation — and under the right observing conditions, they can be used to estimate emissions relevant to inventories. Some technologies are geared toward total landfill emissions quantification, and others isolate emissions at particular regions of interest within the landfill's footprint. As a reminder, we define an *area source* as the total aggregated landfill emission, and a *point source* as a region of high concentration at a landfill that represents a significant contribution to the area source. The frequency of detection and quantification for most technologies is dependent on resources such as cost and labor. In Exhibit 19, we assess the capabilities of selected technologies that measure methane concentrations and are often used to quantify emissions rates.

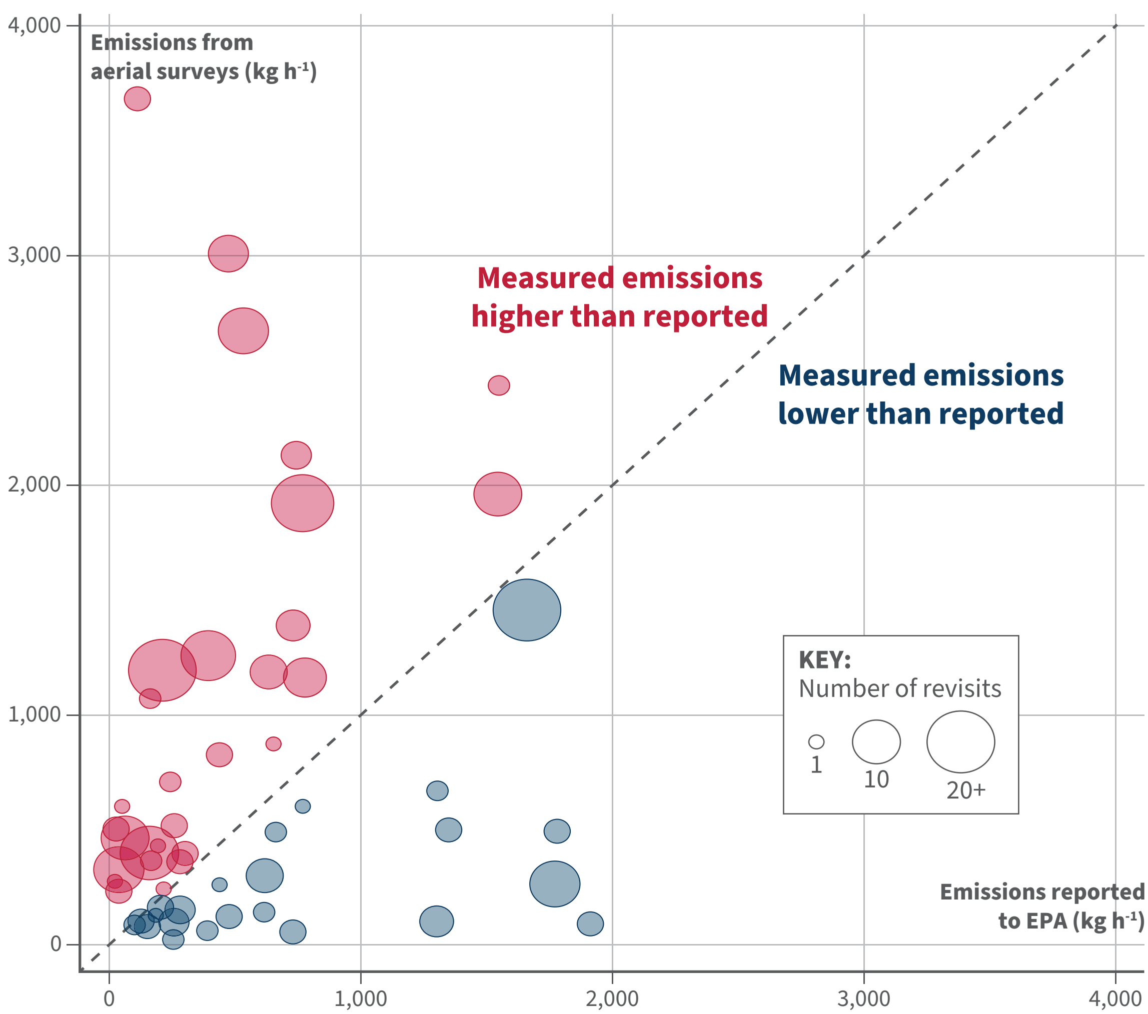
Exhibit 19 Review of Detection and Quantification Technologies for Landfill Methane Gas

Technology	Description	Sensitivity to Emissions (Area or Point Sources) and Spatial Coverage
Flame ionization detector (FID)	An FID is a portable detection system that draws LFG into a gas chromatograph that can differentiate methane gas through combustion. Typically, these monitors can be worn by a single operator and are often used for surface monitoring and LDAR that may be required by a federal, state, or local agency (e.g., EPA Method 21; South Coast Air Quality Management District Rule 1150.1).[94]	Point sources, local coverage
Thermal imaging/optical gas imaging	Thermal cameras that can visualize methane plumes given the right background conditions (i.e., sufficient thermal contrast between a methane plume and the surface) can be used to qualitatively identify leak sources but do not quantify the emissions.	Point sources, local coverage
Eddy covariance flux towers	These towers are used primarily for quantification to estimate an emissions flux for an area through rapid tower measurements of methane concentrations and wind vertical velocity (a proxy for eddies). This approach assumes transport is done by eddies, flux is uniform across the upwind footprint, and terrain is horizontal and uniform.	Area sources, full area coverage
Tracer correlation	In this quantification approach, a tracer gas (e.g., nitrous oxide, acetylene, sulfur hexafluoride) of known quantity is released from a landfill. Downwind of the landfill, a high-precision instrument measures both tracer concentrations and methane. Emissions can be estimated by comparing ratios of measured concentrations and the known release rate of the tracer. This approach has been shown to provide reliable results for quantifying the area sources.[95] This approach requires continuously calibrated tracer emissions to be released from a landfill and may require sufficient downwind measuring sites to account for changes in wind direction.	Point sources, area sources, full area coverage
Vertical radial plume mapping (VRPM)	VRPM is a ground-based quantification approach that uses tunable diode lasers at methane absorption wavelengths to create a plane downwind of an emissions source that a plume intersects.[96] The inferred mass intersecting the plane is used in conjunction with wind speeds and plume modeling to infer an emissions rate for a region of the landfill. This method has shown promise in detecting emissions in isolated regions of landfills. Complex topography can complicate data acquisition, and many VRPM setups need to be deployed across a landfill in order to quantify the area source.	Area sources, local coverage
Airborne/satellite imaging spectroscopy	Airborne and satellite imaging spectrometers are sensitive to backscattered solar radiation of between 400 and 2,500 nanometers (nm) and produce imagery at these wavelengths with spatial resolutions ranging between 3 and 30 meters, depending on flight altitude. Between 2,200 and 2,400 nm, methane is known to be a strong absorber of radiation, and this absorption signal can be used to infer methane concentrations and emissions at landfills.[97] Geolocated plume maps can be generated to identify regions of high concentration on the landfill surface. Imaging spectrometers are sensitive to point sources only for discrete temporal snapshots; they cannot quantify the full area source emissions at landfills but can highlight high-emitting regions that contribute significantly to the area source.	Point sources, full area coverage
Flux chamber	Sealed chambers are placed at various locations on top of the landfill to collect emitted gas.[98] These measurements do not rely on atmospheric transport and are therefore a more direct measurement of emissions fluxes. They quantify emissions at a single point or a few discrete points on the landfill, and may not be representative of spatial variability in emissions.	Point sources, area sources, local coverage

Leveraging Top-Down and Bottom-Up Methods to Reduce Discrepancies in Estimation Approaches

As is true for most industries tracking methane emissions, one of the greatest challenges for the MSW sector is reconciling discrepancies between top-down and bottom-up inventories. For example, emissions estimated from airborne imaging spectrometer surveys of MSW landfills between 2016 and 2021 across multiple states in the United States (Arizona, California, Colorado, Louisiana, New York, Ohio, Pennsylvania, and Utah) show little correlation with emissions reported to the EPA Greenhouse Gas Reporting Program (GHGRP). Landfill operators estimate methane emissions using a LandGEM modeling approach to fulfill the annual reporting requirement of the GHGRP (Exhibit 20). Nearly half of the landfills had observed emissions higher than the GHGRP estimates, and the remainder had lower emissions. Though some of the discrepancies could be explained by sampling limitations of airborne instruments, even sites with 20-plus independent airborne observations did not show improved correlation with the GHGRP estimates.

Exhibit 20 **Comparison of Methane Emissions Estimates from Bottom-Up Inventories (EPA GHGRP) and Top-Down Aerial Surveys (AVIRIS-NG and GAO Imaging Spectrometers) in the United States, 2016–2021**



Source: Carbon Mapper, "Methane, CO_2 Data, Global Open Portal, Carbon Mapper," n.d., accessed June 2, 2022, **https://carbonmapper.org/data/**

Top-down methods with higher minimum detection limits can lead to undercounting of emissions if they cannot properly identify smaller point sources. However, using emissions factors or modeling also tends to undercount emissions due to a failure to account for leaks such as those from equipment malfunctions, construction activities, thin intermediate covers, or low gas capture efficiency.

Other sources of discrepancies are related to the “heavy-tail” effect. This effect comes from the fact that unintended emissions can vary widely in size and can make up a significant portion of the total emissions, often dwarfing the emissions inventories accounted for in models. On a weighted average, the airborne surveys estimated emissions 3.5 times higher than bottom-up estimates. Notably, many of the landfills where large emissions were detected have gas collection systems; therefore, installation of gas capture systems is not necessarily predictive of observed lower emissions rates. This magnitude of discrepancy, if consistent across the global waste sector, could severely affect researchers’ understanding of the waste sector’s contribution to the anthropogenic methane budget.

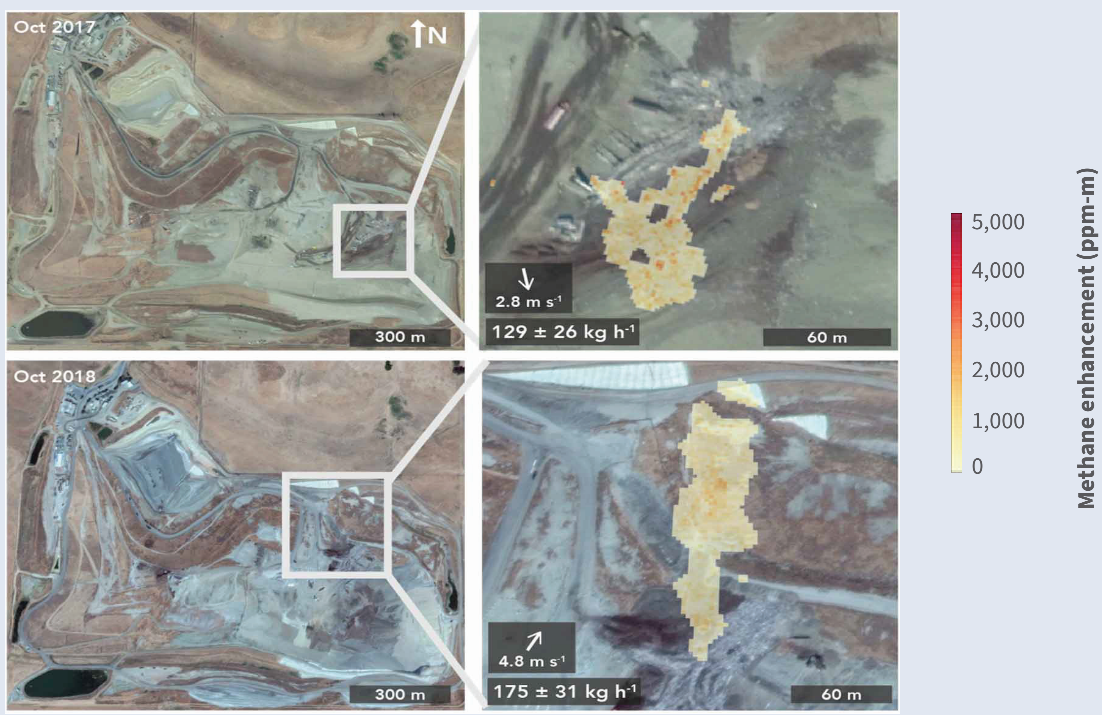
Due to the overwhelming impact of “heavy-tailed” unintended emissions from managed landfill sources (and other methane-generating industries), efforts to calibrate waste-sector inventories should focus on utilizing and improving top-down measurement campaigns that can capture these variable large emissions events.

Case Study: Aerial Emissions Quantification from the Active Face of Potrero Hills Landfill in California

Aerial monitoring presents an opportunity to detect and quantify emissions from the active faces of landfills. It is difficult to measure methane emissions from the active face of a landfill on the ground, because dangerous operating conditions create safety hazards. However, the active face may be a significant source of methane emissions, depending on incoming waste composition, or if the active face is placed on top of an older trash cell.

In 2017 and 2018, the AVIRIS-NG instrument flew over Potrero Hills landfill in California and detected significant emissions (129–175 kg/h) emanating from the active face of the landfill. The active face represented 11%–21% of total emissions quantified by AVIRIS-NG from the landfill at the time of aerial overpass. Ground-based measurement systems (e.g., quarterly surveys using FIDs) would likely fail to capture this discrete source of emissions. The left panels in Exhibit 21 show the Google Earth image of the landfill nearest the time of the AVIRIS-NG overpasses in October 2017 and October 2018. The right panels show the Google Earth location of the active face with the AVIRIS-NG–detected methane plume and its estimated emissions rate.

Exhibit 21 **Methane Emissions from the Active Face of a Landfill as Identified by AVIRIS-NG**



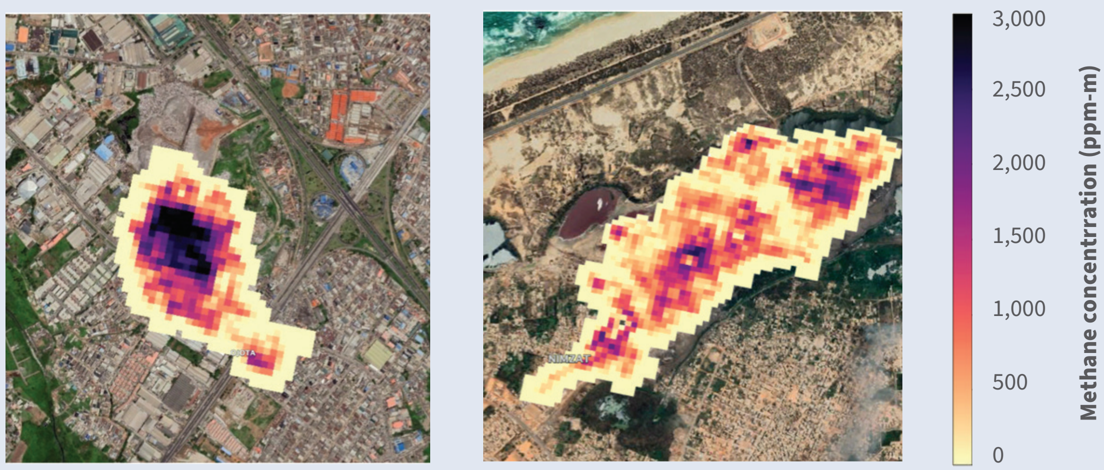
Source: Daniel H. Cusworth et al., "Using Remote Sensing to Detect, Validate, and Quantify Methane Emissions from California Solid Waste Operations," *Environmental Research Letters* 15 (5): 054012, 2020, **https://doi.org/10.1088/1748-9326/ab7b99**

Case Study: Large Emissions Quantified via Satellite at Unmanaged Dump Sites in Nigeria and Senegal

Accurately quantifying and understanding emissions from unmanaged dumping outside the United States remains difficult. Reliable data regarding waste mass and composition is mostly unavailable for model-based estimations. Furthermore, process models that do not explicitly consider inefficient or absent management practices may severely underestimate emissions. Dumping grounds can also be difficult to precisely geolocate due to their informal nature. Opportunistic PRISMA satellite acquisitions of the Olusosun dump site in Lagos, Nigeria, and the Mbeubuess dump site in Dakar, Senegal, detected large emissions (Exhibit 22). The emissions at each of these dump sites were in excess of 5,000 kg/h, higher than reported by any US landfill in the GHGRP. Currently, direct measurement of methane emissions from dump sites is limited by available measurement systems, technical capacity of local institutions, and concerns about personnel safety. Increasing satellite coverage over the next decade can help address parts of these quantification gaps.

Exhibit 22 **Methane Emissions from Landfills in Nigeria and Senegal Observed by the PRISMA Satellite**

Lagos, Nigeria **Dakar, Senegal**



Source: Cusworth et al., unpublished

6. Conclusion

Reducing MSW methane emissions is a crucial step in limiting global warming to 1.5°C by mid-century. Airborne surveys in California show that a small number of waste management facilities are responsible for a disproportionate amount of methane emissions.[99] Further study is needed to understand whether similar findings are observed outside California. Nonetheless, these initial findings suggest a major opportunity to realize significant reductions in sectoral methane emissions.

This report examined the current state of play for managing methane emissions from MSW. Our findings revealed that the waste sector is ripe for targeted action and can begin making deep cuts in MSW methane emissions today by implementing the strategies outlined below.

- **Prevent and reduce food waste** along the supply chain as a first step in managing MSW methane emissions.
- **Divert and process organic waste** via source separation and/or the deployment of organics recovery technologies to prevent decomposable waste from reaching landfills and dump sites, and to convert the diverted organics into beneficial end products.
- **Rehabilitate dump sites** to sanitary landfills that are equipped with LFG collection systems, leachate collection systems, and other environmental controls to capture methane emissions and improve public health and safety.
- **Implement recommended management practices in designing and operating landfills** to optimize the effectiveness of LFG capture systems and minimize methane release to the atmosphere.
- **Conduct comprehensive emissions monitoring at landfills and organics processing facilities** to detect anomalies in daily operations, enable timely repair of methane leaks, support proactive emissions avoidance, and validate implemented abatement strategies.

As a follow-on study, the authors of this report will expand airborne surveys across the United States and internationally. Further, the strategies outlined above will inform a roadmap and framework for rapidly deploying methane monitoring technology along with targeted analysis and tools to inform effective abatement strategies at the facility level. This will be done in partnership with landfill operators, advocacy groups, regulators, policymakers, and other key actors to align industry stakeholders on an effective, actionable, and scalable plan to achieve ambitious — and critical — climate goals in this decisive decade.

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