Olivia Alves

RMI & EDF submit the following attachments to the record alongside the public comment titled "RMI EDF Carb LMR Public Comment November 2025".

January 24, 2025

<u>VIA ELECTRONIC SUBMISSION & ELECTRONIC MAIL</u>
California Air Resources Board
Landfill Methane Regulation
LMR@arb.ca.gov

RE: Recommendations for Revisions to the Landfill Methane Regulation from Californians Against Waste, The Environmental Integrity Project, RMI and Industrious Labs.

To Whom It May Concern,

Californians Against Waste, The Environmental Integrity Project ("EIP"), RMI, and Industrious Labs ("Commenters") respectfully submit the following comments to the California Air Resources Board ("CARB") to facilitate and improve revisions to the Landfill Methane Regulation ("LMR")[1].

We hope that CARB will consider and include these recommendations in the anticipated LMR revisions. Specifically, we recommend that CARB:

- Better define certain terms in the 2010 LMR and include additional defined terms;
- Update and improve surface emission monitoring in several ways:
  - Reduce the surface methane concentration threshold;
  - Ensure monitoring occurs only during normal atmospheric pressure conditions;
  - Include the UAS OTM-51 method as an allowed alternative to SEM;requirements, subject to all appropriate limitations in EPA's ALT-150 Letter;
  - Include a specific process for approval of alternative test methods;
  - Require that SEM be conducted via drones or similar advanced monitoring technologies, and require that this monitoring occur biweekly instead of quarterly;
  - Improve walking pattern and other requirements when Method 21 walking SEM is used; and
  - Improve recordkeeping and reporting requirements.
- Require fenceline monitoring;
- Establish a super emitter response program;

[1] Cal. Code Regs. tit. 17§§ 95460-95476 (2010).

- Improve requirements for the gas collection and control system:
    - Address gas collection and control system downtime by treating 5 days of downtime as a violation;
    - Include improved requirements to address emissions from the active face;
    - Include requirements that would reduce the number of flooded wells;
    - Harmonize the revisions with federal requirements and include additional requirements;
    - Consider requiring remote wellhead tuning technologies; and
    - Require earlier installation of systems.
- Strengthen and streamline landfill cover requirements;
    - Set minimum standards for cover material, especially alternative daily cover; and
    - Consider biocovers in certain circumstances.
- Ban recirculation practices; and
- Require site-specific component leak monitoring and repair plans.

We are available to answer any questions and/or provide additional information as requested. We appreciate this opportunity to provide comments.

I. Background

A. Municipal solid waste landfills produce a significant amount of methane emissions

Municipal solid waste ("MSW") landfills are the third largest source of anthropogenic (human-caused) methane emissions in the United States. Methane is a powerful climate-altering greenhouse gas with about 80 times the global warming potential of carbon dioxide over a 20-year time period. [2] Landfills are estimated to be the third largest source of methane emissions in the U.S. in 2022.[3] However, emissions are likely even higher, where the Greenhouse Gas Reporting Program ("GHGRP") overestimates the performance of landfill gas capture systems and is not including large methane plumes captured in aerial surveys.[4]

[2] Intergovernmental Panel on Climate Change ("IPCC") *Climate Change 2021: The Physical Science Basis* 1017. (2021), https://report.ipcc.ch/ar6/wg1/IPCC_AR6_WGI_FullReport.pdf .
[3] EPA, *DRAFT Inventory of Greenhouse Gas Emissions and Sinks: 1990-2021* ES-13 (2024), https://www.epa.gov/system/files/documents/2024-02/us-ghg-inventory-2024-main-text.pdf
[4] *See* Revisions and Confidentiality Determinations for Data Elements Under the Greenhouse Gas Reporting Rule, 88 Fed. Reg. 32852, 32860, 32877-9 (proposed May 22, 2023) (to be codified at 40 C.F.R. pt. 98).

B. California landfills produce the second highest reported methane emissions in the country.

California ranks second in the nation for estimated methane emissions from MSW landfills. The waste sector is the second largest methane source in California.[5] California's municipal solid waste methane emissions in 2023 are estimated at about 22 million metrics tons of CO_2 equivalent[6]: about the same as 1.3 million passenger cars driven for a year In California.[7]

Communities of color are disproportionately impacted by health-harming air and water pollution. Landfill methane is also a precursor for tropospheric ozone and is co-emitted with hazardous air pollutants and volatile organic compounds (e.g., benzene, vinyl chloride) that harm public health.[8] The grave health impacts of landfills aren't felt proportionately. Of California's highest-emitting landfills (those that report estimated methane emissions higher than 500,000 tons of carbon dioxide equivalent, which are the top nine out of 300 active and closed landfills):

- 90% of the highest-emitting landfills are in communities with larger Black, Indigenous, or People of Color ("BIPOC") populations than the national average.
- 70% of the highest-emitting landfills are in communities where more than half the residents are BIPOC.[9]

Accordingly, California MSW landfills' emissions are not only producing dangerous, climate-altering methane emissions, but they're also negatively impacting surrounding communities' health.

1. Enhanced monitoring techniques and flyovers show that reported methane and NMOC emissions are likely higher

A recent study[10], published in the journal *Science*, led by Carbon Mapper scientists alongside researchers from NASA Jet Propulsion Laboratory, Arizona State University, University of Arizona, Scientific Aviation, and the U.S. Environmental Protection Agency ("EPA") (hereinafter "the 2024 Carbon Mapper study"), provides the largest comprehensive

[5] California Air Resources Board, *Potential Updates to the Landfill Methane Regulation*, Public Workshop (Dec. 18, 2024) at 7 *available at* https://ww2.arb.ca.gov/sites/default/files/2024-12/Staff_Presentation_on_Potential_Updates_to_the_Landfill_Methane_Regulation.pdf [hereinafter "CARB 2024 LMR Workshop"].

[6] Data from EPA Greenhouse Gas Reporting Program based on a 20-year global warming potential for methane.

[7] Calculated utilizing: U.S. EPA Greenhouse Gas Reporting Program (GHGRP) 2022; EPA, *Landfill Methane Outreach Program (LMOP)* (July 2023). EPA, *GHG Equivalency calculator*, *available at* https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator.

[8] EPA LMOP, *Frequent Questions about Landfill Gas*, https://www.epa.gov/lmop/frequent-questions-about-landfill-gas#whatcomponents (last visited Jan. 22, 2025).

[9] Statistics derived from CalEnviroScreen 4.0, https://oehha.ca.gov/calenviroscreen/report/calenviroscreen-40 (last visited April 2024). Landfill geographic points are derived from the EPA, Greenhouse Gas Reporting Program (GHGRP) 2022 and EPA, Landfill Methane Outreach Program (LMOP) (July 2023).

[10] Cusworth, D. et al., "Quantifying methane emissions from United States landfills," *Science* (March 28, 2024) *available at* https://www.science.org/doi/10.1126/science.adi7735

assessment of hundreds of U.S. landfills using direct observations through airborne surveys. The study reveals the outsized impact of landfill point source emissions, which are responsible for a disproportionately large share of pollution. The Carbon Mapper study also sheds light on potential gaps in traditional model-based emission accounting methods that may benefit from sustained direct measurement using emerging surface-, air-, and space-based monitoring technologies.

2. Key findings of the 2024 Carbon Mapper Study

Carbon Mapper et al. found that "evaluating this large data set yielded insights that site owners and operators, policymakers, regulators, and civil society can use to better assess and act on landfill emissions."[11] Fifty-two percent (52%) of surveyed landfills had observable point source emissions, which far exceeds the 0.2% to 1% detection rate observed for super-emitters from surveyed oil and gas infrastructure in California and the Permian Basin.[12] Generally, landfill point source emissions are more persistent compared to their counterparts in oil and gas production. For those landfills with observed emissions, 60% had emissions that persisted over months or years.[13] These persistent emissions totaled 87% of all quantified emissions in the study.[14] Comparatively, the majority of methane super-emitters in the oil and gas sector are related to irregular, short-duration events.[15]

The 2024 Carbon Mapper study also found significant gaps in landfill leak detection and quantification protocols. Advanced monitoring strategies, such as remote sensing from satellites, aircraft and drones can provide a more accurate picture of landfill methane emissions than walking surface emission monitoring ("SEM"). When combined with improved ground-based measurements, remote sensing can provide consistent, comprehensive measurements to better inform models, guide mitigation efforts and verify emission reductions.

Finally, the 2024 Carbon Mapper study also found little agreement with reported and quantified emissions at U.S. landfills, indicating that current methods used to report facility emissions, such as the EPA's GHGRP, are missing or misrepresenting large sources of methane.[16] On average, Carbon Mapper found that aerial emission rates were 1.4 times higher than GHGRP.[17].

[11] Carbon Mapper, *Study finds landfill point source emissions have an outsized impact and opportunity to tackle U.S. waste methane* (March 28, 2024), https://carbonmapper.org/articles/studyfinds-landfill [hereinafter "2024 Carbon Mapper News Release"].
[12] *Id*.
[13] *Id.*
[14] *Id.*
[15] *Id.*
[16] *Id*.
[17] *Id*.

3. CARB and Carbon Mapper 2023 Study

As detailed in the CARB Summary of 2020, 2021 and 2023 Airborne Methane Plume Mapping Studies,[18] CARB partnered with the University of Arizona, and in 2021 partnered with Carbon Mapper to conduct plume mapping flights over the state, resulting in the detection of 502 methane plumes from oil and gas and landfills.[19] CARB shared the findings with operators in the form of "incidence reports," and operators were asked to follow up and identify the source of emissions, if possible, and report their findings to CARB.[20] The report noted that operators were generally responsive, but that the response time was slow—particularly for landfills.[21] The report states, "Additional regulatory language could address operator response rate, response speed, and response quality as well as consider if there are additional sources that need to be covered."[22] CARB further states:

> Finally, there are co-benefits of using this technology to initiate leak repairs. In addition to methane, which is non-toxic, oil and gas developments and landfills are known to emit hazardous air pollutants (HAPs), which can cause acute and chronic health problems. Furthermore, exposure to these emissions is not equally shared by all people; indeed, disadvantaged communities often suffer from higher exposures to these co-emitted pollutants. Therefore, using this technology to initiate rapid repair of high-emitting sources can have a co-benefit of reducing pollutant exposure for affected communities.[23]

CARB already acknowledges the importance of plume mapping in detecting both HAP and methane emissions quicker. Therefore, the revisions to the LMR should include advanced technologies that identify earlier emission exceedances and also include more robust requirements that corrective action is required sooner.

C. Issues with current SEM requirements

Traditional surface-based surveys with handheld methane sensors provide an incomplete picture of emissions. SEM has several limitations, including, but not limited to[24]:

---

[18] CARB, *Summary Report of the 2020, 2021, and 2023 Airborne Methane Plume Mapping Studies* (April 2024), *available at* https://ww2.arb.ca.gov/sites/default/files/2024-04/2020-2021-2023%20Airborne%20Summary%20Report_FINAL.pdf [hereinafter "2024 CARB Summary Report"].

[19] *Id*. at 4.

[20] *Id*.

[21] *Id.*

[22] *Id*. at 24

[23] *Id*.

[24] The list below was identified in a 2024 EPA enforcement alert for MSW landfills. This alert reminds MSW landfill owners and operators of their Clean Air Act obligations and notes where EPA has found recurring compliance issues, leading to significant releases of methane and other air pollutants. EPA, *Enforcement Alert: EPA Finds MSW Landfills are Violating Monitoring and Maintenance Requirements* https://www.epa.gov/enforcement/enforcement-alert-epa-finds-msw-landfills-are-violating-monitoring-and-maintenance (last visited Nov. 21, 2024) [hereinafter "2024 EPA MSW Landfill Enforcement Alert"].

- Inspectors failing to follow the prescribed method for determining compliance with the surface methane standard, Method 21[25]:
    - Variations from prescribed methods (sampling time, sampling speed and instrument calibration);
    - Subjectivity (identification of areas of potential emissions outside of the prescribed path); and
    - Areas excluded from monitoring (improperly excluding areas from monitoring as "dangerous" and regular side slopes).[26]
- Sensitivity to environmental conditions (e.g. atmospheric pressure).

Furthermore, traditional SEM surveys are physically demanding with many miles of walking and potential hazards for technicians (e.g. terrain, weather conditions, and exposure risks). Due to these limitations, traditional SEM surveys miss methane leaks that could be mitigated, and there is often a disconnect between the results of walking surveys and those conducted with more advanced, automated monitoring methods or by federal or state enforcement personnel.

For example, aerial surveys conducted were able to detect significant methane plumes coming from the landfill's active working face ("active face" or "working face," which Commenters define as where the waste is being disposed on a regular basis, including both areas of the landfill with uncovered waste and areas of the landfill under daily cover), an area currently excluded from SEM due to safety concerns.[27] Surveys in the United States and Canada show active face emissions can represent 60-79% of total site emissions, meaning SEM effectiveness would top out at 21-40% of emissions.[28] In addition, Flux Lab commented on the detection performance of walking SEM relative to advanced detection technologies in recent controlled release experiments, noting that "through all of the SEMs we did, we only had one positive indication despite the fact that there were definitely a lot of leak sources active."[29] In his presentation in the 2024 CARB LMR Workshop, Dr. Risk attributed this to the wide spacing, lower resolution, lower sensitivity, and the human dimension of walking SEM, as described in **Figures 1 and 2** below:[30]

---

[25] This is a method for determination of VOC leaks from process equipment using a portable instrument to detect. EPA, *Method 21* (Aug. 3, 2017), https://www.epa.gov/sites/default/files/2017-08/documents/method_21.pdf (last visited November 21, 2024).

[26] *See* Scarpelli, Tia et al., "Investigating Major Sources of Methane Emissions at US Landfills," *Env't Science Tech.* (November 29, 2024), 58, 49, 21545–21556, *available at* https://doi.org/10.1021/acs.est.4c07572.

[27] *Id.*; Risk, Dave, "Advanced Leak Detection Technologies for Landfill Methane," (2024), at slide 18, *available at* https://ww2.arb.ca.gov/sites/default/files/2024-12/Session-2_FluxLab.pdf

[28] Risk, Dave, *Advanced Leak Detection Technologies for Landfill Methane* (December 18, 2024), 18, *available at* https://ww2.arb.ca.gov/sites/default/files/2024-12/Session-2_FluxLab.pdf

[29] Recording: Public Workshop on Potential Updates to the Landfill Methane Regulation, held by CARB (Dec. 18, 2024) at 1:52:00, https://www.youtube.com/watch?v=NCXHDOZIH44; *See Id.*

[30] Risk, Dave, *Advanced Leak Detection Technologies for Landfill Methane* (December 18, 2024), 18-19, *available at* https://ww2.arb.ca.gov/sites/default/files/2024-12/Session-2_FluxLab.pdf.

Figure 1: Walking SEM coverage findings from Dave Risk 2024 CARB LMR Presentation

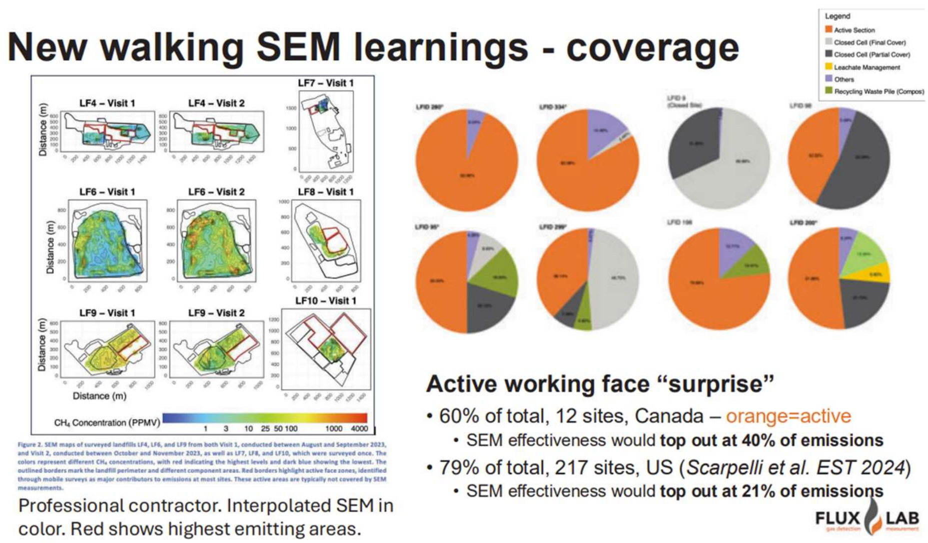
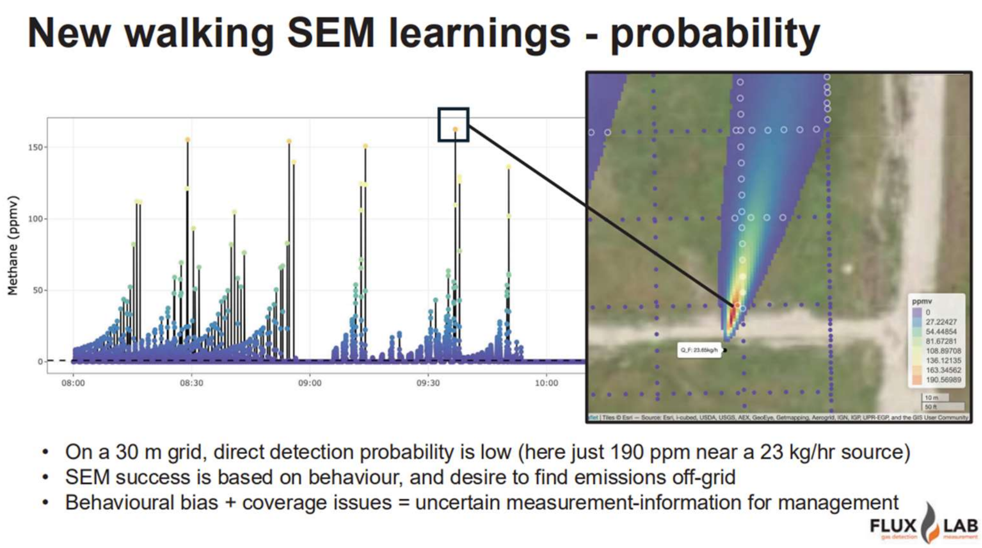


Figure 2: Walking SEM probability from Dave Risk 2024 CARB LMR Presentation



D. Developments in enhanced monitoring

Recent advances in methane monitoring technology — from satellites to aircraft to drones to fixed sensors — are transforming landfill operators’ ability to detect, locate, and reduce their emissions in real time. CARB acknowledged in the 2024 Workshop that they demonstrated the capability of airborne imaging technology to detect methane plumes and quickly pinpoint large emissions that supports timely mitigation on the ground.[31] There are now dozens of companies — often originating from the oil and gas sector — that provide equipment and/or

[31] CARB 2024 LMR Workshop at 10.

services for methane detection at landfills.[32] The presentation from Dave Risk of Flux Lab notes that at least 98 advanced leak detection technologies and methodologies exist.[33]

In recently released white papers published online, EPA includes a review of aerial technologies and approaches, identifying remote sensing[34] and direct sampling[35] as new technologies used to monitor landfill methane emissions. EPA also notes that satellite and aircraft remote sensing technologies can detect and quantify methane emissions quicker than direct sampling methods and spatial resolution of remote sensing highlights large point source emissions making them more visible.[36] EPA also notes that direct sampling (in-situ) methods are less susceptible to weather conditions like cloud cover and solar reflectance and can better capture point and diffuse area sources of methane, which gives a more accurate representation of overall methane emissions from a site.[37] EPA also published a white paper on unmanned aircraft system ("UAS") technologies that can be used to monitor surface methane emissions.[38] Finally, in another white paper, EPA also includes case studies and recommendations for how fenceline monitoring could be required at MSW landfills.[39] CARB should approach the LMR revisions by considering all of these enhanced monitoring options together—aerial monitoring, UAS, and fenceline monitoring—to better identify and quantify methane emissions from MSW landfills.

Moreover, as described above, imaging spectrometers on aircraft and satellites have surveyed hundreds of landfills across the United States, identifying and quantifying large emission events and prompting successful mitigation activities. Some landfill operators are also integrating near-ground advanced methane monitoring technologies into their operations, using drone surveys or rovers to monitor for areas of elevated methane concentration and inform leak repairs and operational decisions. SnifferDRONE already deploys its technology at more than 150 landfills, and the method has been approved by EPA as an alternative test method for

[32] *See See also* EPA, LMOP Webinar: Detecting Landfill Methane Emissions with Drones (Sept. 28, 2023), *available at* https://www.epa.gov/system/files/documents/2023-10/lmop_webinar_september_28_2023.pdf [hereinafter "LMOP Drone Webinar"].

[33] Risk, Dave, *Advanced Leak Detection Technologies for Landfill Methane* (Dec. 18, 2024), 20, *available at* https://ww2.arb.ca.gov/sites/default/files/2024-12/Session-2_FluxLab.pdf

[34] "Remote sensors measure reflected and scattered radiation from the Earth's surface to determine the concentration of methane (column-based concentration) without direct sampling of atmospheric gases. This category can be further divided into approaches that use remote sensors on 1) aircraft or 2) satellites." EPA, *White Paper Series: Municipal Solid Wate Landfills-Advancements in Technology and Operating* Practices, "Aerial Monitoring for Examining Landfill Methane Emissions" (October 2024), 2 [hereinafter "Aerial Monitoring White Paper"].

[35] "Aircraft are used to directly sample "in-situ" atmospheric gases and measure methane using an onboard sensor (e.g., cavity ring down spectrometer (CRDS)." *Id.* at 2.

[36] *Id.* at 6.

[37] *Id.* at 7.

[38] EPA, *White Paper Series: Municipal Solid Waste Landfills-Advancements in Technology and Operating Practices*, "Unmanned Aircraft Systems (UAS) Technologies for Landfill Methane Monitoring"(Dec. 2024) [hereinafter "UAS White Paper"].

[39] *See* EPA, *White Paper Series: Municipal Solid Waste Landfills – Advancements in Technology and Operating Practices*, "Fenceline Monitoring" (Dec. 2024) [hereinafter "Fenceline Monitoring White Paper"].

SEM.[40] In addition, fixed sensor systems positioned across the landfill surface or along the perimeter can provide methane concentration data continuously, helping operators address leaks in real time and evaluate emissions trends over time.[41]

Below, are several examples of how advanced monitoring technologies can provide timely, actionable data for leak detection and repair and to guide and assess best management practices. Relative to walking methods, these technologies can provide greater coverage of the landfill surface, improve worker safety and efficiency, provide more frequent data, and ensure objectivity and transparency.

- **Aerial and satellite remote sensing**: At Sunshine Canyon Landfill in California, aerial flyovers by Carbon Mapper detected large methane plumes from intermediate cover slopes during overpasses in 2016.[42] The landfill then updated its infrastructure and made several changes to the landfill cover and gas collection system to reduce landfill emissions.[43] Subsequent overpasses in 2017 observed a marked decrease in methane emissions (and concurrent increases in landfill gas ("LFG") collection), and these results were validated by fewer neighborhood odor complaints.[44] Through its 2020, 2021, and 2023 Airborne Methane Plume Mapping Studies, CARB documented other examples of successful voluntary leak repairs, prompted by aerial observational data.[45] Current and planned satellite constellations – such as MethaneSAT, GHGSat, and Carbon Mapper/Planet, have the capability to scan large areas and identify high-emission events at frequent cadences, such as days to weeks.[46] California allocated $100 million in funding to support a constellation of satellites that can monitor for large methane plumes to inform and verify fast mitigation.[47]
- **Drones and automated ground-based approaches**: In lieu of walking SEM, operators can use a drone-based alternative test method (OTM-51/ALT150) with a methane detection payload on a drone, coupled with a ground-level-to-drone sampling system. Sniffer Robotics is the only commercial provider that meets these requirements at this time. Drone-based systems can provide operators with more timely, comprehensive, and

[40] Letter from Steffan Johnson, EPA, Office of Air Quality Planning and Standards to David Barron, Sniffer Robotics, LLC (Dec. 15, 2022) at 8-9 *available at* https://www.epa.gov/system/files/documents/2022-12/Barron%20Sniffer%20Alt%20with%20OTM%2051%20attached_signed.pdf [hereinafter "OTM-51 Approval Letter"].
[41] *See* Fenceline Monitoring White Paper.
[42] *See also* Aerial Monitoring White Paper at 3-4.
[43] Earthdata, *From Cow Manure to Landfills: Mapping Methane in California,* https://www.earthdata.nasa.gov/news/feature-articles/from-cow-manure-landfills-mapping-methane-california (last ipdated Dec. 15, 2024).
[44] *Id.;* Ayandele, Ebun et al., RMI, *Key Strategies for Mitigating Methane Emissions from Municipal Solid Waste* (2022), *available at* https://rmi.org/insight/mitigating-methane-emissions-from-municipal-solid-waste/
[45] 2024 CARB Summary Report at 13-17; *See also* Aerial Monitoring White Paper at 3-4.
[46] *See also* Aerial Monitoring White Paper at 4-5.
[47] Press Release, CARB, California launces international methane-reduction iniative during climate week, (Sept. 20, 2023), *available at* https://ww2.arb.ca.gov/news/california-launches-international-methane-reduction-initiative-during-climate-week.

objective data to inform mitigation activities while keeping workers safe. Additionally, there are methane-detecting drone methods that sample at elevation, either through active imaging (e.g., open-path TDLAS Pergam sensors) or in-plume sensing (e.g., closed-path TDLAS by SeekOps or OA-ICOS by ABB). These drone methods can help identify leaks and inform operational decisions, such as where to expand the gas collection system or improve cover materials.[48] For example, San Bernardino County and Orange County conduct leak surveys with methane-detecting drones at their landfills.[49] Other landfills are automating leak detection with small rovers equipped with methane sensors that traverse the surface (e.g., Specialized Robotic Solutions, HATS Consoar).[50]

- **Continuous monitoring and real-time data**: There are several kinds of continuous monitors, from laser-based systems with reflectors (e.g., LongPath, Boreal Laser) to in-plume sensors (e.g., SOOFIE, Qube, Sensirion) to eddy covariance towers (e.g., Li-COR) that can measure methane across the landfill surface, downwind of the facility, or along the perimeter/fenceline. During the industry panel at EPA's Fall Technology Conference, WM, Republic Services, and GFL mentioned deployment of fixed sensors for high-frequency monitoring and to support odor management.[51] EPA's fenceline monitoring white paper includes a case study of Arbor Hills Landfill in Michigan, which as part of an agreement with the Michigan Department of Environment, Great Lakes & Energy ("EGLE") installed and operates six monitoring stations along the perimeter of its facility, equipped with sensors for methane, hydrogen sulfide, and meteorological instrumentation.[52] The sensor data is available to the public online.[53]
- **Automated well-tuning systems:** These automated systems can take continuous measurements of LFG composition, flow, temperature, pressure, and liquid levels and make automated adjustments to the gas collection and control system ("GCCS") to increase methane capture and reduce fugitive emissions[54] In addition, continuous wellhead data can alert operators to other mitigation opportunities, such as remediating an area of damaged cover or de-watering a flooded well. Gas capture data can then verify

[48] LMOP Drone Webinar.
[49] Patino, Vania, "Drones take flight to tackle methane leaks at Orange County landfill," *Spectrum News 1* (Nov. 12, 2024), *available at* https://spectrumnews1.com/ca/southern-california/public-safety/2; Shackleton, Olivia, "SCS Develops 5-year landfill operations contract for California county," *Waste Today* (July 16, 2019), *available at* https://www.wastetodaymagazine.com/news/scs-five-year-landfill-operations-contract-california/
[50] Mann, Shelley, "Specialized Robotic Solutions robot can monitor surface emissions at landfills," *Waste Today* (February 23, 2024), *available at* https://www.wastetodaymagazine.com/news/specialized-robotic-solutions-robot-can-monitor-surface-emissions-on-landfills/ this article mentions california deployment; STAR grant is using autonomous rovers for SEM at CA landfills. EPA, *Grantee Research Project Results: Integrating Measurements Across Platforms to Feasibly Assess Emissions and Mitigation of Methane and VOCs from Landfills* (last updated April 28, 2023), *available at* https://cfpub.epa.gov/ncer_abstracts/index.cfm/fuseaction/display.abstractDetail/abstract_id/11433/report/0
[51] EPA, "MSW Landfill Technology Workshop-Presentation 3: Industry panel, *Regulations.gov*, (Dec. 9, 2024) *available at* https://www.regulations.gov/document/EPA-HQ-OAR-2024-0453-0016
[52] EPA Fenceline Monitoring White Paper at 4-6.
[53] GFL Environmental "Arbor Hills Landfill Air Monitoring," *available at* https://arborhillsmonitoring.com/Home/Index (last visited Aug. 6, 2024); *See also* EPA Fenceline Monitoring White Paper at 4-6.
[54] EPA, White Paper Series: Municipal Solid Wate Landfills-Advancements in Technology and Operating Practices, "Increasing Landfill Gas Collection Rates" (Oct. 2024), 10 [hereinafter "GCCS White Paper"].

the efficacy of mitigation activities. Companies providing this technology currently include LoCI Controls and Apis Innovation. LoCI Controls deploys its real-time data and control solution at more than 65 landfills, including several landfills in California, both private and county-owned.[55] More than 75 landfills in the U.S. and Canada are actively using Apis Innovation's automated wellhead tuning technology.[56]

As discussed further below, OTM-51 is available for CARB to incorporate into its test methods and procedures in the LMR. CARB should also create a streamlined process for allowing other alternative methods that can demonstrate quality assurance and quality control with SEM requirements. Additionally, many operators already utilize the technology above, which is demonstrated to detect emissions at landfills and should also be considered for inclusion in the revised LMR. Finally, fenceline monitoring requirements, when paired with more advanced monitoring technologies and a super emitter response program ("SERP"), could also better enable operators and regulators to measure emissions from MSW landfills. Subsections in Section II below will specifically address how CARB could integrate enhanced monitoring into the revised LMR.

II. Revisions CARB should make to the LMR.

We urge CARB to continue leading the regulatory landscape for landfill methane in its upcoming revisions to the LMR. Commenters appreciate and support many of the proposed concepts presented by CARB in its 2024 Workshop. Additionally, CARB can and should revise the LMR to be stricter and more innovative through enhancing SEM requirements, creating fenceline monitoring requirements, establishing a SERP, improving gas collection and control system requirements, streamlining and strengthening landfill cover requirements, banning recirculation practices and requiring site-specific component leak monitoring and repair plans. Specifically, by strengthening SEM requirements, including a SERP and requiring fenceline monitoring, CARB would be innovating an overall monitoring program for the landfill sector that could serve as a regulatory model that could be adapted as technology evolves and more information is gathered. All these recommended revisions to the LMR are discussed in greater detail in the following sub sections.

A. CARB should better define certain terms.

CARB could make meaningful improvements that are a very low lift by simply defining certain terms. CARB should use the following definitions, and include these as defined terms in a revised LMR:

---

[55] Loci Methane Capture and Emission Reduction, "LoCI Controls Announces Methane Emission Reductions Across its Portfolio of Environmental Attribute Projects," (Dec. 5, 2024), *available at* https://locicontrols.com/loci-news/loci-controls-announces-methane-emission-reductions-across-its-portfolio-of-environmental-attribute-projects.
[56] *See* Apis, *MSW Landfill Technology Workshop-Presentation 10* (Dec. 9, 2024), *available at* https://www.regulations.gov/document/EPA-HQ-OAR-2024-0453-0018.

1. **Instantaneous measurement**: individual measurements of methane concentrations
2. **Zone-averaged measurement**: average concentration for each pre-determined zone area.
3. **Drone monitor**: unmanned aerial system carrying a methane detector capable of traversing the entire landfill with a detector sampling the surface.
4. **Penetration in cover**: wellhead, part of a gas collection or operation system, and/or any other object that passes through the landfill cover. Penetrations in the cover also include cracks or seeps that are not the result of an object passing through the cover. Examples of what is not a penetration for purposes of the LMR include but are not limited to: survey stakes, fencing including litter fences, flags, signs, utility posts, and trees so long as these items do not pass through the landfill cover.
5. **Leak (SEM):** any landfill surface or gas collection and control system component location where the measured methane concentration exceeds 200 ppmv using a hand-held methane detector; in the case of methane emissions measured as a path-integrated methane concentration, a location where the measured path-integrated concentration exceeds 200 ppm.

B. CARB should update SEM in several ways

As previously discussed, walking survey, grid pattern monitoring is insufficient to detect leaks. The White House National Strategy to Advance an Integrated U.S. Greenhouse Gas Measurement, Monitoring, and Information System, published in November 2023, states:

> [R]ecent airborne methane surveys suggest that emissions may be higher and more persistent than previously expected. Emissions of landfill gas to the air are determined in part by the design and operation of the gas collection and control system and the operational characteristics of the site. Factors such as flooded collection wells, cover integrity issues, planned maintenance activities, and equipment failures can result in elevated emissions compared to reported GHGRP estimates and can persist for extended periods of time. In many cases, the presence of preventable excess emissions that may require action cannot be known without some form of methane emissions measurement. Walking survey [SEM] required quarterly by Clean Air Act regulations are not able to detect all anomalous emissions at a landfill that occur over a large footprint, some extending for hundreds of acres.[57]

Additionally, as identified in the 2024 EPA Enforcement Alert, operators and their contractors are failing to comply with the SEM requirements in the federal Clean Air Act

[57] The White House, *National Strategy to Advance an Integrated U.S. Greenhouse Gas Measurement, Monitoring, and Information System* (Nov. 2023) at 50, https://www.whitehouse.gov/wp-content/uploads/2023/11/NationalGHGMMISStrategy-2023.

("CAA").[58] Specifically, EPA noted that "[r]ecent inspections also revealed widespread shortcomings in the SEM program at MSW landfills, including methane emissions at higher rates of exceedance, with many above 50,000 ppm, which is 100 times higher than the regulatory limit."[59] Issues such as monitoring speed and time, departing from the established path, expired calibration gas, and improperly excluding areas from monitoring were also documented by EPA.[60]

CARB can directly address these identified issues with SEM requirements in the revisions to the LMR by:

1. Reducing the SEM concentration threshold;
2. Requiring that SEM monitoring occurs only under normal atmospheric conditions;
3. Including the UAS OTM-51 method as an allowed alternative to SEM requirements, subject to all appropriate limitations in EPA's ALT-150 Letter[61];
4. Including a specific process for approval of alternative test methods;
5. Requiring that SEM be conducted via drones or similar advanced monitoring technologies, and require that this monitoring occur biweekly instead of quarterly;
6. Improving walking pattern and other requirements when Method 21 walking SEM is used; and
7. Improving recordkeeping and reporting requirements.

Each of these recommended improvements are discussed in further detail in the sections below.

1. Commenters support CARB's proposed concept to reduce the surface methane concentration threshold.

In its April 2023 proposed regulatory framework, Canada's regulatory agency, Environment and Climate Change Canada ("ECCC") proposed a 200 ppmv instantaneous surface emission threshold.[62] In 2009, CARB also proposed an instantaneous SEM standard of 200 ppmv.[63] Although ECCC did not propose the 200 ppmv standard in its draft regulations

[58] 40 C.F.R. §§63.1958(d), 63.1960(c)-(d). 2024 EPA MSW Landfill Enforcement Alert.
[59] *Id*.
[60] *Id*.
[61] OTM-51 Approval Letter. ALT-150 is approved as an alternative to requirements in 40 C.F.R. §§ 60.34f(d) and 60.36(c)-(e), which include the SEM operational standards and compliance provisions for monitoring following Method 21 performance evaluation requirements (in 40 C.F.R. § 60.36f(d)(3)). ALT-150 was approved by EPA on January 19, 2023. Recent Postings of Broadly Applicable Alternative Test Methods 88 Fed. Reg. 3408 (Jan. 19, 2023).
[62] ECCC, Reducing Canada's Landfill Methane Emissions: Proposed Regulatory Framework, Government of Canada, https://www.canada.ca/en/environment-climate-change/services/canadian-environmental-protection-actregistry/publications/reducing-landfill-methane-emissions.html [hereinafter "ECCC Proposed Regulatory Framework"].
[63] CARB, *Preliminary Concepts for Potential Improvements to Landfill Methane Regulation* (May 18, 2023) at 12, *available at* https://ww2.arb.ca.gov/sites/default/files/2023-05/LMR-workshop_05-18-2023.pdf.

issued in June 2024, ECCC did cite to the success of CARB's more than a decade long 25 ppmv integrated standard when discussing operators' concerns with this and the lower, 200 ppmv, SEM threshold.[64] As previously discussed, where ECCC initially considered proposing the standard that CARB considered previously, now is the time for CARB to reduce the 500 ppmv SEM threshold. Further, where CARB has found that landfills are already largely operating below 200 ppmv[65], it would be feasible to adjust the threshold below 500 ppmv to the originally contemplated 200 ppmv. We support CARB's proposed concept to reduce the threshold to 200 ppmv.[66] We also support the corrective action and re-monitoring timelines discussed.[67]

2. CARB should require that SEM occurs only under normal atmospheric conditions.

Higher methane emissions are directly associated with atmospheric conditions, like lower barometric pressure.[68] Studies conclude that "fluctuations in barometric pressure have a more pronounced correlation with landfill gas recovery than the absolute pressure values, highlighting the importance of changes in barometric pressure in determining LFG recovery efficiency."[69]

Accordingly, CARB should revise its SEM requirements to ensure that monitoring is conducted when atmospheric (also barometric) pressure is representative of normal site conditions[70]. Wellheads are operated with respect to atmospheric pressure. Therefore, short-term variability in the local pressure can impact the effectiveness of the GCCS, where the vacuum pressure is set monthly, and thus impacts surface emissions. Emissions decrease when atmospheric pressure rises and increase when the pressure falls.[71] Canada's ECCC cautions in

---

[64] "Several stakeholders, including landfill operators and engineering consultants, expressed concerns related to proposed surface methane concentration limits and monitoring requirements. Although a requirement to maintain surface methane concentrations below 500 ppmv has been in place at landfills regulated in Quebec since 2009, an additional concentration limit is included in the proposed Regulations requiring that a "zone-average" surface methane concentration (the average of surface methane concentration measurements in a zone of no more than 4 500 m2) must not exceed 25 ppmv. This "zone-average" concentration limit has been implemented under California regulations since 2010 and is intended to represent the achievable average methane concentration for an active landfill gas recovery system." Env't and Climate Change Can., *Regulations Respecting the Reduction in the Release of Methane (Waste Sector)* (June 29, 2024) *available at* https://canadagazette.gc.ca/rp-pr/p1/2024/2024-06-29/html/reg5-eng.html [hereinafter "ECCC Proposed Rules"].

[65] CARB, *Preliminary Concepts for Potential Improvements to Landfill Methane Regulation* (May 18, 2023) at 12, *available at* https://ww2.arb.ca.gov/sites/default/files/2023-05/LMR-workshop_05-18-2023.pdf

[66] CARB 2024 LMR Workshop at 32.

[67] *Id*. at 35-36.

[68] GCCS White Paper at 5.

[69] *Id*. at 6.

[70] Although current Clean Air Act requirements stipulate that "[m]onitoring must be performed during typical meteorological conditions," the LMR does not contain this requirement. 40 C.F.R. §§ 60.35f(c)(3), 60.765(c)(3). Moreover, the recommendations included in this section would require operators to document that SEM occurred during normal operating conditions.

[71] James L. Hanson & Nazli Yesiller, Cal. Polytechnic State Univ., *Estimation and Comparison of Methane, Nitrous Oxide, and Trace Volatile Organic Compound Emissions and Gas Collection System Efficiencies in California Landfills* 22 (2020), https://ww2.arb.ca.gov/sites/default/files/2020-06/CalPoly%20LFG%20Flux%20and%20Collection%20Efficiencies%203-30-2020.pdf; Liukang Xu, et. al., *Impact of Changes in Barometric Pressure on Landfill Methane Emission*, 28 Glob. Biogeochemical Cycles 679, 685 (2014), https://doi.org/10.1002/2013GB004571.

technical guidance that SEM should not be conducted "[i]f atmospheric pressure is rising sharply or is considerably higher than the average for the area."[72] Therefore, SEM conducted during periods of elevated atmospheric pressure would result in atypical measurements.

Thus, CARB should ensure that SEM is conducted when barometric pressure is within the range of average daily variation at the site. Landfill operators should be required to (1) submit information showing this range; and (2) record and report the barometric pressure at the site during each sampling event to demonstrate that it is within the required range.

3. CARB should include the OTM-51 Method as an allowed alternative to SEM requirements.

As previously explained, via letter dated December 15, 2022, which is classified by EPA as ALT-150, EPA approved the UAS-based alternative method for SEM as Other Test Method 51 on its Air Emission Management Center ("EMC") Website.[73] EPA's December 15, 2022 letter in part, provides that OTM-51 is an approved alternative method to meet federal requirements under 40 C.F.R. Parts 60, 61 and 63 subject to certain limitations.[74]

Through ALT-150, EPA approved OTM-51 as an alternative or modification to SEM procedures required under, in part, 40 C.F.R. Part 60, Subparts WWW[75], XXX[76], Cf[77]; 40 C.F.R. Part 63, Subpart AAAA[78]; and 40 C.F.R. Part 62, Subpart OOO.[79][80] Because of EPA's extensive record of reviewing numerous requests for alternatives and modifications to test methods and procedures, EPA identified that it is equitable and efficient to approve alternative test methods that are broadly applicable to a class, category or subcategory of sources.[81] Subsequently, in January 2023, EPA posted notice in the Federal Register of several of its alternative test method approvals: those issued between January 1, 2022 and December 31, 2022.[82]

Accordingly, CARB can and should incorporate UAS OTM-51 method, subject to all appropriate limitations and provisions explained in EPA's ALT-150 Letter, into the LMR revisions. By including this method, CARB makes clear that UAS-based monitoring is allowed

---

[72] Env't and Climate Change Can., *Estimating, Measuring and Monitoring Landfill Methane-Technical Guidance Document* 30 (last updated April 17, 2023), https://drive.google.com/file/d/1fqods0nXDSEUEmZu7nnkHZwXfGtemWPr/view?usp=sharing [hereinafter "ECCC Technical Guidance"].
[73] The EMC website linking to the Approved Alternative Test Methods also links to the same ALT-150 Approval Letter. *See* EPA, EMC-Broadly Applicable Approved Alternative Test Methods, https://www.epa.gov/emc/broadly-applicable-approved-alternative-test-methods (last visited Dec. 11, 2023).
[74] ALT-150 Approval Letter at 1.
[75] 40 C.F.R. §§ 60.753(d), 60.755(c)-(e).
[76] 40 C.F.R. §§ 60.763(d), 60.755(c)-(d).
[77] 40 C.F.R. §§ 60.34f(d), 60.36f(c).
[78] 40 C.F.R. §§ 63.1958(d), 63.1960(c)-(d).
[79] 40 C.F.R. §§ 62.16716(d), 62.16720.
[80] EPA, Recent Postings of Broadly Applicable Alternative Test Methods, 88 Fed. Reg. 3408, 3409 (Jan. 19, 2023).
[81] *Id*.
[82] 88. Fed. Reg. 3408, 3409.

as an alternative for performing SEM.[83] In its recently updated landfill methane regulations, the State of Washington was the first state to explicitly allow the option of using ALT-150 for SEM, and ECCC is also proposing that ALT-150 be allowed in its SEM requirements.[84] CARB should follow Washington and Canada's examples.

4. CARB should include a specific process for approval of alternative test methods.

As discussed, the technology for enhanced monitoring with advanced technologies is rapidly evolving. CARB can and should accommodate these advances in technologies by prescribing a clear path and process for operators and/or technology vendors to seek approval for alternative test methods in its revised LMR. As described above, there are many technologies and methods that provide better spatial and temporal coverage of the landfill surface relative to walking SEM. CARB should swiftly approve monitoring approaches that demonstrate equivalent or better performance in methane detection, similar to Colorado's Alternative AIMM Program for the oil and gas sector[85], and publish test methods that describe the operating parameters and action thresholds that can be used by all landfills.

In revisions to federal New Source Performance Standards ("NSPS") for the oil and gas sector, EPA includes alternative test methods for methane detection technology and the process for seeking approval and the requirements such request must follow.[86] CARB should include this same or a similar provision in the revised LMR that explicitly allows for alternative test methods and provides a process for seeking approval of the alternative method.

CARB could further improve upon the oil and gas NSPS alternative test method provision and process by shortening the timeframe for determining whether the alternative test method is adequate. The NSPS allows 270 days[87], and CARB could likely realistically approve or disapprove alternative test methods within 100 days.

---

[83] Operators in California would benefit from this clarity. In its ALT-150 Approval Letter, EPA states that "[f]or subpart Cf of 40 CFR 60, which is an Emission Guideline to be used by delegated state and local authorities to develop an individual State Plan, the availability or applicability of this alternative method must be determined on a case-by-case basis." ALT-150 Approval Letter at 8. By specifically including this method in the LMR revisions, CARB eliminates the confusion of "case-by-case basis" in seeking approval from EPA to use the alternative method.

[84] UAS White Paper at 4.

[85] Colorado Dep't of Public Health and Env't, *Approved Instrument Monitoring Method (AIMM) for oil and gas*, *available at* https://cdphe.colorado.gov/oil-and-gas-compliance-and-recordkeeping/approved-instrument-monitoring-method-aimm-for-oil-gas (last visited Jan. 20, 2025).

[86] 40 C.F.R. § 60.5398b(d).

[87] 40 C.F.R. § 60.5398b(d)(1)(iii).

5. CARB should require bi-weekly SEM monitoring using advanced monitoring technologies.

As previously highlighted, EPA found that many MSW landfill operators and their contractors are failing to properly follow Method 21 walking SEM requirements.[88] Additionally, cost is a barrier to conducting walking SEM more frequently than once per quarter. EPA estimated that the annual cost for conducting quarterly walking surveys at 25 foot intervals was approximately $80,000 (2012 dollars) per year per landfill.[89] But with advanced technologies, operators can cost-effectively and safely monitoring multiple times per month, as EPA noted in its Aerial Monitoring White Paper: "[i]f aerial technologies could be used as a replacement for, or as a tool to reduce the frequency of manual (ground-level) surface monitoring events, they could result in lower labor costs and increased efficiencies."[90]

Additionally, CARB noted in the 2024 Workshop that "[r]esearch shows seasonal variability/intermittency" and that "[c]ompliance inspections have found leaks in areas after several years of no reported leaks."[91] However, CARB's proposed concept remains focused on requiring quarterly SEM monitoring. Where walking SEM is both expensive and can frequently fail to adequately measure surface emissions, CARB should consider requiring that SEM monitoring be conducted via advanced technologies biweekly instead of quarterly and cover the entire landfill surface area.

a. Requiring SEM monitoring with advanced technologies is more cost effective, safer and allows operators to monitor more of the surface of than landfill than walking SEM.

Advanced technologies for detecting and quantifying methane are generally cheaper than manual methods used in walking SEM. Specifically, satellite, aircraft, drone, and mobile truck methods range $3,000 to $14,000 per survey[92], and fixed sensors that take continuous measurements cost between $7,000-$30,000 annually.[93] In addition to potential cost savings and performance improvements, these advanced monitoring technologies also enhance workplace

---

[88] 2024 EPA MSW Landfill Enforcement Alert.

[89] EPA, *Small Business Advocacy Review Outreach Briefing: MSW Landfill EG* (2015), slide 12, *available at* https://www.epa.gov/system/files/documents/2021-08/appendix-c-sbarpanel-landfills.pdf.

[90] "The current ground-based SEM is a labor-intensive process that requires personnel time and exposure to potentially hazardous conditions (e.g., slopes, inclement weather, animals, and pests). Using aerial technologies could reduce labor costs and reduce the hazards for personnel. The potential costs for using aerial technologies could be higher, at least initially, for landfill owners and operators purchasing access to aerial surveys; however, these costs could be offset if reductions in manual monitoring (i.e., Method 21) could be achieved as well as overall reduced costs (e.g., labor) while simultaneously reducing site methane emissions. Being able to rapidly detect methane emissions could allow for quicker responses to landfill methane leaks and ability to take remedial actions." Aerial Monitoring White Paper at 11.

[91] CARB 2024 LMR Workshop at 41.

[92] Flux Lab, *A Controlled Release Experiment for Investigating Methane Measurement Performance at Landfills-Final Report* (July 9, 2024) at 63-64, *available at* https://erefdn.org/product/a-controlled-release-experiment-for-investigating-methane-measurement-performance-at-landfills/ [hereinafter "2024 EREF Report"].

[93] *Id*.

safety while allowing landfill operators to monitor more of the surface of the landfill that are currently exempt from walking SEM, such as the active face and steep slopes. EPA also recognizes that using advanced technologies for SEM monitoring can increase operators' accessibility to real-time data that can be used to address onsite issues quickly and efficiently.[94]

CARB could immediately allow operators to conduct SEM monitoring with closed path drones using OTM-51 by including this method as an allowed alternative test method in the revised LMR. Additionally, creating an efficient process for approving alternative test methods would also allow operators to use other advanced technologies—like open path TDLAS or LiDAR, for example—to comply with the SEM monitoring requirements. In fact, ECCC is expected to finalize a method for using open path monitors in the near future[95] and other vendors and contractors are also actively exploring establishing test methods for their technologies.[96] CARB can and should include ALT-150 as a SEM procedure in Cal. Code Regs. tit. 17§ 95471(c). CARB can also create the process for approving alternative methods in this same section.

Although advanced monitoring technologies have known challenges,[97] walking SEM using Method 21 also has known challenges, cited by EPA in an enforcement alert. EPA notes that one of the major challenges faced by ECCC in finalizing a method for open path drone monitoring is the lack of available data sets for the technology and its use in measuring methane at landfills.[98] Because CARB is the leading innovator in the regulatory landscape for landfill methane regulation, this LMR revision process presents the perfect opportunity for CARB to continue to lead. CARB can and should communicate with ECCC and vendors on how they can finalize a downward-facing laser (open path) method. CARB is in a unique position to bridge the gap—both by explicitly allowing for an established method, ALT-150, and creating a process for approving alternative methods—and by continuing to create innovative requirements that reduce methane by working with ECCC, vendors and other stakeholders to develop methods for conducting SEM monitoring with advanced technologies.

Finally, CARB should also require that the bi-weekly SEM conducted with advanced technologies monitors all areas of landfill, including those exempted under current walking SEM requirements for "difficult to monitor" sections (such as steep slopes, stormwater drainage features, elevated infrastructure).

---

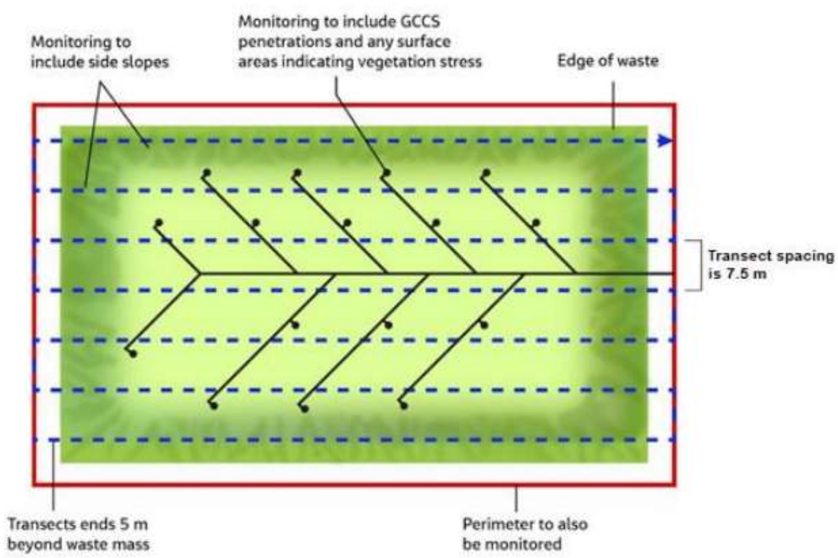
[94] UAS White Paper at 2.
[95] *Id.* at 4.
[96] *Id*.
[97] *See Id*. at 7-10.
[98] *Id*. at 10.

b. **CARB should require more frequent—bi-weekly instead of quarterly—SEM monitoring with advanced technologies.**

The federal CAA allows states to adopt alternative pollution standards or limitations and may also establish rules more stringent than the federal rules.[99] Therefore, in revising the LMR[100], CARB can require more frequent monitoring than the required quarterly SEM inspections in the federal standards.[101] Because several advanced technologies are demonstrated to be more cost effective than walking SEM and because these monitoring methods can survey more of the landfill, it is feasible for CARB to require that operators conduct SEM monitoring with advanced technologies bi-weekly (twice per month).

Additionally, CARB should require a scoping survey for SEM in addition to the existing requirement in the LMR that owners and operators to divide the entire landfill surface into individually identified zones of not more than 50,000 square feet and average path-integrated or surface methane concentrations calculated for each zone.[102] **Figure 3** below provides an example:

Figure 3: From ECCC Proposed Regulatory Framework: zone identification for walking SEM



The scoping survey should also require owners and operators to identify locations for drone set-up, pilot/observer base and take-offs and landings, potential obstructions (including overheard wires).[103]

[99] 42 U.S.C. § 7416.
[100] Which will be CARB's Section 111 plan to implement the federal Emission Guidelines.
[101] *See* 40 C.F.R. §§ 60.763(d), 60.764(a)(6); *see* 40 C.F.R. §§ 60.34f(d), 60.34f(a)(6).
[102] Cal. Code Regs. tit. 17 § 95471(c)(1). *See also* ECCC Proposed Regulatory Framework.
[103] ECCC Proposed Regulatory Framework.

Finally, for all SEM monitoring, CARB should require that for alternative methods approved in the future, the following criteria must be met:

1. **SEM should be conducted over more of the landfill**, including penetrations in cover and areas exhibiting potential stressed vegetation and visible cracks and ensuring that "difficult to monitor" areas are not being improperly excluded.
2. **If using an open-path drone-based measurement, CARB should require the development of monitoring plans that CARB must approve:** these monitoring plans should include:
   a. An upwind sampling location to measure background methane concentrations.
   b. Requiring drone surveys to be conducted at a moderate flight speed (not to exceed 4m/s), which is included in ALT-150.
   c. Require drones to be maintained at a consistent height above the ground using automated terrain. The height selected for the survey will be based on the methane detector specifications and site features, but should be as low to the ground surface as possible while still operating the drone safely, and with no downwash effects from the drone rotors.[104]
   d. Following ALT 150/OTM-51, drone operators must continuously monitor concentration readings from the methane detector on the drone
   e. Following ALT 150/OTM-51, provide for visual observation methods
      i. Use drone onboard camera
      ii. Operator must record instances of stressed vegetation, damaged landfill infrastructure or other indicators of methane emission.
      iii. The GPS coordinates and description of these conditions must be recorded.
      iv. These recorded areas should be monitored within the current SEM survey by temporarily deviating from the planned flight path.
3. SEM surveys must be conducted when GCCS is operating under normal meteorological conditions.
4. SEM surveys shall not be conducted when atmospheric pressure is rising sharply or considerably higher than the average for the area and shall be conducted under normal atmospheric pressure.
5. At the time of a drone-based SEM survey, operators should use a stationary anemometer or portable anemometer mounted on the drone to continuously collect and record wind speed (average and instantaneous) and record at 5-minute intervals.
6. SEM surveys must collect meteorological data, including atmospheric pressure, ambient temperature, weather conditions, date and time.
7. SEM surveys must collect monitoring data including the following information:
   a. Methane concentration in ppmv, recorded at 1 second intervals.
   b. Time stamped GPS coordinates at each sample location.

[104] ECCC Technical Guidance at 37.

c. Photographs of areas where elevated methane concentrations were measured.

6. Commenters support CARB's proposed concept to address landfills with a specified number of SEM exceedances.

In their December 2024 Workshop, CARB proposed a concept that when a landfill has greater than a specified number of SEM exceedances (e.g. ten (10) instantaneous or five (5) integrated exceedances during a three-year period), the operator would need to: increase monitoring frequency, perform cover integrity and collection system analyses and remediate issues discovered. Commenters support this approach.[105] However, we'd also urge CARB should consider persistent recurring SEM exceedances on an annual basis, as opposed to the three-year period presented. Because commenters are urging bi-weekly monitoring frequency as the SEM requirement, we would request that CARB require weekly monitoring for six (6) months for the "persistent emissions" standard.[106]

For the cover integrity analysis, CARB should require that operators conduct weekly cover integrity monitoring for six (6) months for landfills with a certain number of SEM exceedances within a year. In its recent enforcement alert, one of the compliance issues EPA noted was MSW landfill operators' failure to maintain adequate landfill cover integrity.[107] Therefore, it will be even more important that CARB requires more frequent monitoring of cover integrity when a landfill has a certain number of SEM exceedances in a year. Commenters plan to provide more detailed information at a later date to outline how landfills could have a more rigorous program to identify and correct cover integrity problems.

7. CARB should continue to require Method 21 measurements to verify detected exceedances and also include improvements to those procedures.

Although CARB should revise the LMR in Cal. Code Regs. tit. 17§ 95471 to include ALT-150 and allow for the use of advanced monitoring technologies, the Method 21 requirements under §95471(c) should still be included and strengthened. Specifically, CARB should revise the LMR to require Method 21 be used to verify detected exceedances with the enhanced monitoring technologies. Subsections (1), (2) and (3) in §95471(c) could also include additional requirements to ensure that the follow-up walking SEM inspections are performed correctly.

a. Where operators use walking SEM, CARB should improve walking pattern monitoring requirements.

SEM walking surveys consist of traversing the landfill surface following a pre-determined route, using a portable detector to measure methane concentrations immediately

---

[105] CARB 2024 LMR Workshop at 56.
[106] *Id.* at 57.
[107] 2024 EPA MSW Landfill Enforcement Alert.

above the ground surface. SEM walking surveys are helpful in identifying areas of fugitive emissions emanating through the landfill cover system from penetrations or fissures, leaks from the GCCS or leaks from other landfill infrastructure. However, as discussed above, the walking SEM requirements can be further improved to better quantify the methane concentrations on the surface of MSW landfills in California. The recommendations below highlight specific ways CARB can strengthen the walking SEM requirements.

First, CARB should decrease the spacing interval of the walking pattern to less than twenty-five (25) feet and include a walking speed (e.g. one meter per second (1 m/s)). By decreasing the pattern and specifying a walking speed, CARB could address deficiencies noted by EPA in their recent enforcement alert (e.g. if the pace on the serpentine path is too fast, the equipment will not have adequate time to identify an elevated concentration).[108]

Additionally, CARB's revisions should also account for inspectors not properly following Method 21 by reinforcing those requirements with additional recordkeeping requirements, as discussed more in Section II.B.6 below. CARB should also strengthen the requirements by requiring that the sampling inlet should be no more than five (5) centimeters from the surface.[109]

6. Improve recordkeeping, reporting and auditing requirements

First, Commenters support CARB's proposed concepts for applicability, reporting and other miscellaneous items that would require digital maps of infrastructure and monitoring results.[110] Commenters also support CARB's concept of determining the full extent of surface leaks.[111]

Additionally, CARB can further improve SEM by requiring more detailed and robust recordkeeping, reporting, and auditing requirements. These recommendations include:

- **All SEM monitoring readings must be reported and recorded:** Any reading exceeding the applicable limit must be recorded and reported as an exceedance. Operators must report all PPM readings with GPS location, and get approval from CARB for any deviation/excluded areas from the required walking path. The owner or operator must record the date, location, and value of each reading, along with retest dates and results if applicable. The location of each reading must be clearly marked and identified on the digital map, drawn to scale, with the location of both the monitoring grids and the gas collection system clearly identified.
- **Operators must submit a SEM report**: Any owner or operator who conducts SEM must include the following information in the annual report: date(s) of monitoring; location of the monitoring grid coordinates and of each reading, as well as coordinates of

[108] 2024 EPA MSW Landfill Enforcement Alert.
[109] ECCC Proposed Regulatory Framework.
[110] CARB 2024 LMR Workshop at 17.
[111] *Id*. at 38-40.

areas exempted from monitoring on a topographic map; measured concentration of methane in ppmv for each reading, exceedances, and all corrective actions taken.

- **For measurements performed with advanced technologies, must maintain records of**:
    a. Five (5) minute-interval anemometer readings
    b. Collected meteorological data
    c. Survey showing flight transects with path-integrated or surface concentration results and identifying results by concentration range or locations where concentrations exceed any applicable regulatory or action threshold
    d. Description of potential sources or causes of fugitive emissions at locations of elevated methane concentrations (e.g. leaking GCCS infrastructure, cover penetrations)
    e. Equipment calibration records.

Finally, CARB can further strengthen SEM and reduce methane emissions by improving the annual report requirements, which should include:

- records of all instantaneous surface readings of 100 ppmv or greater;
- all exceedances of the limits, including the location of the leak (or affected grid cell), leak concentration in ppmv, date and time of measurement, the action taken to repair the leak, date of repair, any required re-monitoring and the re-monitored concentration in ppmv, and wind speed during surface sampling; and
- the installation date and location of each well installed as part of a gas collection system expansion"

CARB should also require that the landfill owner or operator conducting SEM must submit an Instantaneous Surface Monitoring Report within thirty (30) days after the SEM monitoring survey and make this report available to the public.

C. CARB should require fenceline monitoring.

In the past several years, EPA finalized fenceline monitoring requirements for the refinery[112], chemical manufacturing[113], coke oven[114] and integrated iron and steel sectors[115]. EPA

[112] National Emission Standards for Hazardous Air Pollutants: Petroleum Refinery Sector, 85 Fed. Reg. 6064 (Feb. 4, 2020) (codified at 40 C.F.R. § 63.658).
[113] New Source Performance Standards for the Synthetic Organic Chemical Manufacturing Industry and National Emission Standards for Hazardous Air Pollutants for the Synthetic Organic Chemical Manufacturing Industry and Group I & II Polymers and Resins Industry, 89 Fed. Reg. 42932 (May 16, 2024) (codified at 40 C.F.R. pt. 63, Subpart F).
[114] National Emission Standards for Hazardous Air Pollutants for Coke Ovens: Pushing, Quenching, and Battery Stacks, and Coke Oven Batteries; Residual Risk and Technology Review, and Periodic Technology Review, 89 Fed. Reg. 55684 (July 5, 2024) (codified at 40 C.F.R. § 63.314).
[115] National Emission Standards for Hazardous Air Pollutants for Coke Ovens: Pushing, Quenching, and Battery Stacks, and Coke Oven Batteries; Residual Risk and Technology Review, and Periodic Technology Review, 89 Fed. Reg. 23294 (April 3, 2024) (codified at 40 C.F.R. § 63.7792).

promulgated these fenceline monitoring requirements and associated work practice requirements to mitigate fugitive emissions and other difficult-to-monitor sources, e.g. equipment leaks.[116] EPA collected several years of data since the refinery sector's fenceline monitoring requirements went into effect, and fenceline concentrations dropped by an average of 30 percent.[117]

Although landfills and the refinery sectors are different, because of the large footprint of a landfill and variability in emissions, requiring fenceline monitoring—alongside more robust SEM monitoring and a SERP—could indicate when, and generally, where, there are elevated emissions at landfills.[118] In fact, state agencies required fenceline monitoring in consent decrees for landfills.[119] Instead of placing monitors around the entire perimeter of the landfill, monitors are placed at strategic locations on the landfill perimeter—close to both the active face and surrounding communities (where applicable).[120]

CARB should also require fenceline monitoring in the revised LMR, focusing on placing monitors strategically around known and suspected points of fugitive emissions, especially near impacted communities. CARB can look to the flyover study and associated modeling conducted by the Michigan EGLE and other agencies to determine the number of monitors needed.[121] CARB should establish an action level for methane and other hazardous air pollutants that triggers root cause analysis and corrective action by the operator. Because methane could be produced by nearby sources—such as farms, wetlands, composting facilities—CARB should allow sources to submit site-specific monitoring plans that include site-specific modeling that assesses the particular landfills' fugitive methane emissions.[122] However, CARB should conduct robust oversight of these site-specific monitoring plans to ensure that they adequately address fugitive emissions from each particular landfill.[123]

Additionally, CARB should require that all data is posted publicly and expeditiously. At landfills in both Michigan and North Carolina, after years of odor complaints and due to other compliance issues, the state agencies required fenceline monitoring and that the results be posted publicly, also requiring robust community engagement.[124] Although the North Carolina landfill

---

[116] Fenceline Monitoring White Paper at 1.
[117] *Id*. at 2.
[118] *Id.*
[119] *Id*. at 3.
[120] *Id*.
[121] *Id*. at 4.
[122] *Id*. at 8.
[123] In September of 2024, EPA's Office of Inspector General ("OIG") conducted an audit of the oversight of the benzene fenceline monitoring requirements for refineries. Env't Prot Agency, Office of Inspector General, *Oversight to Ensure that All Refineries Comply with the Benzene Fenceline Monitoring Regulations*, Report No. 23-P-0030 (Sept. 6, 2023), https://www.epaoig.gov/sites/default/files/reports/2023-09/_epaoig_20230906-23-p-0030_errata.pdf (last visited Sept. 19, 2023). The report included a finding that site-specific monitoring plans did not include required monitoring needed to verify offsite source contributions to fenceline benzene levels. *Id*. As a result, EPA-approved site-specific monitoring plans for refineries relied solely upon modeling that likely overestimates near-field source emissions, resulting in unwarranted downward adjustment to the delta c value. *Id*. CARB should note this OIG report and avoid these and similar issues when approving site-specific monitoring plans.
[124] Fenceline Monitoring White Paper at 6-7.

fenceline monitoring requirement is new (consent decree was signed in August of 2024), EGLE notes that odors from the Michigan landfill (though complaints are still received) are reduced.[125]

D. Commenters support CARB's potential update to the LMR that would establish a SERP, leveraging advances in emissions monitoring technologies to quickly pinpoint large methane sources and mitigate leaks.

First, Commenters appreciate and support CARB's proposed concept to adopt a satellite alert and response provision similar to that required for the oil and gas sector in the LMR. CARB posed the following question in the December 2024 workshop:

- Should the technology approval criteria be the same for landfills as for oil and gas?
- Should the notification contents (estimated plume origin, image, etc.) be the same for landfills as for oil and gas?
- What operator response timelines are practical for landfills?
- Are additional steps needed in the process?
- What monitoring area around the plume origin makes sense for the LMR?
- What, if any, activities should be exempt from operator monitoring?[126]

Commenters will address the third, fourth and sixth questions specifically below and also provide additional feedback and recommendations.

First, Canada's ECCC included in its proposed regulatory framework methane leak detection and corrective action requirements that may be required when a third-party measures methane emissions exceeding a specific threshold, e.g. 100 kg/hr and that detection has been published or report to the ECCC.[127] However, ECCC did not include this program in their proposed regulations. Therefore, it is prudent that CARB continues to be the leading regulatory agency by establishing a similar satellite alert and response provision like that required for the oil and gas sector.

First, addressing CARB's question of additional steps needed in the process, CARB should explicitly allow any third party—whether aerial monitoring or through community monitoring—to be considered. CARB may provide for what demonstrations those third parties must make to satisfy the requirements, but CARB should specifically allow for third parties other than satellites be considered.

[125] *Id.*
[126] CARB 2024 LMR Workshop at 23.
[127] ECCC Proposed Rules. Although ECCC did not include in its proposed regulations noticed in June of this year, CARB, as the leading innovator in landfill methane regulation, should instead look to the regulatory framework in revising its LMR.

Canada's proposed framework and the satellite alert and response provision for the oil and gas sector that CARB is considering to also include in the LMR are similar to EPA's SERP for the oil and gas sector. In the final oil and gas rule, EPA describes the SERP as a "backstop to address large methane super emitters," designed for the EPA to receive data submitted by EPA-certified third parties using EPA-approved remote sensing technologies.[128] This SERP is "designed to provide a transparent, reliable and efficient mechanism by which the EPA will provide owners and operators with timely notification of super emitter emissions," allowing the owner or operator to take action in response.[129] EPA's oil and gas SERP certification process could also provide a roadmap to CARB for specifically allowing for third-party measurements other than satellites, as outlined in more detail in the bulleted list below.

Second, we address CARB's last question that none of the areas of the landfill should be exempt from a SERP.

Third, CARB's plan to use data from Carbon Mapper satellites and to purchase additional data coverage (for a "constellation") to conduct its own monitoring and mitigation program of "select high priority areas of interest in California" is promising.[130] CARB's intention to detect methane plumes that can be traced to a specific source and operator and enable rapid mitigation is clear.[131] CARB's planned satellite constellation is innovative and certainly will fulfil its goals of serving a as a model for other states and for EPA.[132]

Fourth, addressing CARB's question about response timelines that are practical, CARB could look to the response timelines for the Arbor Hills landfill fenceline monitoring program.[133] There, the operator is required to correct exceedances within forty-eight (48) hours of detection.[134] Such a timeline would be feasible for expected leaks. Relatedly, CARB's proposed concept of a digital map would bolster the effectiveness of a SERP. Publicly available digital maps would provide information about locations of infrastructure on the landfill. This would better enable operators and third parties detecting plumes to identify likely sources and could also expedite the timeline for response, even for unexpected leaks.

Finally, CARB should consider the following parameters for its SERP:

[128] Standards of Performance for New, Reconstructed, and Modified Sources and Emissions Guidelines for Existing Sources: Oil and Natural Gas Sector Climate Review, 89 Fed. Reg. 16820, 16877 (March 8, 2024)
[129] *Id.*
[130] 2024 CARB Summary Report at 23
[131] *Id*. at 24-25.
[132] *Id.* at 25.
[133] *See* Consent Decree, *Michigan Dep't of Env't, Great Lakes and Energy v. Arbor Hills Landfill, Inc.,* No. 2020-0593-CE, https://www.michigan.gov/-/media/Project/Websites/egle/Documents/Multi-Division/Arbor-Hills/2022-03-07-arbor-hills-consent-judgment.pdf?rev=34c46355d78e4eb1b2af14c9594c42b8 [hereinafter "Arbor hills Consent Decree"].
[134] *Id*. at 23-24.

- The landfill owner or operator must conduct surface emissions monitoring at the identified location and conduct mitigation activities when notified that a super emitter event has been detected by the landfill owner or operator or by a qualified third-party.
- "Super emitter event" means emissions of 100 kilograms (220.5 pounds) of methane per hour or larger.
- A qualification process for third-party notifiers.
- Pre-qualification requirements for third-party notifiers including:
    - Automatic approval for EPA-approved third-party monitors
    - A publicly available checklist of requirements for pre-qualification.
        - The checklist should clearly explain what would render third-party monitoring data invalid (e.g., monitoring results obtained while trespassing)
    - Third-party notifiers should be able to apply and demonstrate their technical expertise in the specific technologies and methodologies
    - Third-party notifiers should create a monitoring plan approved by CARB.

CARB should also require that notification to operators also be copied to CARB and the relevant local air quality management districts (air districts) and local enforcement agencies ("LEAs") to help ensure that the correct contact person/facility has been notified. Including air districts and LEAs in the notification process will enhance transparency, improve response times, and facilitate a unified approach to addressing emissions that may have regional impacts.

E. CARB should improve requirements for gas collection and control systems.

As discussed in EPA's Increasing Landfill Gas Collection Rates White Paper, several factors affect whether a GCCS is operating properly. Gas collection wells can be damaged from construction, the temperature of in-situ waste and from liquid in the wells.[135] EPA further notes that it is crucial to address the management of both gas and liquids in landfills in terms of GCCS performance.[136] Finally, atmospheric conditions and fluctuations also affect well performance.[137]

Accordingly, CARB should revise the LMR to address flooded wells and system downtime. Additionally, CARB should investigate remote wellhead tuning technologies that can dynamically adjust system parameters of the GCCS. CARB should also require earlier installation of a GCCS. Commenters also support various proposed concepts from the 2024 Workshop.

[135] GCCS White Paper at 5.
[136] *Id*.
[137] *Id*.

1. Commenters support CARB's proposed concept to require continuous monitoring of the system vacuum.

Commenters support CARB's proposal to require continuous monitoring of system vacuum and reporting when it deviates from the typical range.[138] Current regulations require continuous monitoring (flare temperature and gas flow rate) to ensure control devices are operated within the parameter ranges established during source testing — but there is no analogous monitoring for the collection system. Pressure sensors are low cost and can help monitor GCCS system uptime and performance. Further, CARB could consider requiring cloud-connected pressure sensors and flow meters on each wellhead, not just at the header, allowing operators and regulators to know if individual wells are offline or not sufficiently collecting.

2. Commenters support CARB addressing GCCS system downtime.

Commenters support CARB's proposed concept to reduce duration and emissions impact of GCCS downtime by requiring best practices such as:

- Reconnecting wells to vacuum at the end of each work day;
- Specifying mitigation measures for component downtime longer than a specified period;
- Limiting the number of wells that can be disconnected at once; and
- Limiting the size of the working face/construction area[139]

Commenters will likely provide more detailed comments on this topic in the future. However, as an initial matter, CARB should approach GCCS system downtime by establishing that a certain number of days—e.g. five (5) days of downtime[140]—constitutes a violation. CARB should also limit the active/working face and construction areas of the landfill as discussed in subsections below.

Commenters also remind CARB that the final LMR revisions should comply with the EPA's policy for startup, shutdown, and malfunction events and EPA has applied this policy to operation of the GCCS.[141]

---

[138] CARB 2024 LMR Workshop at 54.
[139] *Id.* at 51.
[140] Michigan's active gas collection and control system requirements require that "[t]he active gas collection and control system shall not be inoperable or unable to maintain a vacuum required by subdivision (e) for more than 5 consecutive days." Mich. Comp. Laws Ann. § 324.11512b(2)(B)(k).
[141] EPA, National Emission Standards for Hazardous Air Pollutants: Municipal Solid Waste Landfills Residual Risk and Technology Review, 85 Fed. Reg. 17244, 17252-17253 (March 26, 2020).

a. CARB should include improved requirements to address emissions from the active face.

As EPA confirmed in their "Improvements to Working Face and Daily Cover to Reduce LFG Emissions" white paper, methane emissions predominantly originate from the working face or areas with intermediate cover that do not have active gas collection wells.[142] Waste beneath freshly placed waste and adjacent to the working face produces the greatest emissions.[143] CARB can address this issue, in part, by following our recommendations that the GCCS be installed earlier. CARB should also consider the following additional recommendations that could reduce emissions from the active face.

i. Minimize the size of the active face.

Minimizing the active face would not only reduce methane emissions, but also provide operational benefits to landfills.[144] However, because the size of the working face depends on operational practices—e.g. waste delivery schedules, equipment capabilities and site layout—CARB should approach this requirement by defining acceptable active face sizes relative to the volume of incoming waste and requiring operational plans to be implemented by the operator that are tailored to the landfill's specific situation. For example, British Columbia limits the size of the working face relative to the incoming annual tonnage of waste.[145]

ii. Require operators to prepare an active face operation plan.

Additionally, CARB should require that landfills prepare an operational plan for the active face, that includes plans that the landfill will install horizontal gas collection trenches[146] below the active face.[147] The operational plan should also include adjacent gas collection wells near the active face to partially mitigate emissions.[148]

---

[142] EPA, *White Paper Series: Municipal Solid Wate Landfills-Advancements in Technology and Operating* Practices, "Improvements to Working Face and Daily Cover to Reduce LFG Emissions" (October 2024), 1 [hereinafter "Work Face and Daily Cover White Paper"].
[143] *Id*. at 3.
[144] *Id*. at 6.
[145] British Columbia Ministry of Environment, *Landfill Criteria for Municipal Solid Waste,* Second Ed. (June 2016) App. A at 57, *available at* https://www2.gov.bc.ca/assets/gov/environment/waste-management/garbage/landfill_criteria.pdf.
[146] "Horizontal collectors can be placed in active landfill sections and may not significantly interfere with landfill operations compared to vertical wells, as they are installed at or beneath the surface of a waste layer. Unlike vertical wells, horizontal collectors can be installed using standard earthmoving equipment instead of specialized drilling rigs. Horizontal collectors often serve as a temporary solution to begin gas collection from newly filled landfill sections, sometimes while additional waste placement is still underway. For optimal performance, it is necessary to cover these collectors with adequate waste to prevent air from entering from the collection system through the surface. The placement, frequency, and length of horizontal collectors are usually site-specific." Work Face and Daily Cover White Paper at 7.
[147] *Id*. The idea of a comprehensive Operations Plan is also discussed in a book written by a landfill operations expert. Timothy Townsend et al., *Sustainable Practices for Landfill Design and Operation* 347-359 (2015).
[148] Work Face and Daily Cover White Paper at 7.

In addition to including the horizontal trenches and adjacent gas collection well measures in the operation plan, CARB should specifically outline requirements to reduce active face emissions, including the requirement that operators develop this plan relative to the volume of incoming waste. CARB should require that the plan include these specific items and be designed to control methane and minimize flooding by:

- Digging the trench to 1.5 to 5 feet deep into the waste;
- Minimize flooding by:
    - Trench design:
        - Plan to place trenches in areas that are not saturated and/or low lying;
        - Plan to place trenches so that the landfill leachate system can efficiently remove liquids from the waste and prevent blockages in the GCCS.
        - with a central low point; or
        - with the trench sloping towards the landfill outer slope.
    - Install stone sumps or drains at low points; or
    - Using a gravel backfill to enhance drainage and ensure contact with waste.[149]

CARB should also consider allowing operators to include in its operation plan measures in addition to horizontal collection, provided that the operator can demonstrate that these measures would reduce methane emissions. Commenters plan to provide more detailed information on this in the future.

Finally, in addition to including horizontal trenches and tuning vertical gas collection wells adjacent to the active face, CARB should also require that these requirements be addressed in the GCCS Design Plan.[150]

b. Require monitoring of the active face.

In order to assure that minimizing the active face and requiring horizontal gas collection systems controls methane emissions as intended, CARB would need to require some type of monitoring of the active face. Utilizing advanced technologies, such as methane concentration sensors, drones[151] or aerial monitoring, or a combination thereof and including a monitoring plan for the active face in the active face operation plan would be the most practical way for CARB to require this monitoring.

For fixed methane sensors, CARB could continue to innovate by exploring a method for this active face methane concentration monitoring. The method would prescribe the distance at

---

[149] *Id*. at 8.
[150] Cal. Code Regs. tit. 17 § 95464(1).
[151] For example, in the Arbor Hills Landfill Consent Decree, the operator is required to use drones to conduct SEM over the working face of the landfill. Arbor Hills Consent Decree at 22.

which fixed sensors would be placed downwind from the minimized working face area.[152] The method would also consider the fetch distance, which is the distance downwind from the source where the sensor can reliably capture the center of the methane emission plume.[153]

Additionally, CARB could draw from fenceline monitoring requirements in California's own refinery community monitoring and fenceline monitoring requirements[154] and recent federal fenceline monitoring requirements for refineries[155] and coke ovens[156] to establish active face methane concentration monitoring requirements. For example, CARB could consider establishing a methane action level that would trigger implementing a corrective action plan within twenty-four (24) hours.[157] Corrective actions could include application of additional daily cover and/or installing/repairing horizontal collectors. CARB should also include in the established method and in the monitoring plan that the owner or operator shall collect and record meteorological data.[158]

3. CARB should include additional requirements that would reduce the number of flooded wells.

It is common for landfill operators to discover that liquids—e.g. leachate and gas condensate—accumulate in gas collection wells.[159] The presence of liquid in the collection wells decreases the amount of gas collected and can impede gas flow, potentially leading up to the buildup of heat and pressure.[160] Data also shows that gas collection efficiency at landfills with high leachate levels is significantly lower than at landfills with lower levels of leachate.[161]

First, CARB should include in its design plan requirements[162] that the GCCS be designed to extract liquids. In their design plan, for example, operators could demonstrate that the GCCS will extract liquids by including dual phase wells, which are designed to extract both gas and liquids from the landfill simultaneously.[163] Operators could also include in their design plans vertical or horizontal gas wells equipped with dedicated leachate pumps.[164] By requiring that the design plan meet the requirement that the GCCS is designed to extract liquids, CARB will ensure both gas and leachate are effectively managed and improve overall system performance, which will reduce methane emissions.

152 Work Face and Daily Cover White Paper at 8.
153 *Id.*
154 *See* Cal. Health & Safety Code § 42705.6.
155 *See* 40 C.F.R. § 63.658.
156 *See* 40 C.F.R. § 63.
157 *See* 40 C.F.R. § 63.314(e).
158 *See* 40 C.F.R. §63.314(b).
159 *Id.*
160 *Id.*
161 *Id.* at 8.
162 Cal. Code Regs. Tit. 17 § 95464(a)(1).
163 GCCS White Paper at 11.
164 *Id.*

Additionally, CARB should also include monitoring[165] and corrective action requirements for flooded wells. Although the current monitoring requirements require monitoring each wellhead monthly for pressure, and includes corrective action requirements, no similar requirements address liquid in the wells.[166] Because the presence of liquid in wells impacts the efficiency of the GCCS and of the collection of gas, CARB should also require operators to monitor and initiate corrective action for wells containing leachate or other liquid. Corrective action would include pumping leachate and other liquids out of the well to restore necessary vacuum conditions to effectively collect the landfill gas.[167] For landfills without dual phase wells, leachate pumps or other measures in the design plan that extract liquids, corrective actions could also include requiring the installation of some of these methods.

Finally, CARB should also consider mandating that wastewater sludge should be dried prior to being placed in landfills. Such a requirement would avoid low-permeable wet patches in landfills and reduce clogging of leachate drainage systems.[168]

4. CARB should harmonize the LMR with federal requirements and include additional requirements.

Efficient gas capture is affected by the dynamic nature of emissions at landfills, influenced by changing atmospheric conditions and temperature.[169] The current LMR requires only monthly monitoring for pressure, and landfills are also required to monitor monthly for oxygen and temperature under federal requirements.[170] Commenters support CARB's intention to add all requirements referenced in 40 CFR § 62.1115(b)(2) in the revised LMR.[171] Commenters note that it is advantageous to harmonize the LMR with federal plan requirements. In the unlikely event that the Emission Guidelines are revised to omit these oxygen and nitrogen monitoring requirements, explicitly including these requirements in the LMR revision would preserve these important requirements.

Next, CARB should include corrective action requirements for measured exceedances of nitrogen and oxygen in the revised LMR.[172] If the prescribed standards for temperature, pressure,

---

[165] Within Cal. Code. Regs. Tit. 17 § 95469(b),(c).
[166] Cal. Code. Regs. Tit. 17 § 95469(c)(1)-(3).
[167] GCCS White Paper at 11.
[168] GCCS White Paper at 12.
[169] *Id*. at 10.
[170] Although the LMR does not cover the oxygen and temperature monitoring requirements, EPA's Federal Plan to Implement the Emission Guidelines and Compliance Times does include this requirement in 40 C.F.R. Part 62, subpart F to identify that existing landfills in California must implement these requirements in addition to the LMR requirements. Federal Plan Requirements for Municipal Solid Waste Landfills That Commenced Construction On or Before July 17, 2014, and Have Not Been Modified or Reconstructed Since July 17, 2014, 86. Fed. Reg. 27756, 27758 (May 21, 2021).
[171] 2024 CARB LMR Workshop at 46.
[172] In the 2020 revisions to the NESHAP, a higher temperature standard was newly established (145 degrees Fahrenheit) and the rule replicated the NSPS approach to nitrogen and oxygen content, requiring monitoring but no corrective action or reporting. *See* Standards of Performance for Municipal Solid Waste Landfills, 81 Fed. Reg.

and oxygen or nitrogen are exceeded, then corrective action should include repairs or adjustments to the GCCS and any actions necessary to manage the presence or risk of a subsurface fire. In addition, ongoing monitoring and reporting of these parameters along with carbon monoxide content and methane content should be required. This monitoring should continue until the monitored parameters have stabilized to conditions that indicate that methanogenic decay has resumed or the fuel for the fire is exhausted.

Finally, CARB should also include revisions from the 2020 NESHAP that established enhanced monitoring requirements at wellheads where temperatures exceed 145º F that include carbon monoxide and methane content of the landfill gas at the wellhead and visual observations for evidence of subsurface oxidation such as smoke, ash, or damage to the well.[173] CARB should also require more frequent monitoring of these parameters when there was a thermal event or fire at an MSW landfill. Once the thermal event or fire is identified, the operator should monitor the temperature, oxygen, carbon monoxide, and methane content daily until conditions stabilize. Then, for the next six (6) months the operator should be required to monitor for oxygen and temperature bi-weekly and prepare a report that conditions have stabilized, demonstrating that further risk of fire and a thermal event is not present. This is warranted given the significant consequences of a landfill fire and the risk to surrounding communities.

5. CARB should consider requiring remote wellhead tuning technologies.

Although Commenters support harmonizing the LMR with the federal requirements, those monitoring requirements are still too infrequent relative to the dynamic conditions of landfill emissions. Moreover, associated corrective action requirements for positive pressure readings do not adequately capture rapid temporal changes effectively, which leads to inconsistencies in gas capture of the GCCS and thus increased emissions.[174] Therefore, Commenters support CARB's consideration of supporting automated wellhead technologies[175] that are capable of continuously monitoring emissions and adjusting the vacuum to improve pressure.[176]

Since finalizing the first CARB LMR, technologies emerged that are capable of adapting gas recovery strategies in response to meteorological conditions. Automated wellhead tuning

59332 (Aug. 29, 2016). In addition, in the 2020 NESHAP revisions, EPA finalized "minor edits" to the 2016 NSPS and EGs "allowing landfills to demonstrate compliance with the 'major compliance provisions' of the NESHAP in lieu of complying with the analogous provisions in the NSPS and EGs." National Emission Standards for Hazardous Air Pollutants: Municipal Solid Waste Landfills Residual Risk and Technology Review, 85 Fed. Reg. 17244, 17248 (Mar. 26, 2020) (codified at 40 C.F.R. pts. 60 and 63). Thus, a source may choose to comply with the NESHAP rather than the corresponding provisions of the NSPS and EGs. Practically, this amounts to operators otherwise subject to the NSPS or EGs being allowed to instead comply with the operational standards for the GCCS and the compliance provisions of the NESHAP.

[173] National Emission Standards for Hazardous Air Pollutants: Municipal Solid Waste Landfills Residual Risk and Technology Review, 85 Fed. Reg. 17244, 17270 (March 26, 2020).

[174] GCCS White Paper at 10.

[175] CARB 2024 LMR Workshop at 17.

[176] GCCS White Paper at 10.

technologies, which are in use at many landfills across the U.S., as discussed in Section I.D., are able to dynamically adjust GCCS parameters like vacuum pressure and flow rates in response to real-time data collected through continuous monitoring of atmospheric conditions.[177] This technology has the potential to actively monitor gas collection wells, notify operators as soon as issues occur, identify out-of-range parameters, and allow for automatic wellhead tuning.[178] Automated wellhead tuning can also allow operators to identify issues much more frequently than once per month, and thus could also result in a more well-functioning GCCS and reduce damage to the GCCS.[179] The automated system is also capable of improving gas quality by optimizing the balance between oxygen and methane content, which reduces air intrusion risks.[180]

Accordingly, we encourage CARB to further investigate the efficacy and cost of automated wellhead tuning for all landfills. Especially where a number of California landfills already utilize the technology, CARB should consider requiring the installation of wellhead tuning systems that automatically adjust vacuum levels based on the methane concentration in the landfill gas and other identified parameters that affect landfill gas flow and quality. SCS Engineers estimates that costs would be more affordable over time than traditional manual monitoring.[181]

Finally, at the very least, CARB should require automated wellhead tuning at landfills with persistent issues. Commenters support CARB's concept of requiring continuous wellhead monitoring and more frequent or automated wellhead tuning for landfills with frequent or persistent issues.[182] SCS Engineers also presented that their automated wellhead tuning technology would be more affordable than traditional monitoring for large landfills with issues.[183] CARB should also consider mandating the use of automated wellhead tuning at a certain size threshold.

6. CARB should require earlier installation of GCCS.

Recent information indicates that methane is being released at landfills earlier than previously thought. Thus, it is imperative to collect and control landfill gas earlier. Research from the EPA, for example, found "[a]n estimated 61 percent of methane generated by landfilled food waste is not captured by landfill gas collection systems and is released to the atmosphere. Because food waste decays relatively quickly, its emissions often occur before landfill gas

[177] *Id.*
[178] *Id.*
[179] *Id.*
[180] *Id.*
[181] SCS Engineers, *US EPA Landfill Technology Workshop-SCS RMC Automated Wellheads* (October 29, 2024) at slides 5-6, *available at* https://www.regulations.gov/document/EPA-HQ-OAR-2024-0453-0038.
[182] CARB 2024 LMR Workshop at 58.
[183] *Id.*

collection systems are installed or expanded."[184] The EPA also recently revised the decay rate constant used in its first-order decay method for estimating landfill methane under the GHGRP rules to reflect higher emissions earlier in a landfill's life.[185]

Additionally, EPA shows that it is technically feasible and cost-effective to install and expand a GCCS *within one year* after waste is placed. According to EPA's Landfill Gas Energy Project Development Handbook "early" landfill gas collection can be implemented "within a few months of waste placement."[186] In fact, by using horizontal collectors and/or bottom-up caisson wells, operators can collect gas as waste is being buried.[187] Analysis by EIP, based on Eastern Research Group's ("ERG") analysis for EPA's 2019 technology review ("2019 Technology Review") found that earlier expansion of GCCS (after 1 year) could reduce methane emissions by 400,000 tons per year at a cost-effectiveness of about $140 per metric ton of methane reduced (or just ~$2/ton CO2e using the 20-year global warming potential).[188]

Finally, the State of Washington's Landfill Methane Emissions Rule requires any owner or operator of an active MSW landfill to install and operate a GCCS *not later than 18 months* after the date that the landfill is required to comply with the rule.[189] Washington's rule also requires landfills to submit a design plan for the GCCS *within one year* of applicability, though landfills can defer GCCS installation if they demonstrate that there is no surface methane concentration greater than or equal to 200 ppm.[190] Michigan also requires that new landfills or expansions must require a GCCS during construction, prior to accepting waste.[191] Michigan requires existing landfills to provide a design plan within twelve (12) months of applicability and to install and operate a GCCS within six (6) months of approval of that plan.[192]

Accordingly, given the cost-effectiveness and methane reduction potential, CARB should require earlier GCCS installation. Specifically, CARB should require that owners and operators must install and operate a GCCS within at least one (1) year, possibly within six (6) months,

---

[184] Env't Prot. Agency, *Food Waste Management-Quantifying Methane Emissions from Landfilled Food Waste* (Oct. 2023) *available at* https://www.epa.gov/system/files/documents/2023-10/food-waste-landfill-methane-10-8-23-final_508-compliant.pdf.
[185] Revisions and Confidentiality Determinations for Data Elements Undern the Greenhouse Gas Reporting Rule, 89 Fed. Reg. 31802, 31852 (April 25, 2024).
[186] Landfill Methane Outreach Program, *LFG Energy Project Development Handbook* (Jan. 2024) at 7-4 *available at https://www.epa.gov/system/files/documents/2024-01/pdh_full.pdf* [hereinafter "2024 LFG Project Handbook"].
[187] *Id*. at 7-10.
[188] Kelly, Leah, Lewis, Haley, EIP, Petition for Rulemaking to Revise the New Source Performance Standards and Emission Guidelines for Municipal Solid Waste Landfills (June 22; 2023), 21 *available at https://environmentalintegrity.org/wp-content/uploads/2023/06/FINAL-Petition-for-Rulemaking-CAA-111-Landfills.pdf* [hereinafter "EIP Petition to EPA"]; Memorandum from E. Rsch. Grp., Inc. on Clean Air Act Section 112 (d)(6) Tech. Rev. for Mun. Solid Waste Landfills to Allison Costa and Andy Sheppard, EPA, Off. of Air Quality Planning & Standards, at 29-30, 31-32, 36- 41, 44-45 (June 25, 2019) [hereinafter "2019 Technology Review Memo"].
[189] Wash. Admin. Code r. 173-408-080(5)(a)(xii).
[190] Wash. Admin. Code r. 173-408-080(1)(a),(2).
[191] Mich. Comp. Laws Ann. § 324.11512h(3)(a).
[192] Mich. Comp. Laws Ann. § 324.11512h(3)(b)

instead of eighteen (18) months[193], from the approval of the Design Plan. Additionally, CARB can expedite the timeline for submitting a design plan once meeting the threshold to within six months as opposed to one year.[194] Finally CARB can more quickly approve or disapprove of design plans, seventy-five (75) days would be feasible.[195]

F. CARB should streamline and strengthen cover requirements.

Methane oxidation in landfills is critical to mitigating the release of methane into the atmosphere, and landfill cover plays a critical role in methane oxidation.[196] Landfill covers minimize gas emissions, control odors, reduce leachate formation and prevent water infiltration into the landfill.[197]

A Cal Poly field investigation of methane gas emissions from a representative set of California landfills analyzed all operational parameters at landfills and emissions measured on the ground.[198] The researchers found that the type of cover on a landfill was a significant factor impacting the flux of emissions.[199] Specifically, they found higher methane emissions with the use of intermediate and daily covers and lower methane emissions as the percentage of the landfill area with final cover increased.[200] The report recommended limiting the working face and because daily cover had the most emissions potential, intermediate cover should be installed within days—not weeks—of waste placement.[201] Specific recommendations included:

> (1) for daily cover: minimize the area and duration of coverage and avoid highly porous and open structure bulk materials;
> (2) for intermediate cover: increase thickness up to one (1) meter (about three (3) feet) with fines content over 30%, and minimize area; and
> (3) for final cover: thickness of over 150 cm (about 4.9 feet), fines over 60%, clay over 12%, and plasticity over 20%.[202]

Moreover, as seen in **Figure 4** below, cover cracks most frequently cause emission incidences:

---

[193] Cal. Code Regs. Tit. 17 § 95464(a)(2)
[194] Cal. Code Regs. Tit. 17 § 95464(A)(1).
[195] *Id*.
[196] EPA, *White Paper Series: Municipal Solid Wate Landfills-Advancements in Technology and Operating* Practices, "Improvements In Intermediate and Final Covers to Mitigate Emissions" (October 2024), 2 [hereinafter "Intermediate and Final Cover White Paper"].
[197] *Id*.
[198] James L. Hanson & Nazli Yesiller, Cal. Polytechnic State Univ., *Estimation and Comparison of Methane, Nitrous Oxide, and Trace Volatile Organic Compound Emissions and Gas Collection System Efficiencies in California Landfills* (2020), https://ww2.arb.ca.gov/sites/default/files/2020-06/CalPoly%20LFG%20Flux%20and%20Collection%20Efficiencies%203-30-2020.pdf [hereinafter "Cal Poly Report"].
[199] *Id*. at 23.
[200] *Id*. at 5.
[201] *Id*. at 351.
[202] Cal Poly Report at 350-351.

Figure 4: Causes of landfill emission plumes observed in California 2021 and 2022 Airborne Methane Plume Mapping Studies[203]

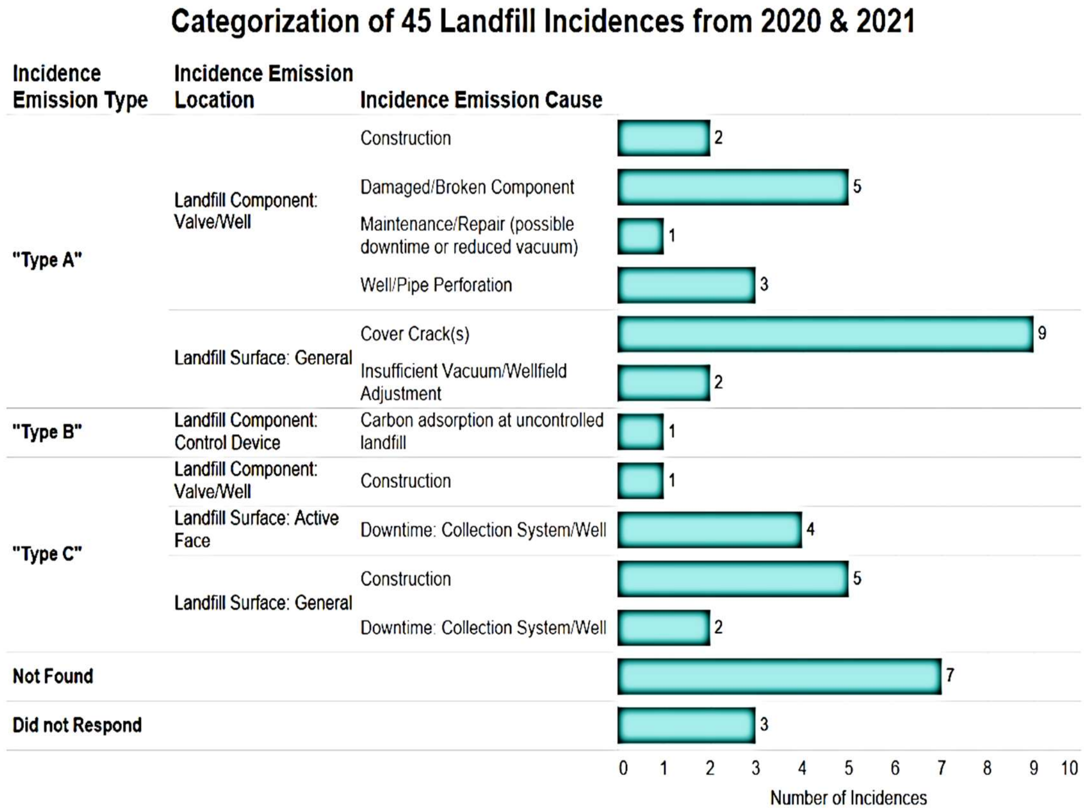


Figure 8. A graphic depicting the results of landfill operator feedback from the 2020 and 2021 airborne campaigns. Note that the Incidence classifications (Emission Type, Emission Location, and Emission Cause) were assigned by CARB staff based on operator responses.

Although landfill cover plays a critical role in mitigating landfill emissions, they are not addressed extensively in either the CARB LMR or the federal CAA requirements for landfills. In their white paper, EPA states that "additional regulatory measures would be needed to ensure the ongoing maintenance and durability of landfill covers. Bare soils, in particular, are especially vulnerable to damage from precipitation, which can compromise cover effectiveness and increase the potential for emissions."[204] Thus, CARB should revise the LMR to include a new section for landfill cover, enumerating specific requirements for daily, intermediate and final cover. CARB should ensure that these requirements are also in concert with any solid waste requirements for MSW landfills. The requirements should set standards for cover material and outline specific required actions to ensure cover integrity maintenance, such that every month the landfill operators must visually inspect the entirety of the landfill cover, both interim and final.

---

[203] CARB, *Summary Report of the 2020, 2021, and 2023 Airborne Methane Plume Mapping Studies* (April 2024), 21, *available at* https://ww2.arb.ca.gov/sites/default/files/2023-05/Published%20Summary%20Report%20_1.pdf.
[204] Intermediate and Final Cover White Paper at 14.

Where visual investigations indicate elevated concentrations of landfill gas, the owner or operator should conduct SEM. The requirements should further specify procedures and minimum actions the landfill operator or owner must undertake to repair the cover.

1. CARB should set minimum standards for cover material, especially for alternative daily cover.

It is critical for CARB to establish default standards for cover material. Cover materials should be required to consist of soils. There should also be minimum requirements for permeability in covers that will be in place for an extended period of time (intermediate and final covers). Selection of soils should also consider properties that would promote oxidation such as texture, porosity, and pH.

First, improvements to intermediate and final landfill covers can mitigate landfill gas emissions by promoting methane oxidation and enhancing the efficiency of gas collection systems.[205] Beginning with intermediate cover, CARB should consider whether to require that intermediate covers incorporate a high permeability layer near the surface.[206] CARB should also increase the required thickness of intermediate cover to ensure proper methane mitigation.[207] Three feet of soil cover, as recommended by Hanson et. al.[208], would more effectively control methane emissions. CARB should require that operators submit a cover design plan, or require a landfill cover section in the design plan already required under the LMR, in which they demonstrate careful material choice and design relevant to the climate and waste characteristics of their landfill. CARB should also require that intermediate cover within one (1) month.

Next, federal solid waste regulations mandate that final cover systems are designed to minimize liquid infiltration and prevent soil erosion and must include at least 18 inches of earthen material as an infiltration or barrier layer, topped by at least six inches of another earthen layer that facilitates vegetative growth.[209] CARB should include in the cover requirement section of the LMR revision specific requirements for final cover that build off of the solid waste requirements. CARB should require that final cover be installed on an ongoing basis once a landfill cell reaches its final grade or after a predetermined number of years in order to avoid long term use of intermediate covers.[210] CARB should require that the cover design plan (or the cover section of the design plan) include a specified timeline for waste placement in each cell along with a detailed schedule for installing final cover once waste placement is complete.[211]

Finally, alternative daily cover ("ADC") should rarely, if ever, be used. Although ADCs are designed to meet daily regulatory requirements, many of the materials used do not sufficiently oxidize methane and allow more liquid infiltration, which leads to higher leachate

---

[205] Intermediate and Final Cover White Paper at 3.
[206] *Id*. at 9.
[207] *Id.* at 14.
[208] Cal Poly Report at 350-351.
[209] *See* 40 C.F.R. §258, subpart F.
[210] Intermediate and Final Cover White Paper at 14.
[211] *Id*.

levels.[212] In its recent white paper series, EPA states that "[f]or landfills subject to NSPS/EG control requirements, minimum standards and test methods for NMOC and methane mitigation from ADCs could be established to ensure equivalency to six inches of soil, or a stricter standard. This would not conflict with state approval of ADC for all landfills in the solid waste context, but rather would be establishing further standards for landfills required to mitigate their NMOC and methane emissions under the NSPS/EG framework."[213] Several states have already identified performance-based standards for evaluation of suitability of ADC.[214] CARB should require that any operator using ADC submit demonstration that the ADC controls odors, methane and NMOC. CARB should establish a test method for operators to ensure that the permeability of ADC is equivalent to six (6) inches of compacted soil, or a stricter standard.[215] CARB should also require more frequent cover performance monitoring[216] for landfills that choose to use ADC.

2. CARB should consider including as alternative compliance options the use of biocovers.

In their 2024 Workshop, CARB presented concepts for addressing declining gas generation.[217] One way CARB could address declining gas generation is by allowing operators to install a biocover to compensate for under performance of the GCCS. To guard against unintended consequences, CARB should define what materials should be used in a biocover.

While oxidation generally occurs in most soils, biocovers—an engineered bioactive layer promoting conditions that enhance and support oxidation by methanotrophic bacteria—can be applied above existing landfill covers to improve methane oxidation and reduce emissions of methane.[218] Biocovers typically consist of a layer of oxidizing material spread over a layer of coarse materials that promotes even distribution of the gas. [219] The design of biocovers promotes

---

[212] The EPA said in recent white paper that "[t]here have been many instances where intermediate covers are used for long periods of time—decades, in some cases. Potential regulation changes could include mandating the installation of final or enhanced cover once a landfill cell reaches its final grade or after a predetermined number of years to avoid long term intermediate covers. This could be enforced by requiring landfill design plans to include a specified timeline for waste placement in each cell, along with a detailed schedule for installing the final cover once waste placement is complete. Similarly, regulation requirements could strengthen around the depth of intermediate covers to ensure proper methane mitigation." Work Face and Daily Cover White Paper at 10. 11-12.
[213] Work Face and Daily Cover White Paper at 11.
[214] "Ohio EPA (2023) identified that ASTM D 6826 and 7008 provide methods for evaluating certain types of ADC, including efficacy for odor control based on ASTM E 96 Test Methods for Water Vapor Transmission of Materials. Wisconsin Department of Natural Resources (2014) similarly recommends use of ASTM E 96 to evaluate potential odor control, and notes that certain ADC types can contribute to odors and emissions issues." *Id.* at 12.
[215] *Id.*
[216] EPA defined performance monitoring for ADC as "[m]onitoring the performance of ADCs over time is critical to assess their effectiveness in controlling odors, preventing litter, minimizing disease transmission, and addressing other landfill concerns. Regular inspections, field testing, and data analysis enable proactive management of ADC application and adjustment as needed." *Id.*
[217] CARB 2024 LMR Workshop at 62.
[218] *See* Marion Huber-Humer et al., *Biotic Systems to Mitigate Landfill Methane Emissions* 26(1) Waste Mgmt. & Rsch. 33(2008), https://pubmed.ncbi.nlm.nih.gov/18338700/.
[219] *See id*; *see also* EPA, Available and Emerging Technologies for Reducing Greenhouse Gas Emissions from Municipal Solid Waste Landfills 17 (2011) [hereinafter "2011 EPA Emerging Technologies Report"]. In 2011, EPA estimated that a biocover could reduce methane emissions by 32% and would cost $48,000/acre. *Id.* at 9, 17.

methane oxidation because biocover has greater porosity and thermal insulation than traditional landfill cover.[220] Biocovers can be used as a supplement to a GCCS to capture fugitive emissions or to reduce emissions at closed landfills.[221] Research has also shown that biodegredation of NMOC occurs with biocovers, including a reduction in VOCs.[222]

In their Proposed Regulatory Framework, Canada also included an engineered biocover system, biofilter or other device utilizing thermal or biological oxidation processes that can demonstrate 90% destruction efficiency as a requirement for methane destruction.[223] It is worth noting that Canada included this requirement alongside flares and a GCCS in its list of methane destruction devices or treatment systems as being part of an operator's landfill methane control approach design. The Proposed Regulatory Framework also includes monitoring requirements to ensure methane destruction via oxidation is maintained in biosystem designs.[224] Although Canada did not go as far in the proposed regulations, even still the biocover is still defined and allowed as an alternative for controlling methane.[225]

For the requirements CARB should consider for biocovers, it should consist of two layers: a gas distribution layer and an oxidation layer. The gas distribution layer should be comprised of gravel, broken glass, sand, or similar coarse material.[226] The oxidation layer should consist of soil, finished compost, mulch, peat or other organic material that operators are required to demonstrate has oxidizing capacity.[227] The oxidation layer should be stabilized with vegetation to prevent erosion and help to control moisture in the cover.[228] CARB should specifically ban raw compost or green waste from the biocover. Biocovers should not be allowed as daily or intermediate cover.

Additionally, CARB should also consider allowing biocovers as alternative compliance options in certain scenarios. For example, an engineered biocover could be required at landfills that have no GCCS or where a GCCS has been shut down. In addition, landfill operators at which a GCCS is operated should be required to address the feasibility of using a biocover in its design plan.

---

[220] Huber-Humer et al., *supra* note 219.
[221] 2019 Technology Review Memo at 26 (*quoting* Helene Hilgeret al., *Reducing Open Cell Landfill Mane Emissions with a Bioactive Alternative Daily Cover* (June 2009), https://www.osti.gov/servlets/purl/971176).
[222] 2019 Technology Review Memo at 27; Hanson & Yesiller, *supra* note 72.
[223] ECCC Proposed Regulatory Framework.
[224] Annual in situ testing to monitoring temporal changes to microbial oxidation capacity and of media properties (including, but not limited to, bulk density, organic matter, moisture etc.) and semi annual monitoring of the biocover surface to identify fissures and erosion and to confirm the biocover is properly draining are listed as possible monitoring requirements. *Id.*
[225] ECCC Proposed Rules.
[226] Huber-Humer et al.; Bala Yamini Sadasivam et al., *Landfill Methane Oxidation in Soil and Bio-based Cover Systems: a Review*, 13(1) Revs. in Env't Sci. and Bio/Technology 79 (2014), https://doi.org/10.1007/s11157-013-9325-z.
[227] *Id*.
[228] Huber-Humer et al., *supra* note 219.

G. CARB should ban recirculation practices.

Leachate recirculation is the practice of reintroducing collected leachate into a landfill. This can be conducted as a strategy for managing leachate onsite rather than incurring the cost of offsite disposal or as a means of increasing the moisture content of the waste and accelerate methane generation (operating the landfill as a "bioreactor").[229] In either case, leachate recirculation increases the total moisture in the landfill as liquids are introduced on an ongoing basis through moisture in waste as it is placed at the site and as a result of infiltration of precipitation through cover material.[230] Some landfills may also be permitted to add additional liquids to enhance the bioreactor function of the landfill.[231]

Leachate recirculation is permitted in California if the facility meets the requirements for leachate recirculation in RCRA Subtitle D and it is approved by the Regional Water Quality Control Board.[232] In addition, the state can also issue "research, development, and demonstration" ("RD&D") permits which allow the introduction of additional liquids to the landfill. USEPA adopted regulations allowing states to issue these permits in 2004 and in 2007 approved changes to California's municipal solid waste regulations allowing the state to issue this type of permit.[233] At least two such permits have been issued in California – at Yolo County Central Landfill and CWM Kettleman Hills Facility.[234] While the state regulations allow only for the issuance of RD&D permits to MSW landfills "for which the owner or operator proposes to utilize innovative and new methods" and where certain design requirements for the handling of the additional liquids are met,[235] there are a range of operational and structural problems that can be caused by adding liquids to landfills that are not fully addressed by these design requirements.

A review of bioreactor and wet landfills shows problems that can arise when liquids are added which can affect the integrity and efficiency of the gas collection system. Liquids can become "perched" in the waste mass when relatively impervious layers are located within the waste mass (such as areas where daily or intermediate cover was not fully removed before new waste was added).[236] Perched liquids are of particular concern for the control of landfill gas – gas can become isolated in a pocket or trapped beneath a layer of saturated waste where it is unable

---

229 USEPA (September 2014), Permitting of Landfill Bioreactor Operations: Ten Years after the RD&D Rule (EPA/600/R-14/335) at 3.

230 While the cover design, including maximizing the imperviousness of the cover and managing slopes to provide runoff pathways for rainfall, can minimize infiltration, some infiltration will occur, particularly where there is daily or intermediate cover in place. *See* Intermediate and Final Cover White Paper at 1.

231 USEPA (September 2014), Permitting of Landfill Bioreactor Operations: Ten Years after the RD&D Rule (EPA/600/R-14/335) at 3.

232 27 C.C.R, § 20340(g).

233 Research, Development, and Demonstration Permits for Municipal Solid Waste Landfills 69 Fed. Reg. 13242, (March 22, 2004); 40 C.F.R. Part 258.4; Adequacy of California Municipal Solid Waste Landfill Permit Program 72 Fed. Reg. 59288 (October 10, 2007).

234 USEPA (September 2014), Permitting of Landfill Bioreactor Operations: Ten Years after the RD&D Rule (EPA/600/R-14/335) at 29.

235 27 CCR, Sec. 20070.

236 USEPA (September 2014), Permitting of Landfill Bioreactor Operations: Ten Years after the RD&D Rule (EPA/600/R-14/335) at 14; GCCS White Paper at 8.

to reach the gas collection system.[237] In addition, the rapid decomposition of the waste can lead to settlement within the waste mass, potentially damaging the gas collection infrastructure and compromising the structural integrity of the site's side slopes.[238]

Liquids can also cause exothermic reactions with certain reactive wastes, such as secondary aluminum production waste or steelmaking slag, and cause elevated temperatures that could lead to subsurface fires.[239] Without any explicit exclusions of such waste in a landfill, leachate recirculation and liquids addition increase the risk of this type of catastrophic event.

Accordingly, CARB should consider in its LMR revisions explicitly prohibiting leachate recirculation activities at landfills. CARB should ensure that these revisions are also harmonious with revisions needed in the current

H. CARB should require site-specific component leak monitoring and repair plans.

CARB requested comment on whether it should revise the LMR in regard to component leak monitoring and repair plans. Specifically, CARB suggests that the LMR could be revised to require leak detection and repair plans like those required in California's Oil and Gas Methane Regulation at 17 CCR § 95669.[240] Commenters generally support the concept of requiring specific plans for component leak detection. In CARB's presentation, it notes that landfill operators have expressed confusion as to where leak monitoring is required.[241] Increased detail regarding the components to be monitored (and possibly the method of monitoring) would likely help to address this confusion. Commenters intend to submit additional, more detailed comments on this later but offer initial thoughts here.

CARB's Oil and Gas Methane Regulation, like EPA's New Source Performance Standards[242] and Emission Guidelines[243] for the oil and gas industry,[244] generally requires the development of a site-specific plan for component leak monitoring, while setting minimum standards that must be met. This appears to allow the operator some flexibility regarding how to comply while providing a degree of certainty regarding emission reduction by holding the plans to minimum standards. In addition, the plans are required to address different kinds of components, like unsafe-to-monitor and difficult-to-monitor components.[245] Addressing

[237] GCCS White Paper at 9.
[238] USEPA (September 2014), Permitting of Landfill Bioreactor Operations: Ten Years after the RD&D Rule (EPA/600/R-14/335) at 8.
[239] Comment submitted by Rick Carleski, Assistant Chief, Division of Materials and Waste Management, Ohio Environmental Protection Agency (Ohio EPA) (March 29,2019), Docket ID EPA-HQ-RCRA-2015-0354-0071, https://www.regulations.gov/comment/EPA-HQ-RCRA-2015-0354-0071 at 1-2, 3; Comment submitted by Lisa A. Hughey, Deputy Director of Central Office, Tennessee Department of Environment and Conservation (TDEC), Docket ID EPA-HQ-RCRA-2015-0354-0076, https://www.regulations.gov/comment/EPA-HQ-RCRA-2015-0354-0076 at 4-5.
[240] CARB 2024 LMR Workshop at 43.
[241] *Id.* at 44
[242] 17 CCR § 95669.
[243] 40 C.F.R. § 60.5397c.
[244] 40 C.F.R. § 60.5397b.
[245] *See, e.g.,* 17 CCR § 95669(d)(1)(E); 40 C.F.R. § 60.5397c(g)(2)(3).

components with more specificity will likely provide increased certainty to operators, making it easier to comply.

In the future, Commenters will likely have additional input on the monitoring approach. in the component leak regulations. However, overall, we believe that requiring site-specific component leak and repair plans with a similar level of detail and specificity to those required for the oil and gas industry is an improvement to the LMR that CARB should pursue.

III. Co-Benefits: Reducing Landfill Fire Risk and PFAS in Water Pollution Discharges

In addition to reducing emissions of methane and other air pollutants, many of Commenters' recommendations herein likely have important co-benefits. Improvements in cover practices, wellhead monitoring, and measures to reduce liquids present in the landfill can likely reduce the risk of landfill fires and subsurface thermal events. These practices are also likely to reduce the volume and/or concentration of per- and polyfluoroalkyl substances ("PFAS") in landfill leachate, which EPA has announced it plans to address in a rulemaking under the Clean Water Act.[246] Commenters plan to submit additional information to CARB on these co-benefits in the future.

IV. Conclusion

CARB leads the way for innovative landfill methane regulations since 2010. Commenters support many of the proposed concepts in the 2024 LMR Workshop. However, Commenters also identify specific and feasible recommended revisions CARB should make to the LMR. We look forward to continued conversation and engagement as CARB prepares its regulatory package. Commenters remain a resource for CARB as it continues to serve as a regulatory leader for controlling landfill methane.

Respectfully submitted,

Leah Kelly, Senior Attorney
Haley Lewis, Attorney
Environmental Integrity Project
888 17th Street, NW, Suite 810
Washington, DC 20006

Nick Lapis
Director of Advocacy
Californians Against Waste
9211 11th St., Suite 502
Sacramento, California 95814

Eleanor Garland
RMI
2490 Junction Pl #200
Boulder, Colorado 80301

Katherine Blauvelt
Circular Economy Campaign Director
Industrious Labs
530 Walnut Street, Suite 200
Cincinnati, Ohio 45202

[246] EPA, Preliminary Effluent Guidelines Program Plan 16 at 35 (Dec. 2024), https://www.epa.gov/system/files/documents/2024-12/preliminary-plan-16_december2024_508.pdf.

LEADING WITH LANDFILLS

The Immense, Cost-Effective Potential of Advanced Technology To Reduce Methane Emissions at Landfills Nationwide

Author: Michael S. Lerner

JULY 2025

Photo Source: LoCI Controls

ENERGY VISION

Table of Contents

Foreword

Cutting methane pollution is the most immediate, cost-effective way to slow warming over the near term. Since methane traps significantly more heat than carbon dioxide — but dissipates from the atmosphere sooner — fast action to curb methane is essential to keep our climate targets within reach. That is why RMI is working with a partner network of satellite and sensor operators through its WasteMAP platform to make methane emissions visible and define mitigation measures, policies, and market incentives that slash this super-potent greenhouse gas.

Landfills are a major but addressable source of climate pollution, generating methane as buried organic waste decomposes. Recent aerial and satellite remote sensing surveys have observed super-emitting methane plumes at landfills across the United States, with emission rates 40%-50% higher on average than inventory estimates. Landfill emissions also tend to be larger and more persistent than other sources of methane, which underscores the strong potential climate benefits of addressing these fugitive emissions.

The good news is that we have viable solutions to cut landfill methane pollution today. To avoid future methane generation, we must keep organic waste out of landfills — through waste prevention, food rescue, and organics recycling. At the same time, we must strengthen pollution controls for the landfilled waste that will continue generating methane for decades to come. There are proven best practices and readily available technologies that can increase landfill gas collection and slash methane pollution. As this Energy Vision study shows, expanding gas collection systems to more landfills, installing these systems earlier, and using real-time monitoring and controls can cut 59.2 million metric tons of CO2e annually at just $9.58/ton CO2e.

Advanced landfill gas controls can unlock meaningful progress toward global 2030 methane reduction targets. And, the environmental, health, and economic benefits far exceed implementation costs. Stronger landfill pollution controls reduce local exposure to odors, ozone, and health-harming compounds in landfill gas — protecting workers and nearby residents. It also makes business sense: advanced landfill gas capture can save landfills money over time on operations while generating additional revenue for energy projects.

As this Energy Vision study makes clear, improving landfill gas collection is one of the most cost-effective opportunities to slow near-term warming, while boosting domestic energy production, improving air quality, and protecting public health. Policymakers and landfill operators can help close the gap on the Global Methane Pledge by integrating these best practices into landfill operations and regulatory and incentive programs today.

Tom Frankiewicz, *Principal, RMI Climate-Aligned Industries Program*

Executive Summary

- Methane is an extremely potent but short-lived greenhouse gas. Cutting methane emissions now is the strongest lever available to slow global warming in the coming decades.

- Landfills are the third-largest source of U.S. methane, accounting for 17% of total anthropogenic emissions, according to EPA greenhouse gas inventories. Food waste has an outsized impact, as it accounts for 20% of municipal solid waste (MSW) landfill tonnage but is responsible for 58% of fugitive methane emissions.

- Upon meeting fairly lax thresholds under federal law, or stricter thresholds in a few states, MSW landfills must build gas collection and control systems (GCCS) to capture the methane-rich gas generated by decomposing organic matter. But these gas collection systems are often quite inefficient and usually do not collect landfill gas from active cells where waste is still being deposited.

- It is an important yet long-term endeavor to prevent food from being landfilled in the first place, by redistributing the edible portion and diverting the rest to generate renewable energy and recycle nutrients. However, we also need solutions *now* based on the status quo where a huge amount of methane is being emitted from both food waste and non-food organic waste in landfills.

- The good news is that there are extremely cost-effective options to improve the efficiency of existing landfill gas collection systems through real-time monitoring and automated tuning systems, install them much earlier at working faces (in time to capture the methane-rich biogas from decomposing food waste), and to build them at high-emitting landfills that have no gas collection systems whatsoever. In this report, we refer to these options collectively as "advanced landfill tech."

- **Implementing these three options – 1) real-time tech; 2) early action; and 3) new gas capture systems at all economically feasible high-emitting landfills – would cut U.S. MSW landfill emissions by 49.1% from the 2023 level. This would decrease total U.S. methane emissions by approximately 7.2% (49.4 million metric tons of CO2 equivalent) relative to the 2023 level.** (All CO2 equivalency calculations in this report are based on the EPA standard 100-year Global Warming Potential of methane being 28 times as powerful as CO2.)

- Total estimated capex for these three feasible options, affecting nearly 900 landfills, would be $1.3 billion and anticipated annual operations and maintenance would cost $250 million. **The fully loaded annual cost of implementing advanced landfill tech – factoring in capex and opex** (based on the equipment having an 8-year lifespan) **– is just $8.35 per metric ton of CO2 equivalent abated. That is considerably**

less expensive than other notable greenhouse gas reduction options including oil and gas methane reduction measures, switching from fossil natural gas to renewable power generation, cleaning up the transportation sector, and implementing direct air capture of CO2.

- Alternatively, including new gas capture at high-flow but less economically feasible landfills would deepen the cumulative cut from these options to 58.9% from MSW landfills or 8.63% from total U.S. methane (59.2 million metric tons of CO2 equivalent). This combination would cost approximately $1.8 billion in capex and $340 million in annual opex. The fully loaded annual cost would be $9.58 per metric ton of CO2 equivalent abated – still incredibly cost-effective relative to the other greenhouse gas reduction options.

- Energy Vision also calculated that if all food waste were ultimately diverted from landfills, implementing the real-time tech option and new gas capture systems options would still cut 4.1% from total U.S. methane in 2023. This underscores that **these advanced landfill tech options are worth implementing even as efforts to redistribute and divert food waste gradually gain momentum. There is no conflict between these priorities; both should be pursued.**

- There are also many second- and third-order methane mitigation measures worth pursuing at landfills, including incorporating remote/aerial monitoring of leaks, adopting best practices in daily and intermediate cover, and decreasing the spacing between wellheads.

- There is also almost entirely untapped potential at some industrial landfills, which face no existing or planned regulatory requirements to install GCCS, yet collectively emit almost one fifth of the emissions that MSW landfills do.

- Options to accelerate implementation of advanced landfill tech include tighter regulations; direct subsidies; and expanding incentives for beneficial use of gas (to produce renewable natural gas or generate electricity) at landfills implementing best practices for gas capture. Additional methane capture at landfills above and beyond regulations could also be made eligible for use in state-level "compliance offset protocols," for example, to help meet mandatory reductions in power emissions.

- The current landfill market incentives heavily favor the production of renewable natural gas (RNG), which can have significantly lower greenhouse gas emissions than fossil natural gas when produced at landfills with high collection efficiency. Over 100 landfill RNG projects are operational and over 100 more are planned or under construction. We therefore expect that virtually all the captured gas from the three feasible options today would be upgraded to RNG, which, at 93 million MMBTU/year, would nearly double the total U.S. RNG supply (as of 2023).

- **The business case for adopting advanced landfill tech is very compelling.** Conservatively valuing the additional 93 million MMBTU/year of RNG produced at $20/MMBTU (environmental attributes plus the commodity gas) in the years ahead, that equates to $1.86 billion annually in new gross revenue generated. Meanwhile, the estimated cost of the three options feasible today is $1.3 billion in onetime capex and $250 million in annual opex. Aggregated across all the candidate landfills, this means an average overall payback period of less than a year once the new equipment is operational, after which this would be a significant net revenue earner for many years. *(The calculations in this report are based on the direct costs of all the advanced landfill tech feasible today and the additional revenue from the incremental gas capture; they exclude capex or opex associated with RNG plant installation.)*

- The bottom line: adopting advanced landfill tech to address a large source of current U.S. methane emissions would be a major, quick win at a very low cost relative to many other climate solutions.

A landfill wellhead with real-time tech. Photo Source: LoCI Controls.

I. Introduction

The world needs practical, cost-effective solutions to cut greenhouse gases and start bending the curve on climate change. The top near-term priority is to slash emissions of methane, an extremely potent but short-lived greenhouse gas. Cutting methane emissions soon is the strongest lever available to slow global warming in the coming decades. 159 countries, including the U.S. under the Biden administration, have signed the Global Methane Pledge, each committing to cutting their methane emissions 30% by 2030 (known as "30x30") from 2020 levels.

The challenge is how the U.S. can feasibly and cost-effectively reach 30x30 in the next five years. Energy Vision's May 2024 report *Meeting the Methane Challenge* set out the first concrete roadmap for exactly how the U.S. could achieve 30x30. It evaluated multiple options for how much methane could feasibly be reduced, at what costs, on what timeframes, and at what comparative "bang for the buck" (or cost-effectiveness) in methane abatement. Recognizing various city, state, federal, and international goals to divert materials – especially organic waste – from landfills, that report intentionally focused on non-landfill solutions to address the U.S. methane challenge.

This report serves as a follow-up to *Meeting the Methane Challenge* on the matter of methane emissions from landfills. According to EPA greenhouse gas inventories, landfills account for 17% of U.S. methane emissions, making them the third-largest source, behind only enteric fermentation (i.e., cow belches) at 27% of U.S. methane emissions and natural gas systems at 25%.[1] Moreover, recent remote sensing surveys suggest that actual landfill methane emissions may be 40-50% higher than bottom-up estimates like EPA GHG inventories, but for the sake of consistency we use the EPA data.[2]

While fully diverting food waste out of landfills remains an important long-term goal, we recognize that the U.S. needs cost-effective options *now* to tackle methane emissions by 2030. (See the box in Section III titled, "How Advanced Landfill Tech Fits into Multiple Paths to 30x30.") This report therefore focuses on feasible, cost-effective options for implementing advanced technology at municipal solid waste landfills *today*, based on the status quo, where an enormous amount of methane leaks into the atmosphere from both food waste and non-food

1 https://www.epa.gov/system/files/documents/2024-04/us-ghg-inventory-2024-main-text_04-18-2024.pdf

2 https://www.science.org/doi/10.1126/science.adi7735; https://acp.copernicus.org/articles/24/5069/2024/

organic waste.

Almost 60 million metric tons of food waste are disposed in U.S. landfills every year, accounting for 20% of landfill tonnage. However, food waste has an outsized impact, as it is responsible for 58% of fugitive methane emissions.[3] This is partly because food waste is so prevalent and conventional landfill gas collection systems are generally inefficient, and partly because food waste breaks down quickly – before most landfill gas collection systems are installed. As this report details, there are extremely cost-effective options to improve the efficiency of existing landfill gas collection systems, install them much earlier at working faces (in time to capture the methane-rich biogas from decomposing food waste), and to build them at high-emitting landfills that have no gas collection systems whatsoever.

This report also quantifies how much methane would be captured if advanced landfill technology were implemented *and* all food waste were ultimately diverted from landfills. The results are still significant, showing that installing advanced landfill technology and diverting food waste from landfills are not rival approaches and both should be pursued. Advanced landfill technology can be implemented faster, making more of a difference to reaching 30x30, so it should be a high priority. The report concludes with policy options that would accelerate the installation of advanced landfill technology and start cutting methane emissions right away.

3 https://www.epa.gov/system/files/documents/2023-10/food-waste-landfill-methane-10-8-23-final_508-compliant.pdf

Snapshot of EPA Landfill Regulations

Greenhouse Gas Reporting Program (GHGRP)

The EPA Greenhouse Gas Reporting Program (GHGRP) was created in 2009, covering landfills and other stationary sources of air pollutants and greenhouse gases. Any landfill – whether open or closed – that emits at least 25,000 metric tons of carbon dioxide equivalent (CO2e) per year must report its emissions to the GHGRP, except if it stopped accepting waste prior to 1980.

A landfill can discontinue reporting to the GHGRP if its emissions fall below 25,000 metric tons of CO2e per year for 5 years in a row, or below 15,000 metric tons of CO2e for 3 consecutive years. However, it would have to resume reporting if its recorded emissions ever rose above 25,000 metric tons of CO2e.

Of note, however, the Greenhouse Gas Reporting Program's future is uncertain. In April 2025, a senior Trump Administration EPA official ordered staff to draft a rule that would exclude 40 of the 41 sectors that are now required to submit data to the GHGRP, including landfills.[4] Regardless, the following gas capture regulations for landfills still apply.

Gas Capture Regulations for Municipal Solid Waste Landfills

The existing gas capture regulations for municipal solid waste landfills date back to 1996 (and were mostly kept intact in the EPA's latest New Source Performance Standards or NSPS from 2016). These require a landfill to install a gas collection and control system (GCCS) if it has both:

- A permitted landfill design capacity of at least 2.5 million megagrams as well as at least 2.5 million cubic meters of municipal solid waste; and
- An estimated emission rate of at least 34 megagrams per year of non-methane organic compounds (NMOCs) for open landfills or 50 megagrams per year of NMOCs for closed landfills.

Upon reaching both of these thresholds, a landfill must do all of the following:

- Develop and submit a gas collection and control system (GCCS) design plan within 12 months

4 https://www.propublica.org/article/trump-epa-greenhouse-gas-reporting-climate-crisis

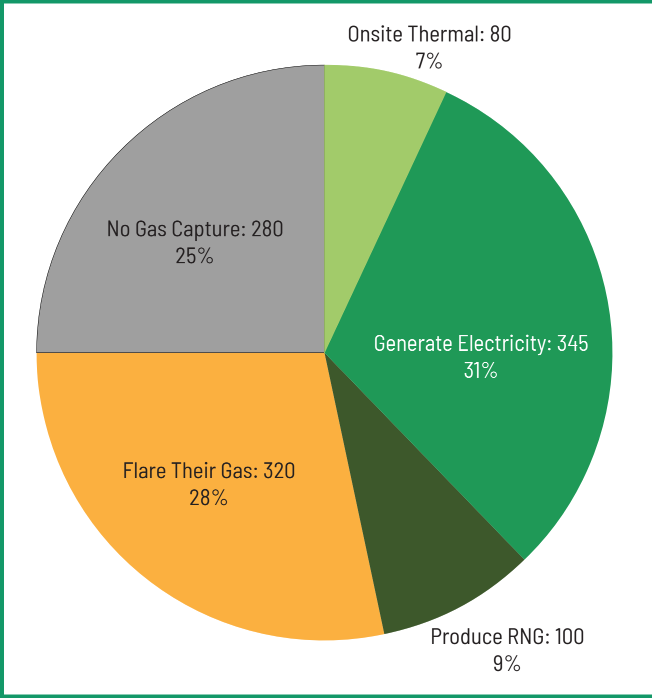
of initially exceeding the NMOC emission rate threshold.

- Install and operate a GCCS within 30 months of first exceeding the NMOC emission rate threshold. The system must meet specific NMOC reduction criteria.
- Take measurements at each gas collection point once per month to ensure negative pressure as well as the temperature of the landfill gas being within specified limits.[5]
- Monitor surface emissions once per quarter to ensure the GCCS is working properly.
- Expand any existing GCCS into each area where waste is placed within 5 years if actively accepting waste, or within 2 years if the area is closed or at final grade.

About a quarter (280) of the 1,125 municipal solid waste landfills reporting to the GHGRP in 2023 did not have gas collection systems, because even though they were emitting at least 25,000 metric tons of CO2e annually, they did not reach the two separate thresholds on permitted size and NMOC levels that would have required them to install gas collection systems. In a few instances, landfills may have been in the process of building gas collection systems but they were not yet operational at the time of reporting. For context, 100 landfills (almost 10%) reporting to the GHGRP in 2023 produced renewable natural gas (RNG), about 80 others used their gas for onsite thermal uses (i.e., as boiler fuel), around 345 other GHGRP landfills generated electricity, and roughly 320 others reporting to the GHGRP flared their landfill gas (see Figure 1 to the right).

There are many ways in which landfill regulations could be changed to cut the sector's large fugitive methane emissions, such as adopting a methane emissions threshold and reducing the size requirements and lag time for installing gas capture systems. EPA published a very useful series of white papers in October 2024 on these potential measures.[6] Several states – California, Oregon, Washington, Michigan, and Maryland – have indeed adopted much stronger landfill regulations compared to the federal baseline, and Colorado is in the process of doing so (see case study in Section IV, Policy Options to Accelerate Implementation). We discuss the technical measures later in this section and the policy measures in Section II. There may be equally effective incentives to encourage installation of gas capture prior to it being required, especially if there is sufficient demand from voluntary carbon markets that recognize the GHG reduction and climate benefits of doing so (see Section IV for more).

Figure 1: How the 1,125 Landfills Reporting to the GHGRP in 2023 Used Their Gas



Source: Energy Vision chart based on EPA GHGRP Reporting Year 2023 data, EPA Landfill Methane Outreach Program (LMOP) data from September 2024, Energy Vision-Argonne National Laboratory RNG Database 2023 Calendar Year

5 Oxygen and nitrogen concentrations must also be monitored once per month at each gas collection point and recorded but the 2016 NSPS removed the need for operators to take corrective action for exceedances in either case. https://www.federalregister.gov/documents/2016/08/29/2016-17687/standards-of-performance-for-municipal-solid-waste-landfills

6 https://www.epa.gov/stationary-sources-air-pollution/non-regulatory-public-docket-municipal-solid-waste-landfills

II. High-Impact Landfill Options That Can Be Implemented Today, Based on the Status Quo

Energy Vision's calculations in this report are based on the methane reductions of different scenarios run in the Environmental Protection Agency (EPA)'s Landfill Gas Emissions Model (LandGEM), as well as empirical cost estimates from industry practitioners. All CO2 equivalency calculations in this report are based on the EPA standard 100-year Global Warming Potential of methane being 28 times as powerful as CO2.

Top Three Impactful Measures to Cut Methane from Landfills

Energy Vision found that the three highest-impact options feasible now to cut methane leaking from municipal solid waste landfills are:

1. Improve the efficiency of existing landfill gas collection systems through the use of real-time technology. We refer to this option as "**real-time tech**."

2. Install gas collection systems much earlier at working faces (in time to capture the methane-rich biogas from decomposing food waste). We refer to this option as "**early action**."

3. Build gas collection systems at high-emitting landfills that currently lack them, but which are not otherwise required to do so yet. We refer to this option as "**new gas capture systems**."

These high-impact options are detailed below and summarized in Figure 2 (see next page). It was beyond the scope of this study to model additional, second- and third-order landfill options that can also be implemented today based on the status quo, but we provide a brief overview of them in the box at the end of this section, along with a snapshot of the significant potential at industrial landfills.

Figure 2 (see next page) features the following individual options as well as the Total Feasible Today combination and the Total with Stretch Targets combination:

Option 1 is installing real-time well monitoring and automated tuning systems at all existing landfills with gas collection systems.

Option 2 is early expansion (by at most one year after waste is deposited) of gas collection systems to landfill working faces which emit at least 5,000 metric tons of carbon dioxide equivalent (MT of CO2e) annually, incorporating real-time monitoring and automated tuning systems.

Option 3.a. is installing gas collection systems with real-time monitoring and automated tuning systems at landfills that don't have any gas collection systems but which emit at least 50,000 metric tons of CO2e annually, with gas flow rates of at least 700 standard cubic feet per minute (scfm).

Option 3.b. is installing gas collection systems with real-time monitoring and automated tuning systems at all landfills that don't have any gas collection systems but which emit at least 50,000 metric tons of CO2e annually (including less economically viable "stretch targets" with gas flow rates between 250 and 700 scfm). See the accompanying text for more details on each option.

Figure 2: Emission Reductions, Costs, and Bang for the Buck of Advanced Technology Options at Municipal Solid Waste Landfills

Advanced Landfill Technology Option	Annual Emission Reductions*	Percent Reduction from MSW Landfill Methane in 2023	Percent Reduction from Total U.S. Methane in 2023	Capital Costs**	Annual Operations & Maintenance Costs**	Bang for the Buck: Methane Reduction (MT CO2e) Annually Per Million Dollars of Capex Invested**	Fully Loaded*** Annual Cost Per MT of CO2e Abated (at 8-Year Equipment Lifespan)
1. Real-Time Tech	22.3 million MT CO2e	22.1%	3.24%	$658 million capex	$141 million opex	33,852	$10.02
2. Early Action	21 million MT CO2e	20.8%	3.05%	$430 million capex	$72 million opex	48,697	$6.01
3.a. New Gas Capture Systems at High-Emitting, High-Flow Landfills	6.2 million MT CO2e	6.1%	0.90%	$213 million capex	$37 million opex	28,915	$10.32
3.b. New Gas Capture Systems at High-Emitting Landfills of All Flow Rates	16 million MT CO2e	15.9%	2.33%	$732 million capex	$127 million opex	21,870	$13.64
Total Feasible Today (Options 1+2+3a)	49.4 million MT CO2e	49.1%	7.19%	$1.3 billion capex	$250 million opex	37,955	$8.35
Total with Stretch Targets for Landfills Lacking Gas Capture Systems (Options 1+2+3b)	59.2 million MT CO2e	58.9%	8.63%	$1.82 billion capex	$340 million opex	32,541	$9.58

Source: Energy Vision calculations using data from EPA Landfill Gas Emissions Model (LandGEM) scenarios and empirical cost estimates from industry practitioners. 2023 U.S. methane emissions data is from EPA's 2025 Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2023.[7]

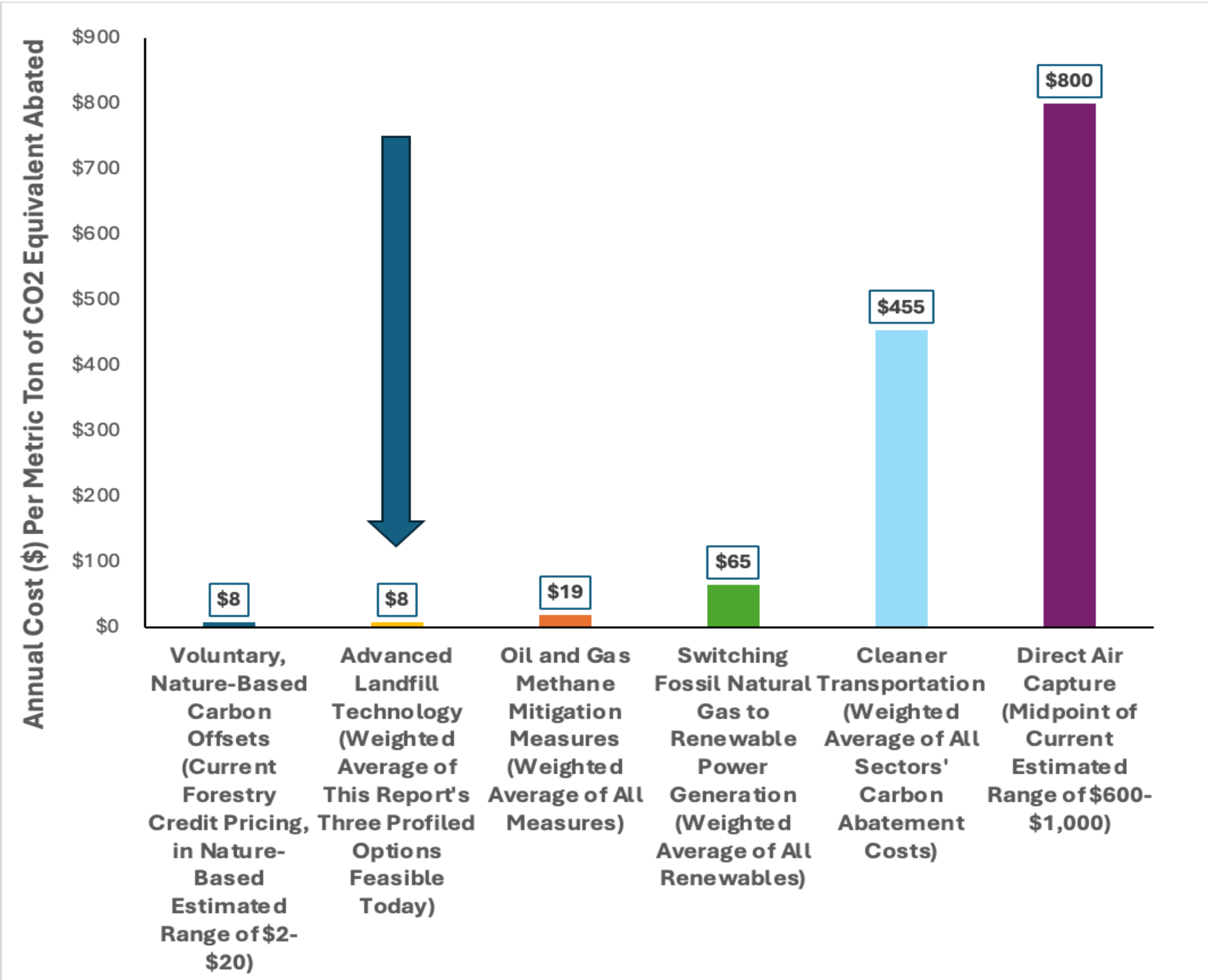
**Annual emission reductions reflect the amount of methane collected by gas capture systems minus a conservative 5% lost in the upgrading process to renewable natural gas (which is what we expect virtually all the captured gas to be used for given the current market incentives; see Section IV for more) or to flaring where applicable. We then subtract another 5% from that to conservatively account for methane leakage in pipelines on the way to the end users. These losses are typically lower empirically, and pipeline leakage may not be relevant for the small systems who wouldn't realistically produce RNG, but we err on the side of being conservative to play it safe and have ample margin to cover other real-world inefficiencies that may occur, such as during maintenance. CO2e calculations are based on the EPA standard 100-year Global Warming Potential of methane being 28 times as powerful as CO2.*

***These are the direct costs of the advanced landfill tech, excluding capex or opex associated with RNG plant installation.*

****Fully loaded annual cost means capital costs divided over the 8-year advanced landfill technology equipment lifespan plus annual opex.*

7 The Trump administration declined to publish the final EPA greenhouse gas inventory report, but it was obtained by Environmental Defense Fund via a Freedom of Information Act request on May 7, 2025 and posted in full on their website. https://www.edf.org/freedom-information-act-documents-epas-greenhouse-gas-inventory?tab=complete_report

Figure 3: Advanced Landfill Tech Has Lower Annual Cost Per Metric Ton of CO2 Equivalent Abated Than Other Notable Climate Strategies



Source: Energy Vision chart. The voluntary nature-based carbon offsets column uses current forestry credit pricing from Allied Offsets of $7.84 per metric ton of CO2 equivalent abated as of July 8, 2025, rounded up to match the other columns at the nearest whole dollar value, with recent empirical examples of nature-based voluntary carbon offsets ranging from approximately $2 to $20 per metric ton of CO2 equivalent abated. The landfill column is drawn from Energy Vision calculations for this report's three profiled options that are feasible today, using data from EPA Landfill Gas Emissions Model (LandGEM) scenarios and empirical cost estimates from industry practitioners (see Figure 2 above); it is rounded down from $8.35 per metric ton of CO2 equivalent abated to match the other columns at the nearest whole dollar value. The oil and gas methane mitigation column is from Energy Innovation, which found in a 2021 analysis using the U.S. Energy Policy Simulator 3.3.0 that the weighted average cost of all oil and gas industry methane abatement measures (like properly casing and sealing wells, monitoring for methane leaks, and improving pipeline and equipment maintenance) in the Build Back Better and Infrastructure Investment and Jobs Acts is $19 per metric ton CO2e. The switching fossil gas to renewables and cleaner transportation columns are from Goldman Sachs, whose 2025 Carbonomics analysis found slight decreases in the costs of renewables and cleaner transportation from the previous year, with larger decreases in solar photovoltaic costs and battery-electric passenger car costs diluted by stubbornly high costs for offshore wind and heavy-duty vehicles, respectively. The direct air capture column is from the Boston Consulting Group, whose 2023 analysis concluded that in order for direct air capture to be widely adopted, its full cost would need to fall from $600-$1,000 per metric ton of CO2 today to below $200 and ideally closer to $100 by 2050, if not earlier.

A landfill wellhead with real-time monitoring and automated tuning technology. Photo Source: LoCI Controls.

1. Real-Time Tech

THE BOTTOM LINE

Real-time well monitoring and automated tuning systems at all existing landfills with gas collection and control systems (GCCS) would reduce MSW landfill emissions by 22.1% and total U.S. methane emissions by 3.24% (22.3 million metric tons of carbon dioxide equivalent) from the 2023 level.

Estimated capital costs would be $658 million; annual operations and maintenance costs would be $141 million (with the equipment lasting at least 5 years, and likely 8-10 years total). In terms of methane reduction for capex invested, or "bang for the buck," this is the second-most cost-effective of the three landfill options analyzed in this report (see Figure 2 above)**. The fully loaded annual cost factoring in capex and opex (based on the equipment having an 8-year lifespan) is only $10.02 per metric ton of CO2 equivalent abated.** (These calculations are based on the direct costs of the real-time tech; they exclude capex or opex associated with RNG plant installation.)

The incremental costs per wellhead equipped with this technology are relatively low: $7,000 in capex and $1,500 in annual operations and maintenance, with a baseline 75% coverage of wellheads at a typical landfill sufficient to significantly improve overall results.

The real-time tech option assumes installation at all 845 open and closed landfills reporting in the EPA Greenhouse Gas Reporting Program (GHGRP, see box above) that already have GCCS in place. We conservatively assume an average 15% increase in gas capture thanks to these systems, although empirically some increases may be significantly higher (see box below, Empirical Results of Real-Time Tech).

DESCRIPTION

About 91% of municipal solid waste landfilled in the U.S. is disposed in landfills with gas capture and collection systems according to EPA[8], but these systems are typically inefficient and rarely extend to working faces (see "Early Action" option below). Furthermore, without continued investment, conventional GCCS often decline in efficiency as they age.

Meanwhile, landfill gas emissions are dynamic – they change significantly on a daily and seasonal basis.

8 https://www.regulations.gov/document/EPA-HQ-OAR-2024-0453-0008

Emission rates of these gases, particularly methane, are influenced by fluctuations in atmospheric conditions such as barometric pressure, temperature, and wind speed. However, existing federal regulations only require landfill operators to check wellhead pressure, temperature, nitrogen content, and oxygen content on a monthly basis. As a result, a traditional GCCS with wellheads whose vacuum is adjusted manually on a monthly basis (if at all) results in inconsistent flow rates and quality of gas being captured amid the constantly changing environmental conditions.

Too much vacuum means low-quality gas (especially elevated nitrogen levels, which often has to be flared instead of used productively) and elevated temperatures. Too little vacuum means gas is escaping elsewhere, which is harmful to the climate, causes the landfill to lose revenue it could have earned by using that gas to generate electricity or renewable natural gas (RNG), and raises odor concerns for the local community. (RNG is derived from decomposing organic waste and is upgraded to be virtually identical to fossil natural gas, but crucially it involves no leaky fossil fuel extraction or fracking, and it can have significantly lower lifecycle greenhouse gas emissions than fossil gas when sourced from landfills with high gas collection efficiency. According to Q3 2024 data from California's Low Carbon Fuel Standard program, landfill RNG used in the transportation sector averaged a 52.4% lower carbon intensity than gasoline/diesel.[9] See Section IV for more on landfill RNG carbon intensity.)

A GCCS can achieve optimal performance throughout changing environmental conditions via the installation of real-time monitoring and automated tuning systems at wellheads. These systems monitor all relevant parameters (including gas composition, flow rates, temperature, and pressure) and remotely adjust valves to change vacuum rates and gas composition as often as needed to maximize GCCS uptime and efficiency. High gas quality is maintained by optimizing the balance between oxygen and methane composition, reducing the risks of air intrusion from any cracks in piping. This also helps prevent sub-surface fires, improving community safety. Additionally, automated tuning systems compensate for underperforming wells by increasing vacuum pressure in adjacent active wells to capture more gas.

Furthermore, these systems provide rapid notification of problems that must be fixed manually like well malfunction. Operators quickly receive a notification rather than the traditional default of the issue remaining undetected until the next monthly manual inspection. This means malfunctioning wellheads or leaking pipes could be fixed much sooner, preventing extended releases of methane into the atmosphere and improving the GCCS bottom line.

Empirical Results of Real-Time Tech

Real-time well monitoring and automated tuning systems were pioneered by private company LoCI Controls. LoCI systems support gas collection operations on over 65 U.S. landfills.[10]

Several of LoCI's results, which are calculated according to the prestigious American Carbon Registry (ACR)'s "Methodology for the Quantification, Monitoring, Reporting, and Verification of Greenhouse Gas Emissions Reductions and Removals from Landfill Gas Destruction and Beneficial Use Projects,"[11] are publicly available.

At the Hamm Landfill in Lawrence, Kansas, the use of LoCI's real-time tech led to an average 32% increase in gas capture over four years. The project generated a 614,633 MMBTU incremental increase in methane captured over four years, or an estimated $3.8 million increase in gross annual revenue to

9 See chart on p. 14 of Energy Vision's report, *A Path to a Healthier America: Ditching Old Diesel Trucks* https://energy-vision.org/wp-content/uploads/2025/03/ditching-diesel.pdf

10 https://www.prnewswire.com/news-releases/loci-controls-increases-methane-capture-at-landfill-group-project-by-32-302274332.html

11 The ACR's landfill gas credits were one of the first methodologies to meet the Core Carbon Principles of the Integrity Council for the Voluntary Carbon Market in April 2024. https://acrcarbon.org/our-markets/integrity-council-for-the-voluntary-carbon-market-icvcm/

the producer at an assumed $25/MMBTU (environmental attributes plus commodity gas). The project operator was also able to reduce downtime at the plant by over 90%, from 73 hours per month to just 6.[12]

At the Roosevelt Regional Landfill, Klickitat Public Utility District in Washington State, the amount of gas captured had been declining for years prior to the installation of LoCI's real-time tech. The LoCI system reversed that trend, increasing gas capture by 12% compared to the starting point, totaling more than 150,000 MMBTUs over 2.5 years. It also significantly improved the quality of the collected gas by lowering the proportions of nitrogen and oxygen, meaning more landfill gas could be upgraded to RNG.[13]

Another private firm in the advanced landfill tech industry, Apis Innovation, has deployed its technology at over 80 landfills and has published the results of one project so far:

At Vancouver Landfill in British Columbia, Canada, the use of Apis real-time tech led to a 12% increase in methane capture over one year relative to the baseline of the two previous years.[14]

For many landfills considering an RNG project, they would need to capture 2-4% more landfill gas to reach the breakeven point for the required investment. Higher gas capture rates like the 15% being averaged from deployment of LoCI technology mean a payback period of a couple months compared to a typical payback period of a few years.

2. Early Action

THE BOTTOM LINE

Early expansion of gas collection systems to landfill working faces, with real-time monitoring and automated tuning systems, would cut MSW landfill emissions by 20.8% and total U.S. methane emissions by 3.05% (21 million metric tons of carbon dioxide equivalent) from the 2023 level.

Estimated capital costs would be $430 million; annual operations and maintenance costs would be $72 million (with the equipment lasting at least 5 years, and likely 8-10 years total). The horizontal wells in working faces do not function nearly as long as the standard vertical wells in closed parts of landfills, but they are much cheaper and simply left in place as more waste is added and more horizontal wells are installed higher up. The real-time monitoring and tuning devices last much longer; they would be removed from the abandoned horizontal wells and installed at subsequently placed ones, which is factored into the annual opex estimates. **In terms of capex "bang for the buck" in methane reduction, this is the most cost-effective of the three landfill options analyzed in this report (see table above). The fully loaded annual cost factoring in capex and opex (based on the equipment having an 8-year lifespan) is just $6.01 per metric ton of CO2 equivalent abated.** (These calculations are based on the direct costs of the early action equipment; they exclude capex or opex associated with RNG plant installation.)

The early action option assumes the system extension is operational by at most one year after waste has been deposited, at all 432 open landfills reporting in the GHGRP whose working faces emit at least 5,000 metric tons of CO2 equivalent annually (based on modeled generation from LandGEM figures) – a reasonable threshold to justify the expense of extending the GCCS.

We assume an approximately 75% efficiency at the newly installed systems in working faces, which in-

12 https://locicontrols.com/hubfs/PDFs/Case%20Studies/LoCI-CaseStudy-LFG-RPP_11124.pdf?hsLang=en

13 https://locicontrols.com/hubfs/PDFs/Case%20Studies/LoCI-CustomerCaseStudy-KlickitatPUD_080124.pdf?hsLang=en

14 https://www.apisinnovation.com/post/vancouver-case-study

Horizontal gas collectors with real-time tech at a landfill. Photo Source: LoCI Controls.

cludes a 15% increase relative to the baseline of a new traditional GCCS thanks to the real-time technology.[15]

DESCRIPTION

EPA estimates that 61% of methane generated by landfilled food waste is not captured by GCCS and escapes into the atmosphere.[16] Because food waste decays in just a few years (50% of the carbon in food waste is degraded to landfill gas within 3.6 years), its emissions frequently occur before landfill gas collection systems are installed or expanded into working faces. Current federal regulations only require existing GCCS to be expanded to new areas within five years of waste being deposited at an active face, or within two years if the area is closed or at final grade.

Expansion of GCCS to active faces within a year of waste being deposited could therefore capture a huge amount of methane that is otherwise escaping into the atmosphere. This is especially the case from food waste, whose methane emissions in landfills increased steadily by 295% from 1990 to 2020 due to increasing amounts of food waste being disposed even as overall landfill emissions declined due to general improvements in GCCS (see Figure 4 below).[17]

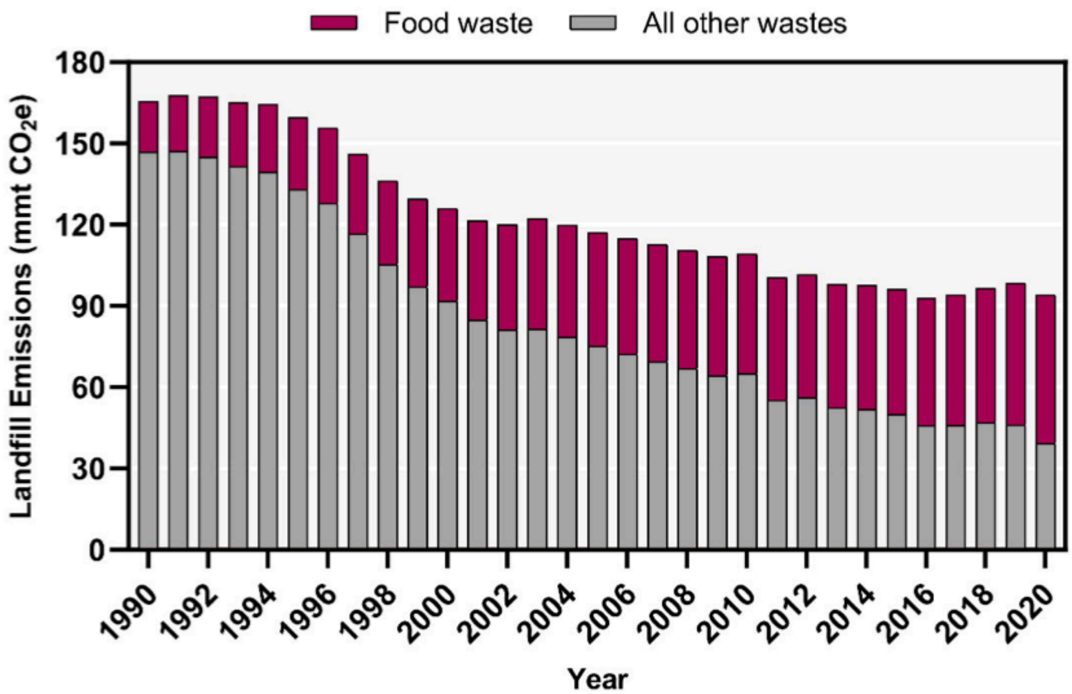
This early action option has unique logistical challenges, but they can all be addressed cost-effectively with existing technology. The working faces of landfills are inherently less stable than closed faces, since waste is still being deposited and is not fully compacted. There is a greater potential for the gas collecting equipment to be damaged by the movement of heavy machinery and by waste being placed. This accordingly means greater safety risks for workers operating in these areas. Plus there may

15 Specifically, we assume a 65% baseline efficiency for a new traditional GCCS + 15% more than that from real-time tech, or .65 x 1.15 = .7475.

16 https://www.epa.gov/system/files/documents/2023-10/food-waste-landfill-methane-10-8-23-final_508-compliant.pdf

17 Ibid.

Figure 4: Contributions of Food Waste to Methane Emissions at U.S. Municipal Solid Waste Landfills



Source: EPA, [Quantifying Methane Emissions from Landfilled Food Waste](), October 2023.

be higher risks of fires breaking out in active faces since less top cover means more oxygen gets in and can feed any flames. Gas quality is also unstable there since the waste is at different stages of decomposition, with new volumes being added regularly. Lesser but very addressable challenges include applying and removing daily cover and potentially more issues of pests and rodents getting into recently deposited waste.

The solution to capture methane from working faces, based on existing technology, is to install horizontal gas collecting wells there. As noted above, they don't function nearly as long as the standard vertical wells in closed parts of landfills. However, they're much less expensive and are meant to be disposable in place. When they inevitably get damaged or filled in by leachate, they're simply left there as more waste is added above and additional horizontal wells are installed higher up.

The incorporation of real-time tech would improve the efficiency of the horizontal gas collectors and streamline their replacement process, as landfill operators would receive rapid notifications of problematic performance. And when it's time to abandon the horizontal wells, the much longer lasting real-time devices are removed and installed at subsequent wells. As noted above, early action could capture a huge amount of methane, making this the most cost-effective option analyzed in this report.

Once an active face with horizontal wells is done accepting waste, then conventional vertical collection wells would be drilled.

3. New Gas Capture Systems

THE BOTTOM LINE

We assessed two options for new gas capture systems: a smaller feasible subset and a larger stretch goal. The feasible option (see 3.a. below) of installing gas collection systems with real-time monitoring and automated tuning systems (including at working faces) at high-emitting, high-flow landfills that don't have any gas collection systems would lower MSW landfill emissions by 6.1% and total U.S. methane emissions by 0.9% (6.2 million metric tons of carbon dioxide equivalent) from the 2023 level. Alternatively, the stretch goal (see 3.b. below) of installing these systems at high-emitting landfills with lower gas flows would cut MSW landfill emissions by 15.9% and total U.S. methane emissions by 2.33% (16 million MT of CO2e) from the 2023 level.

- **3.a. New Gas Capture Systems at High-Emitting, High-Flow Landfills**

  The 0.9% reduction in total U.S. methane emissions assumes installation at all 43 open landfills in the GHGRP that currently lack a gas collection system and whose annual emissions are at least 50,000 metric tons of CO2 equivalent, with gas flows of at least 700 standard cubic feet per minute (scfm). This subset with gas flows of 700+ scfm are the most economically viable for gas capture and beneficial use.[18] We assume an approximately 75% efficiency at the newly installed systems in working faces, which includes a 15% increase relative to the baseline of a new traditional GCCS thanks to the real-time technology.[19]

  Estimated capital costs for this subset of landfills would be $213 million; annual operations and maintenance costs would be $37 million (with the equipment lasting at least 5 years, and likely 8-10 years total). Compared to real-time tech and early action at landfills with existing GCCS, this option has lower bang for the buck in terms of methane reduction for capex invested, but it is still extremely cost-effective (see Figure 2 above)**. The fully loaded annual cost factoring in capex and opex (based on the equipment having an 8-year lifespan) is only $10.32 per metric ton of CO2 equivalent abated.** (These calculations are based on the direct costs of installing new GCCS with real-time tech; they exclude capex or opex associated with RNG plant installation.)

- **3.b. New Gas Capture Systems at High-Emitting Landfills of All Flow Rates**

  The alternative 2.33% reduction in total U.S. methane emissions assumes installation at all 187 open landfills in the GHGRP that currently lack a gas collection system and whose annual emissions are at least 50,000 metric tons of CO2 equivalent, including ones with lower gas flows (at least 250 scfm). Landfills in this larger set with lower gas flows (between 250 and 700 scfm) are generally not seen by developers as attractive candidates for biogas-to-electricity or biogas-to-RNG systems. However, certain types of flares can operate well at low landfill gas flows, combusting the methane and releasing the less potent greenhouse gas CO2 instead of the much more potent methane escaping into the atmosphere. Emissions from these high-emitting landfills with low flows are still deemed addressable methane, even if they don't result in an energy recovery project.

  Estimated capital costs for all these new GCCS would be $732 million; annual operations and maintenance costs would be $137 million (with the equipment lasting at least 5 years, and likely 8-10 years total). Relative to the other options analyzed in this report, installing new gas capture systems at high-emitting landfills of all flow rates has the lowest bang for the buck in terms of methane reduction for capex invested, but it is still very cost-effective (see Figure 2 on page 9) **relative to other GHG reduction measures. The fully loaded annual cost factoring in capex and opex (based on the equipment having an 8-year lifespan) is $13.64 per metric ton of CO2 equivalent abated.** (These calculations are based on the direct costs of installing new GCCS with real-time tech; they exclude capex or opex associated with flaring or any beneficial use projects.)

---

18 This is especially true for landfills that can avoid the major expense of a Nitrogen Rejection Unit in the RNG production process by using real-time tech in GCCS to control inlet nitrogen concentrations to reach the desired specifications. A Nitrogen Rejection Unit typically accounts for 35-50% of a landfill RNG project's capex and a large portion of its opex, as it's one of largest electricity-consuming parts of the processing system. For landfill GCCS with manual tuning, forgoing a Nitrogen Rejection Unit often means that 25% less landfill gas makes it to RNG, but the use of real-time tech with automated tuning covers that difference while meeting the nitrogen specifications for RNG production. Many larger landfills have Nitrogen Rejection Units to maximize the amount of landfill gas they can upgrade to RNG, but smaller landfills often can't afford them, so it's useful to know there is a viable workaround via real-time tech.

19 Specifically, we assume a 65% baseline efficiency for a new traditional GCCS + 15% more than that from real-time tech, or .65 x 1.15 = .7475.

A vertical wellhead with real-time tech at a landfill. Photo Source: LoCI Controls.

DESCRIPTION

About 9% of municipal solid waste landfilled in the U.S. is disposed in landfills without gas capture and collection systems, according to EPA. But as detailed above, within that subset, many landfills emit high amounts of greenhouse gases and accordingly have to report to the GHGRP. They just may not meet the formal federal criteria for having to install a GCCS, whether because their permitted landfill design capacity is below the threshold or their non-methane emissions are below the threshold.

This leaves a clear gap, wherein a landfill could be emitting large amounts of methane and yet legally not have to do anything about it. Installing GCCS at high-emitting landfills that don't have them is the most obvious step to capture methane emissions. Doing so is more capital-intensive because full GCCS are considerably more expensive than just adding real-time tech or expanding an existing system to a working face. Incorporating all three aspects into a new GCCS is even more expensive but allows for the greatest methane capture.

We have therefore separated out the most economically attractive subset – those with gas flows above 700 scfm – as a feasible option today.[20] Its capex cost-effectiveness is close to the real-time tech option at landfills with existing GCCS (see Figure 2 above).

Meanwhile, we consider the larger set including gas flows of 250+ scfm to be a stretch goal that is achievable but not based on private sector funding alone (at least in the current market). Due to the relatively high costs of installing a GCCS from scratch combined with lower flows of methane captured, this broader option's capex bang for the buck is the lowest of all those analyzed in this report. There would need to be government funding, much higher voluntary carbon abatement credit prices, or other incentives in order for the economics to be viable.

Total Potential Impact from the Options

Implementing these three feasible options – real-time tech, early action, and new gas capture systems at high-emitting, high-flow landfills – would cut MSW landfill emissions by 49.1% and total U.S. methane by 7.19% (49.4 million metric tons of CO2 equivalent) based on 2023 emissions (or 7.37% from total U.S. methane in 2020). **Total capex would be $1.3 billion and annual operations and maintenance would cost $250 million. The fully loaded annual cost,** factoring in anticipated capex and opex (based on the equipment having an 8-year lifespan), **is only $8.35 per metric ton of CO2 equivalent abated.** (These calculations are based on the direct costs of the advanced landfill tech, excluding capex or opex associated with RNG plant installation.)

20 As noted in Footnote 18, these plants would be especially viable for RNG production if they were to adopt real-time tech and not have to install a Nitrogen Rejection Unit.

If new collection systems are installed at all open landfills emitting at least 50,000 MT of CO2e annually, including ones with lower gas flows (250+ scfm), then the three options would collectively cut MSW landfill emissions by 58.9% and total U.S. methane by 8.63% (59.2 million metric tons of CO2 equivalent) based on 2023 emissions (or 8.84% from total U.S. methane in 2020). In that case, **total estimated capex would be $1.82 billion and annual operations and maintenance would cost $340 million. The fully loaded annual cost,** factoring in capex and opex (based on the equipment having an 8-year lifespan), **is just $9.58 per metric ton of CO2 equivalent abated.** (As noted above, these calculations are based on the direct costs of the advanced landfill tech, excluding capex or opex associated with RNG plant installation.)

These are much lower costs per metric ton of CO2 equivalent abated than other notable climate strategies like oil and gas methane reduction measures, switching from fossil natural gas to renewable power generation, cleaning up the transportation sector, and implementing direct air capture of CO2. Advanced landfill tech's costs per metric ton of CO2 equivalent abated are just slightly above current pricing for forestry voluntary carbon credits ($7.84 as of July 8, 2025) and well within the recent empirical range for nature-based voluntary carbon credits of $2-20 per metric ton of CO2 equivalent abated (see Figure 3 on page 10).

Additional Landfill Options That Can Be Implemented Today, Based on the Status Quo

We recognize that there are additional second- and third-order options that could be implemented today at many landfills to increase methane capture. It was beyond the scope of this paper to model them, so we just note there is further potential to reduce landfill methane emissions by adopting any of the following example options:

- **Incorporate advanced monitoring of methane leaks.** A growing number of studies using aerial/satellite methane detection have shown that many landfills are emitting far more methane than they have self-reported, typically from data gathered on very limited, error-prone walking surveys once per quarter that avoid working faces.[21] Incorporating methane emissions data taken by drones, rovers, airplanes, satellites, or continuous fenceline monitors would allow operators to pinpoint where large methane plumes are occurring and take early corrective action.

- **Decrease space between landfill gas collection wells.** Installing wells at for example a 100-foot radius instead of a 200-foot radius would capture landfill gas that may otherwise be escaping where the vacuum is weakest in between vertical wells.

- **Better leachate removal.** Since the accumulation of liquid ("leachate") in landfills harms the efficiency of gas collection systems, it is important to integrate pumps (including dual-phase wells that extract both gas and liquids simultaneously in separate pipes).

- **Minimize the size of working faces and improve daily cover.** Since working faces often leak the most methane at landfills, reducing their size to the smallest extent possible for safe, effective operations and adopting best practices for materials and application of daily cover could prevent significant methane leaks.

21 See for example https://www.science.org/doi/10.1126/science.adi7735 and https://cdn.sanity.io/files/xdjws328/production/4820df5770ec505062a6f29d5f6c6f9bb7f31071.pdf

- **Improve intermediate and final cover.** Some additional methane could be naturally "oxidized" into CO2 (a much less potent greenhouse gas) and water by passing through well-designed intermediate and final soil covers – especially when biochar or biocover is added, as it increases the aeration of the soil and promotes the growth of methane-oxidizing bacteria.

- **Switch to using enclosed flares.** A majority of landfills use open flares to burn off gas they don't want or that's of too low quality for productive use, but enclosed flares are more efficient in methane destruction, and over time the emissions reduction would be substantial. The EPA white paper on this topic estimates that installing only enclosed flares at new landfills would result in 320,000 fewer metric tons of methane (nearly 9 million metric tons of CO2 equivalent) emitted cumulatively by 2060, while doing that plus replacing all existing open flares with enclosed flares would cut 2.7 million metric tons of methane (75.6 million metric tons of CO2 equivalent) cumulatively by 2060.[22]

The aforementioned EPA series of white papers goes into depth on many of these topics and is a very useful resource.[23] In some cases EPA models how much additional methane could be captured relative to the baseline, noting that many of these options would involve additional costs for landfill owners/operators but generally not going into further detail on costs or cost-effectiveness in methane abatement.

Almost Entirely Untapped Potential at Industrial Landfills

While this paper focuses on municipal solid waste (MSW) landfills, industrial landfills have emitted almost one fifth the methane produced by MSW landfills for the last few years (in 2023, they emitted 18.9 million metric tons of CO2 equivalent compared to 100.6 million metric tons of CO2 equivalent from MSW landfills). Unlike MSW landfills, industrial landfills face no requirements to install GCCS once certain thresholds are met, but they may have major potential to cut their methane emissions as well.

Industrial landfills are only required to measure their emissions if they have a design capacity of at least 300,000 metric tons and accepted waste since 1980. If these emissions are at least 25,000 metric tons of CO2 equivalent per year, then the owners/operators must report them to the EPA Greenhouse Gas Reporting Program (GHGRP), but they don't have to do anything to mitigate them. This is another major gap in the current landfill regulations. Nor is there any real appetite in the industrial landfill sector thus far for capturing and putting the landfill gas to beneficial use, largely due to the substantial capex costs and the absence of any approved pathways to earn federal/state credits.

Two sectors are responsible for virtually all industrial landfill methane emissions: the pulp and paper sector and the food and beverage sector. Of the 11.1 million tons of industrial waste landfilled in 2021, slightly more than half came from pulp and paper and slightly less than half came from food and beverage processing.[24] In many ways, these industrial waste streams are very well suited for anaerobic digestion or other non-landfill processing/disposal, and as with MSW landfills, it is likely that industrial landfills will continue to operate and accept material for years to come. Paper and pulp waste doesn't generate methane as quickly as food waste does, but it does so for much longer, making it a highly suitable feedstock for GCCS (without necessarily needing early action).

However, only one out of the 167 industrial landfills reporting to the Greenhouse Gas Reporting Program (GH-

22 EPA, MSW Landfill Gas Collection and Control System (GCCS) Installation Lag Time and Nonmethane Organic Compound (NMOC) Destruction Efficiency, October 2024. https://www.epa.gov/stationary-sources-air-pollution/non-regulatory-public-docket-municipal-solid-waste-landfills

23 https://www.epa.gov/stationary-sources-air-pollution/non-regulatory-public-docket-municipal-solid-waste-landfills

24 https://www.epa.gov/system/files/documents/2024-04/us-ghg-inventory-2024-main-text_04-18-2024.pdf

GRP) had an active gas collection system in 2021.[25] This was the highest-emitting industrial landfill in the country, Vonco II in Minnesota, which flared all the gas it captured, emitting 227,196 metric tons of CO2 equivalent in 2023.[26] (For reference, if the gas currently being flared were upgraded to RNG, it would amount to over 75,000 MMBTU/year, with a potentially significant upside if additional wells were installed and real-time tech were adopted. Vonco II reported having 27 wells on its approximately 70 acres of landfill area, a density almost three times lower than EPA's default one well per acre recommendation for MSW landfills.)[27] Data is scarcer for industrial landfills and some may have different constraints than their MSW counterparts that might make installing gas collection systems unviable on chemical/safety grounds, but this is not the case for all industrial landfills.

Some could install gas collection systems utilizing real-time tech, including on working faces if food and beverage processing waste is being deposited, along with any or all of the second- and third-order options listed above. Installing gas capture systems from scratch would be expensive, but the most bang for the buck would come from focusing on the much smaller subset of industrial landfills emitting the most methane. Notably, of the 162 entities in the Industrial Waste category reporting to the GHGRP in 2023, the 45 emitting over 50,000 metric tons of CO2 equivalent annually (the same total emissions threshold we used in Option 3 above) accounted for 68.1% of the total reported in that category.[28] Of those, 16 facilities emitted over 100,000 metric tons of CO2 equivalent annually, accounting for 35.3% of the total, and 4 emitted over 200,000 metric tons of CO2 equivalent annually, accounting for 13.1% of the total.

It was beyond the scope of this report to assess the feasibility of installing GCCS at specific industrial landfills. However, based on GHGRP facility level data for the 16 highest-emitting industrial landfills, the vast majority – 13 – contained paper and pulp waste. (Of the remaining three, one had wood waste and two had "other industrial solid waste" so they would probably not be as feasible candidates.) Two of those 13, including Vonco II, also had food processing waste. So while we cannot assess GCCS feasibility without further details of each site, this subset is indicative of the large theoretical potential among industrial landfills overall.

Collectively, installing GCCS at suitable industrial landfills could make a significant impact. For example, a modest 20% overall reduction in industrial landfills' methane emissions would cut total U.S. methane by 0.55% (from the 2023 level), and a more ambitious 40% overall reduction in their methane emissions would cut total U.S. methane by 1.1% – that's more than the 0.9% from the option of installing new gas capture systems at high-emitting, high-flow MSW landfills (see Option 3.a. above). Every percentage point matters on the way to 30x30.

The bottom line: industrial landfills should not get a de facto free pass to keep emitting large amounts of methane and other greenhouse gases largely unchecked. Any combination of tighter regulations, state support, and market incentives (see Section IV, Policy Options to Accelerate Implementation, below) could make a significant difference in curbing emissions from this important yet overlooked sector.

25 Ibid. ; https://www.epa.gov/ghgreporting

26 https://ghgdata.epa.gov/ghgp/service/facilityDetail/2023?id=1004449&ds=E&et=&popup=true

27 https://ghgdata.epa.gov/ghgp/service/html/2023?id=1004449&et=undefined This calculation is based on the reported 300 scfm flow rate to the flare, as well as the methane concentration and operating hours. It also factors in a 5% loss in the RNG upgrading process and another conservative 5% loss from pipeline leakage in distribution to end consumers.

28 https://ghgdata.epa.gov/ghgp/main.do

III. Remaining Impact of Advanced Landfill Technology in Idealized Future Scenario Where All Food Waste is Diverted From Landfills

As noted previously, Energy Vision's 2024 report *Meeting the Methane Challenge* calculated the total feasible potential for anaerobic digesters (ADs) to process the country's food waste. Those calculations assumed that the edible half of the food that's currently discarded would first be redistributed and the other, inedible half would be diverted from landfills to ADs instead. Reducing food waste going to landfills is a key priority for cutting methane emissions, recovering nutrients, reducing the overall waste burden, and living more sustainably. So what remaining impact would the advanced landfill technology options detailed in this report have if all food waste were to be redistributed and diverted?

To model that, we assume that the real-time tech option and the new gas capture systems option are fully implemented and then all food waste would eventually be diverted from landfills. The food waste already in landfills would decompose within a few years, leaving only non-food waste in landfills. (The early action option would be vastly less impactful once food waste is no longer present in working faces, so we have conservatively excluded that option from this scenario.) **Energy Vision calculated that once food waste is out of the picture, implementing the real-time tech option and new gas capture systems options would still cut 4.11% from total U.S. methane in 2023** (or 3.81% from the higher total of U.S. methane in 2020; see box below for how this would fit in a viable path to 30x30).

That's almost half of the 8.63% total methane reduction from the three options deployed at the status quo (including the aforementioned stretch goals for landfills without gas capture systems). The estimated annual cost per metric ton of CO2 abated would be $13.76 (based on the direct costs of the advanced landfill tech, excluding capex or opex associated with RNG plant installation), which is still very cost effective relative to other notable climate solutions (see Figure 3 on page 10).

This underscores that these advanced landfill technology options are worth implementing even as efforts to redistribute and divert food waste gradually gain momentum. There is no conflict between these priorities; both should be pursued simultaneously. From a practical standpoint, the advanced landfill technology options could be implemented in just a few years (including just a few months for installing real-time tech at existing gas capture systems) – much faster than massively scaling up food redistribution and diversion from landfills to anaerobic digesters. Given the urgency of cutting methane emissions soon to stave off the worst of climate change, implementing these extremely cost-effective advanced landfill technology options should be a tangible, immediate priority.

Food waste. Photo Source: FoodandYou (Flickr)

Meanwhile, working to scale up food redistribution and food waste diversion is a much larger and more difficult endeavor, as it requires behavioral change by hundreds of millions of people, as well as major new logistics and infrastructure investments across the country (to separate and transport food for redistribution or diversion from landfills to ADs). Other developed countries have shown that food waste can be reduced significantly: for example, Japan cut its overall food waste per capita by 31% between 2008 and 2020, and the U.K. cut its overall food waste per capita by 18% from 2007 to 2021.[29]

29 https://wedocs.unep.org/handle/20.500.11822/45230; https://www.wrap.ngo/resources/report/courtauld-commit-

Although very little progress has been made in the U.S. in the past decade in terms of reducing food waste going to landfills, the programs and infrastructure are finally being put in place to tackle it in much of the U.S. For example, New York City has now implemented mandatory organics separation from regular garbage collection, meaning more of its food waste will be diverted from landfills to ADs. And when completed in Q1 2026, the Linden Renewable Energy food waste to RNG project being developed by private firms South Jersey Industries, RNG Energy Solutions and Captona in Linden, NJ will be able to process 1,475 tons of food waste daily from New York City and northern new Jersey. That amount is equal to nearly 40% of the food waste generated in New York City, to be processed at a single plant using anaerobic digesters.[30]

More broadly, the private company Divert processed over 315,000 tons of inedible food waste in 2024 in the U.S. using ADs, a 52% annual increase; it is expanding its food redistribution and food waste AD infrastructure to 30 facilities across the U.S. by 2031 that will be within 100 miles of 80% of the population.[31] That expansion would allow Divert to process 5% of all wasted food in the U.S. by 2031.[32]

ment-milestone-report-2023

30 https://www.wastedive.com/spons/sjis-flagship-rng-facility-earns-2024-energy-vision-leadership-award/729302/; https://www.nyc.gov/assets/dsny/downloads/resources/reports/zero-waste-plan/zero-waste-plan.pdf

31 https://divertinc.com/divert-processed-over-630m-pounds-of-unsold-food-products-in-2024/

32 https://www.wastedive.com/news/divert-north-carolina-anaerobic-digestion-food-waste/712641/

How Advanced Landfill Tech Fits into Multiple Paths to 30x30

There are multiple paths to cutting methane 30% by 2030 (30x30). *Meeting the Methane Challenge* laid out the potential methane reductions from building anaerobic digesters (ADs) and from various options in the oil and gas sector.[33] The figures used there are based on 2020 emissions, so for consistency here we likewise use the absolute landfill methane reductions relative to 2020 emissions to calculate progress to 30x30. We lay out two sample paths below, one based on the status quo of minimal food waste diversion and the other based on full diversion of food waste.

Figure 5: Paths to 30x30 Based on Status Quo of Minimal vs. Full Food Waste Diversion

	Reduction from Total U.S. Methane (2020 Level)	
Option	**Minimal Food Waste Diversion Scenario**	**Full Food Waste Diversion**
Food Waste Redistribution & ADs	0%	7.5%
Advanced Landfill Tech	8%	3.8%
Manure ADs	6.1%	6.1%
Plugging Stripper Wells	10.7%	10.7%
Other	5.2%	Over 1.9%
Total	**30%**	**Over 30%**

Source: Energy Vision Calculations

33 https://energy-vision.org/wp-content/uploads/2024/06/EV-National-AD-Report-1.pdf

Path to 30x30 Based on Status Quo of Minimal Food Waste Diversion

- If all three advanced tech options were implemented at municipal solid waste landfills (affecting roughly 1,000 sites, including lower-flow landfills via stretch goals), that would cut 8% from U.S. methane (as per 2020 levels).
- If about 4,000 manure ADs were built at all feasible dairy and swine farms in the U.S., that would cut 6.1% from U.S. methane.
- If all roughly 700,000 low-output "stripper" oil and gas wells were plugged, that would cut 10.7% of U.S. methane.
- The three bullet points above total 24.8%. The remaining 5.2% could likely come from a combination of other smaller options:
    - advances in cutting methane from enteric fermentation (i.e., cow belches); this is the subject of a forthcoming Energy Vision report
    - adopting secondary methane mitigation measures at municipal solid waste landfills (see box at the end of Section II)
    - adopting the three advanced tech options at industrial landfills as well as any secondary methane mitigation measures there
    - cutting methane in the oil and gas industry (through cost-effective measures like replacing leaky components with more efficient ones)
    - reducing methane from abandoned coal mines and rice cultivation
    - redistributing some edible food that would otherwise be disposed in landfills which are too small to support gas collection systems
    - diverting some food waste that would otherwise be disposed in landfills which are too small to support gas collection systems to instead go to ADs or to well-aerated composting sites.

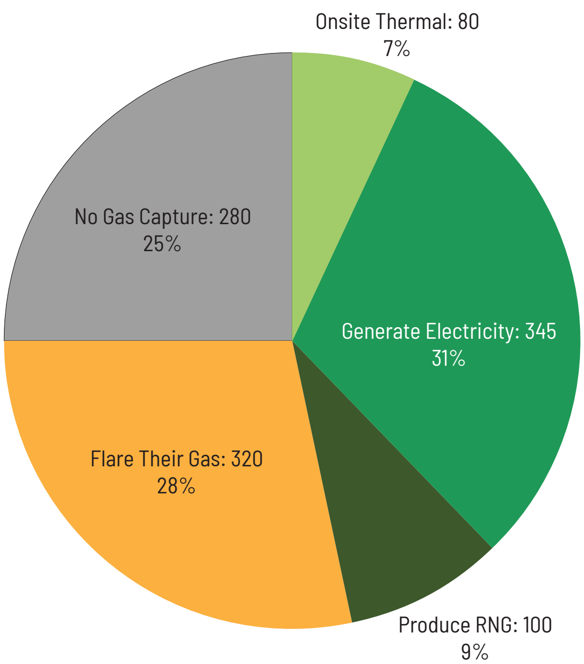
Path to 30x30 Based on Full Food Waste Diversion

- If the edible half of all food currently discarded were redistributed and the inedible half were diverted from landfills to about 700 food waste ADs, that would cut 7.5% of U.S. methane (from the 2020 level).
- If real-time tech and new gas capture systems were implemented at municipal solid waste landfills, (affecting roughly 1,000 sites, including lower-flow landfills via stretch goals), once food were totally diverted that would cut 3.8% of U.S. methane (from the 2020 level).
- If about 4,000 manure ADs were built at all feasible dairy and swine farms in the U.S., that would cut 6.1% from U.S. methane.
- If all roughly 700,000 low-output stripper oil and gas wells were plugged, that would cut 10.7% of U.S. methane.
- The four bullet points above total 28.1%. The remaining 1.9% could likely be attained and exceeded from a combination of other smaller options:
    - advances in cutting methane from enteric fermentation (i.e., cow belches); this is the subject of a forthcoming Energy Vision report
    - adopting secondary methane mitigation measures at municipal solid waste landfills (see box at the end of Section II)
    - adopting the three advanced tech options at industrial landfills as well as any secondary methane mitigation measures there
    - cutting methane in the oil and gas industry (through cost-effective measures like replacing leaky components with more efficient ones)

IV. Policy Options to Accelerate Implementation

Recognizing the current political reality of the Trump administration systematically dismantling federal environmental and climate regulations, near-term progress in tackling landfill emissions will likely happen at the state and local levels as well as in the private sector. Many of the same policy options noted below could be enacted at the federal or state levels. They would make a bigger overall difference if enacted at the federal level, however unlikely this is at present. State-level policies could be very impactful within the much smaller subset of landfills within their borders, and some progressive states are indeed tackling landfill methane emissions (see the Colorado case study below).

Figure 1: How the 1,125 Landfills Reporting to the GHGRP in 2023 Used Their Gas



Source: Energy Vision chart based on EPA [GHGRP Reporting Year 2023] data, EPA Landfill Methane Outreach Program ([LMOP]) data from September 2024, Energy Vision-Argonne National Laboratory [RNG Database] 2023 Calendar Year

As noted previously, 100 of the 1,125 municipal solid waste landfills (almost 10%) reporting to the Greenhouse Gas Reporting Program (GHGRP) in 2023 produced RNG. About 80 others used their gas for onsite thermal uses (i.e., as boiler fuel), around 345 other GHGRP landfills generated electricity, and roughly 320 others reporting to the GHGRP flared their landfill gas. The remaining 280, about a quarter of the total, did not have gas collection systems.

Tighter Federal/State Regulations

The policy options to accelerate implementation, as detailed in the EPA white papers[34] and exemplified in the Colorado case study below, include:

- **Changing the landfill size threshold requiring GCCS installation to be actual tonnage of waste in place rather than permitted capacity.** Federal regulations require GCCS installation if a landfill has a permitted design capacity of at least 2.5 million megagrams and at least 2.5 million cubic meters of municipal solid waste. By contrast, California, Oregon, Washington State, and Maryland have all enacted regulations requiring GCCS installation based on much smaller thresholds of waste in place: typically 450,000 tons (408,000 megagrams), meaning less than one fifth of the 2.5-million-megagram federal design capacity threshold. Oregon's threshold is the tightest at 200,000 tons (181,000 megagrams).

- **Lowering the emissions thresholds for landfills that must install a GCCS.** Whether based on emissions of non-methane organic compounds or methane, the threshold for having to install a GCCS can always be made more stringent while still being at a feasible level for operators to comply with.

- **Mandating earlier installation of GCCS, including in working faces.** As noted in Option 2 (Early Action), there is untapped yet massively cost-effective potential to capture methane emissions from food waste in active faces through horizontal collection wells.

34 https://www.epa.gov/stationary-sources-air-pollution/non-regulatory-public-docket-municipal-solid-waste-landfills

A horizontal gas collector with real-time tech at a landfill working face. Photo Source: LoCI Controls.

- **Requiring more frequent and accurate emissions reporting, including through such options as real-time tech and aerial/satellite monitoring.** The minimum federal reporting requirements for an operating GCCS are that collection points must be monitored once per month and surface emissions must be monitored once per quarter to ensure the system is working properly. But these are wholly inadequate, given how much landfill emissions vary over time (as noted in Option 1, Real-Time Tech) and how limited and error-prone walking surface measurements are (as noted in the Box on Additional Landfill Options). More frequent and more accurate monitoring and reporting requirements would identify problems sooner and spur corrective action, whether mandated or incentivized. And if this leads to wider adoption of real-time tech at landfills, all the better. Option 1 shows the hugely cost-effective methane reduction potential of installing real-time tech at all landfills with GCCS.

Overall, these measures would result in more high-emitting landfills having to install GCCS. That would entail unexpected costs for landfill owners, but as noted in Option 3 (New Gas Capture Systems), this would capture large amounts of methane very cost-effectively. By pairing enhanced regulation with expanded access to renewable energy/fuel markets, it's likely that the economic incentives and benefits can outweigh concerns about increased compliance costs.

Colorado Sets the Pace with Proposed MSW Landfill Methane Reduction Plan

In April 2025, Colorado released its proposed draft of what would be the country's most stringent MSW landfill methane emissions standard.[35] Landfills are the state's third-largest source of methane emissions. Addressing them is a near-term priority given that Colorado has passed legislation requiring a 26% reduction in GHG emissions by 2025 compared to 2005 levels; this will extend to a 50% reduction by 2030, 65% by 2035, 70% by 2040, 95% by 2045, and net-zero emissions by 2050.

Colorado's proposed landfill methane reduction plan, which will proceed to a rulemaking hearing in August 2025, incorporates the three advanced tech options and many of the secondary impact best practices as described in this report. It is based on a methane emissions threshold and actual waste in place, unlike the existing federal regulations. More Colorado MSW landfills would be required to install GCCS under this plan to manage their emissions. The rules would also require that corrective action be taken in a timely manner to address any malfunctions or detected leaks.

1. Real-time tech is highly encouraged if not de facto required

- Under the proposed rules, owners/operators of landfills subject to the GCCS requirements must install a sampling port and measuring devices, or an access port for measuring devices, at all wellheads. On at least a weekly basis at each wellhead, they must monitor and record nitrogen or oxygen concentrations in the landfill gas, the gauge pressure, and the temperature of the landfill gas.
    - In the case of measuring any positive gauge pressure or temperature exceedance, owners/operators must complete corrective action within 5 days; if it would take longer than that, they have to do a thorough system-wide investigation and take corrective action according to the findings.
- Overall, GCCS must be designed to:
    - Handle the maximum expected gas generation flow rate over the lifespan of the waste.
    - Maintain a negative pressure at all wellheads without causing air infiltration, including any new wells added to the system.
    - Collect gas to comply with the surface methane emission limits, minimize or prevent equipment leaks, and meet all other performance standards.
    - While these criteria don't explicitly mandate real-time monitoring and automated tuning systems, those are the type of gas capture systems that would enable compliance with all of these requirements for frequent monitoring and adjusting to minimize leaks.

2. Early action is mandatory

- Colorado's proposed landfill regulations require that a GCCS be capable of expansion, including installation of horizontal collecting wells.
- For an MSW landfill accepting less than 200,000 tons per year of solid waste, GCCS must be expanded so that it is operational collecting from areas where solid waste has been in place for 12 months.
- For an MSW landfill accepting at least 200,000 tons per year of solid waste, GCCS (including horizontal collecting wells) must be installed prior to solid waste being placed and while further waste is added.
    - These systems must begin operations after at least 15 vertical feet of solid waste has

35 See REG.SBAP.pdf at https://drive.google.com/drive/folders/1oUQ6xyMl5ejJTyIYvmaVF_ijWRqbvjIV

been placed over a horizontal collector, and when landfill gas pressure is detected by mandatory weekly pressure monitoring or the waste has been in place for at least 12 months.

3. New gas capture systems are required based on tighter criteria

- Unlike the federal landfill regulations based in part on a large permitted capacity of 2.5 million megagrams and 2.5 million cubic meters of municipal solid waste, Colorado's proposed rules use a much smaller threshold of actual waste-in-place (450,000 short tons, equivalent to 408,000 megagrams) triggering regulatory coverage.

- Colorado's proposed landfill rules require regular methane emissions measurements and/or calculations, and they require GCCS installation based on a methane threshold (at least 1,814 metric tons per year). This is in stark contrast to the federal landfill regulations based on emissions of non-methane organic compounds.

- Owners/operators of landfills meeting these thresholds would also have to install and operate GCCS sooner under Colorado's proposed regulations than under federal ones.

  - Active MSW landfills required to install and operate GCCS must do so within 18 months after the deadline for submitting the design plan to the state authorities.

  - Inactive or closed MSW landfills required to install and operate GCCS must do so within 24 months after the deadline for submitting the design plan to the state authorities.

4. Other best practices are required or eligible

- Colorado's proposed rules incorporate the usage of remote monitoring, including from third parties as approved by the Colorado Hazardous Materials and Waste Management Division (referred to as "the Division") or by the EPA.

  - The Division can send notification to operators within 7 days of receiving complete monitoring data for a given incident.

  - Within 5 days of receiving such a notification, the owner or operator of an MSW landfill must investigate the cause of the emissions and perform any necessary corrective actions. In some cases this may mean installing a gas capture system if one is not in place already.

  - The owner or operator must report the results of the investigation and any corrective actions to the Division within 15 days of being notified, plus send a follow-up report within 7 days of the mitigation measures being completed.

- Owners/operators must also implement measures to prevent emissions from landfill working faces, such as minimizing the size of working faces based on how much waste is being deposited.

- Surface emissions monitoring must be conducted at 25-foot spacing on landfills rather than the 100-foot spacing required under federal regulations, improving detection of leaks.[36]

- If regular surface emissions monitoring detects a leak above the stringent allowed threshold, owners/operators must take corrective action such as cover repair and well vacuum adjustments. This must be initiated no later than 3 days after detection and completed no more than 5 days after detection.

- Horizontal collection wells must be properly sloped to drain liquids that accumulate.

- Permitted flares can be enclosed or open for the next few years. But open flares will no

36 See EIA.pdf at https://drive.google.com/drive/folders/1oUQ6xyMl5ejJTylYvmaVF_ijWRqbvjlV

longer be allowed at any MSW landfill starting in 2029, unless the methane generation rate is less than 664 metric tons (732 tons) per year, or the open flare is used as a backup, or it was recently installed (between 2020 and 2025). The latter two caveats don't apply if the open flare is within one mile of a disproportionately impacted residential community.

- Owners/operators must use a biocover (a porous layer such as sand or gravel and an organic layer such as compost) as part or all of a landfill's intermediate cover, specifically to promote activity by methanotrophs (microorganisms that break down methane).

- For active or inactive MSW landfills with at least 450,000 tons of waste in place, owners/operators must monitor cover integrity and implement any necessary cover repairs or maintenance on a monthly basis.

Anticipated Costs

Colorado's proposed landfill methane reduction plan would impose additional costs for MSW landfill owners/operators, especially if GCCS would have to be built at landfills that currently lack them. If the rules are enacted, 18 MSW landfills that do not have GCCS currently would be required to build them or conduct surface emissions monitoring to determine if a gas capture system must be installed.[37] For the 14 Colorado landfills with existing GCCS (12 of which are required to have them under federal regulations and 2 others have installed them voluntarily), costs would rise to a lesser degree to come into full compliance if the rules are enacted.

According to the Economic Impact Analysis (EIA) submitted by the Colorado Department of Public Health and Environment, the capital cost of installing GCCS over the 956 acres of filled-in area across the 18 landfills that do not yet have GCCS is $49 million. (That surface area is expected to increase by an average of 10 acres per year collectively among the 18 landfills.) Annual opex for GCCS at those 18 landfills would be $7.5 million. Additionally, it would cost each landfill an estimated $14,400 to prepare the waste-in-place, methane generation, and annual compliance reports ($4,800 apiece), and surface emissions monitoring would be another $29,200 per year. Between 2029 and 2050, the total cost of compliance (using a 2.5% discount rate), including reporting, early installation of horizontal collectors, and GCCS, would be $175 million.

Staff from major landfill owner/operator companies Waste Management and Republic Services voluntarily joined a state-convened Technical Working Group whose input helped inform balanced and thorough recommendations for curbing landfill methane emissions. Over the course of six meetings, they provided feedback on matters including operational and maintenance requirements for GCCS as well as the timing for when those systems should be installed.[38] Some expressed the need for further testing, with Waste Management's senior director of air programs noting, "Landfills are complicated, emissions vary over time, and we have emissions 24/7. Drones produced a lot of false positives—and we need more work understanding how fixed sensors can be applied in a landfill environment."[39]

Many of the landfills that would likely have to install GCCS under the new rules are operated by counties. An open letter in support of the rules was signed by 42 local officials including commissioners from Boulder, San Miguel, Adams, Larimer, Eagle, and Pitkin Counties.[40] "Landfills across Colorado, including in Eagle County, are leading sources of methane pollution – a powerful greenhouse gas and significant contributor to the climate crisis," said Eagle County Commissioner Matt Scherr. "When it comes to reducing these emissions, we should take advantage of every tool in the toolbox. As a local elected official, I support a robust rule that embraces advanced technologies to cut pollution, protect public health,

37 See EIA.pdf at https://drive.google.com/drive/folders/1oUO6xyMl5ejJTylYvmaVF_ijWRqbvjlV

38 https://www.wastedive.com/news/colorado-landfill-methane-rule-proposal-public-meetings/741641/

39 https://www.fastcompany.com/91343766/colorados-landfills-generate-as-much-pollution-as-driving-1-million-cars-for-a-year

40 https://www.americaisallin.com/elected-officials-cdphe-cut-landfill-methane

and help the methane mitigation industry thrive."[41] Such county support is not universal, though. At a hearing on the proposed rules in February 2025, Delta County Commissioner Craig Fuller said, "We are a small rural county, and a multimillion-dollar containment system is going to be more than we can build. The financial equation of this whole thing is absolutely mind-boggling—we are struggling as it is to provide health and human services."[42]

However, state health officials suggested that the costs of installing GCCS could be offset by putting the captured landfill gas to beneficial use – i.e., generating electricity or producing renewable natural gas. Several grant programs may be available to help fund GCCS, including Colorado's Clean Air Program Grants to reduce industrial air pollution and the Closed Landfill Remediation Grant Program to remediate closed landfills that are owned by eligible local governments.[43] There are also precedents for publicly owned landfills complying with such thresholds in other states (California, Oregon, Washington, Michigan, and Maryland), for example helping to meet the additional funding obligations by issuing municipal bonds.

The EIA also noted that based on the experiences of other states, the proposed rule would not be expected to raise tipping fees for consumers to deposit waste at landfills. After passing their own state-level landfill methane rules, California saw tipping fees increase by $5 and Oregon saw tipping fees decline by $14. Rather than the methane rules, the most important factors affecting those tipping fees were the cost of vehicles, fuel, labor, and negotiated contracts between landfills and haulers.[44] But even if the full cost of annual compliance with Colorado's proposed rule were transferred to the nearly 350,000 affected households, it would only amount to a $22.90 increase in the average annual tipping fee per household.

Expected Emissions Reductions and Cost-Effectiveness

All told, the proposed rule would lead to the capture and destruction of 12.3 million metric tons of CO2 equivalent from Colorado MSW landfills between 2029 and 2050. This would avoid $1.05 billion in direct and indirect climate change damages, based on the U.S. government's 2021 social cost of carbon and a 2.5% discount rate. That means that between 2029 and 2050, the total cost of compliance ($175 million) with the proposed rule would avoid six times that amount in climate change costs ($1.05 billion).

Based on these results, the cost per metric ton of CO2 equivalent reduced under Colorado's proposed plan would be $14.28 – near the middle of cost estimates for similar rules in other states, which have ranged from $6 to $25 per metric ton of CO2 equivalent reduced. The EIA also calculated that the plan would create 402 direct jobs and 1,382 indirect jobs by 2050.

41 https://www.americaisallin.com/colorado-leaders-call-nation-leading-landfill-methane-rules-advance-climate-goals-protect-public

42 https://www.fastcompany.com/91343766/colorados-landfills-generate-as-much-pollution-as-driving-1-million-cars-for-a-year

43 https://energyoffice.colorado.gov/cap-grants; https://cdphe.colorado.gov/hm/closed-landfill-remediation-grant-program

44 https://erefdn.org/product/analysis-of-msw-landfill-tipping-fees-2023/

Expanded Federal/State Incentives

- **Expand incentives for beneficial use at landfills implementing best practices in gas capture.** Incentives to put landfill gas to beneficial use – RNG production or electricity generation – are the largest driver of real-time tech adoption and new GCCS construction. Some states have enacted "compliance offset protocols" – for example, directives to reduce power emissions by a certain percentage – in which additional landfill gas captured could generate credits if the end use is transportation. Updating compliance offset protocols to include landfill methane emission reductions from real-time tech would facilitate broader adoption for landfills, whether or not they include beneficial use projects for the captured gas. Additional states can adopt their own incentives for beneficial use tailored to their needs and preferences.

  To incentivize the greatest climate benefits, eligibility could be limited to landfills that are following best practices as noted in this report (real-time tech, early action, minimized working faces, appropriate cover, remote monitoring, etc.) and which are not leaking significant amounts of methane (for example, from areas producing lower-quality landfill gas that would be more expensive to upgrade to RNG). This aspect of comprehensive stewardship is important because significant methane emissions have been detected through remote aerial monitoring from over 20 large landfills that have RNG projects, especially from working faces.[45]

45 https://pubs.acs.org/doi/10.1021/acs.est.4c07572

Lifecycle Carbon Intensity of Landfill RNG

Most landfill RNG projects are destined for the transportation sector. The RNG is typically sold into state-level Clean Fuel Standard programs in California, Oregon, and Washington (New Mexico has enacted one due to take effect in 2026 and about 10 other states are considering adopting one of their own). Under a Clean Fuel Standard, each fuel's lifecycle greenhouse gas emissions are calculated, either generating credits or deficits as the overall target for decarbonizing the transportation sector gets more stringent each year.

According to approved pathways in California's Low Carbon Fuel Standard as of Q3 2024, landfill RNG used in the transportation sector had an average lifecycle carbon intensity of 47.9 grams of carbon dioxide equivalent per megajoule (g CO2e per MJ), 52.4% less than the 100.6 g CO2e per MJ of gasoline/diesel. For reference, the 47.9 g CO2e per MJ from landfill RNG was just above the 44.8 g CO2e per MJ from electric vehicles using electricity from the California grid (which still had considerable fossil fuel generation in addition to renewables).[46]

If these state-level Clean Fuel Standard programs were to recognize the avoided upstream methane emissions at sites adopting advanced landfill tech beyond regulatory requirements, then the applicable projects could verifiably achieve lower lifecycle carbon intensity scores. Those projects would therefore generate more credits, improving their economic viability and accelerating the uptake of advanced landfill tech elsewhere to follow suit.

46 See chart on p. 14 of Energy Vision's report, *A Path to a Healthier America: Ditching Old Diesel Trucks* https://energy-vision.org/wp-content/uploads/2025/03/ditching-diesel.pdf

A vertical landfill wellhead with real-time tech. Photo Source: LoCI Controls.

- At the federal level, the creation of eRINs (credits for electricity used in transportation under the Renewable Fuel Standard) could help drive more landfills to generate electricity from their captured gas, but this pathway was proposed a decade ago and has not yet been implemented by US EPA. It is also unlikely to materialize under the Trump administration, as the latest Renewable Fuel Standard proposed rulemaking (released in June 2025) would eliminate any eligibility for eRINs.[47]

  The current incentive structure for landfill gas heavily favors RNG. There are over 100 operational landfill RNG projects, and the overwhelming majority (103) of landfill beneficial use projects under construction or being planned are pursuing RNG rather than electricity (13), according to EPA's Landfill Methane Outreach Program.[48] There is very little new investment in landfill electricity generation, and it mostly consists of add-ons to current projects. Most landfill electricity generation facilities are seriously considering or actively pursuing a transition to RNG after their existing Power Purchase Agreements expire.

- **Provide direct subsidies for GCCS.** Installing and maintaining GCCS both entail significant costs. The EPA white paper on landfill size threshold cites one estimate showing that capex for traditional GCCS (without real-time tech or deployment at active faces) can be in the range of $1-3 million. Meanwhile, opex for traditional GCCS is $150,000-$400,000 per year, plus another roughly $60,000 annually for monitoring, recordkeeping, and reporting requirements.[49] EPA's LFG Energy Project Development Handbook also provides cost estimates on a per acre basis. Adjusted for inflation from the 2020 figures provided in the handbook to 2024 figures, GCCS installed capital costs for a mid-sized landfill are $39,850/acre, and annual O&M costs are $6,680/acre.[50]

---

47 https://www.epa.gov/system/files/documents/2025-06/420f25008.pdf

48 https://www.epa.gov/lmop/lmop-landfill-and-project-database (updated September 2024)

49 EPA, MSW Landfill Size Threshold, October 2024. https://www.epa.gov/stationary-sources-air-pollution/non-regulatory-public-docket-municipal-solid-waste-landfills

50 https://www.epa.gov/system/files/documents/2024-01/pdh_full.pdf; https://www.minneapolisfed.org/about-us/

Adding real-time tech would increase these costs, again on the baseline 75% coverage of wellheads at a typical landfill being sufficient to significantly improve overall results. Each wellhead equipped with real-time tech would cost an incremental $7,000 in capex as well as $1,500 in annual opex.

Given the significant costs involved with GCCS, any subsidies would facilitate their adoption. Subsidies are more realistic at the state level than at the federal level given EPA funding cuts and hostility to methane mitigation measures from the Trump administration. For example, the State of Washington offers landfill methane emissions reduction grants, including for GCCS construction, maintenance, and maximization of gas capture beyond regulatory requirements; the most recent application round in 2024 had a total of $9.6 million available.[51]

On a separate but relevant note, voluntary carbon offset markets do include non-mandatory methane capture at landfills, based on multiple certification protocols using the best available science. Some landfills that were not required to install gas capture systems have done so in part to generate voluntary carbon credits (VCCs). Even landfills that are required to install GCCS can generate VCCs by going above and beyond the regulations to enhance gas capture with advanced tech, proving the additionality of the captured gas. Many of the landfills that voluntarily installed GCCS have subsequently grown to the point where they are required to operate such systems and no longer generate VCCs (unless they capture more gas than the minimum requirements). That said, between 35 and 50 U.S. landfills have been generating VCCs over the past few years through voluntary GCCS operation or by implementing advanced technologies to increase methane capture.[52] However, the prices for these VCCs are relatively low, because demand has been limited.

A Proven, Cost-Effective Solution Deserving of Serious Consideration

As noted above, the current market incentives heavily favor landfill RNG production and more than 100 landfill RNG projects are planned or under construction. We therefore anticipate that virtually all of the captured methane from implementing the Total Feasible Today combination of the three advanced landfill tech options in this report would likewise be upgraded to RNG. (For this big picture conclusion we exclude the stretch goals for lower-flow landfills that don't have GCCS, since they would probably not be able to put their captured gas to beneficial use and would instead flare it.)

The additional methane captured by the Total Feasible Today combination, once upgraded to RNG and factoring in a conservative 5% leakage rate in pipelines, would amount to a very substantial 93 million MMBTU/year.[53] That would be more than double the amount of RNG produced by landfills and used in the U.S. transportation sector (the overwhelming end use) in 2023: 73.5 million MMBTU. Of note, landfills produced two thirds of all RNG for the U.S. transportation sector in 2023. Another 93 million MMBTU would be close to the total amount of RNG produced in 2023 that went to the transportation sector: 108.4 million MMBTU.

Together, almost 900 landfills would be candidates for the three options feasible today featured in this report (845 with GCCS could adopt real-time tech, including 432 open ones with GCCS also adopting early action, plus 43 high-emitting, high-flow landfills could install new gas capture systems). They would be capturing and putting to beneficial use far more energy than they are today, where much of it is wasted.

While every site has its own unique characteristics, overall there is a very compelling business case to implement the Total Feasible Today combination.

monetary-policy/inflation-calculator

51 https://ecology.wa.gov/about-us/payments-contracts-grants/grants-loans/find-a-grant-or-loan/landfill-methane

52 https://gspp.berkeley.edu/berkeley-carbon-trading-project/offsets-database

53 Calculated by dividing the Total Feasible Today emissions reductions of 49.4 million metric tons of CO2 equivalent per year (which factors in a 5% loss in the RNG upgrading process and another conservative 5% loss from pipeline leakage in distribution to end consumers) by the Global Warming Potential of 28 for methane, then multiplying by 52.7 MMBTU per metric ton of methane, which amounts to 93 million MMBTU/year of RNG.

Conservatively valuing the additional 93 million MMBTU/year of RNG produced at $20/MMBTU (environmental attributes plus the commodity gas) in the years ahead, that equates to $1.86 billion annually in new gross revenue generated. Meanwhile, the estimated cost of the Total Feasible Today combination is $1.3 billion in onetime capex and $250 million in annual opex. Aggregated across all the candidate landfills, this means an overall payback period of less than a year once the new equipment is operational, after which this would be a significant net revenue earner for many years. (As noted previously, this is based on the direct costs of all the advanced landfill tech feasible today and the additional revenue from the incremental gas capture; it excludes capex or opex associated with RNG plant installation.)

Plus, adopting advanced landfill tech is among the lowest cost carbon abatement options available. The technology is proven, commercial, and scalable. And it specifically cuts fugitive methane emissions, which means each new installation provides "additionality" – often a preference for potential renewable energy and voluntary carbon credit buyers, and a key component of reaching 30x30 in time to forestall the worst effects of climate change.

It was beyond the scope of this report to model the air quality and public health benefits from adopting advanced landfill tech, but they would be significant, based on two facts. One is that methane is a precursor to the formation of ground-level ozone, a toxic air pollutant that is particularly harmful to people and vegetation (including crop yields).[54] The second is that landfills emit other hazardous air pollutants alongside methane, such as volatile organic compounds, ammonia, and hydrogen sulfide, which would likewise be captured in GCCS and burned off, which is far better than being breathed in by landfill workers and nearby residents.

The bottom line: adopting advanced landfill tech is a major, quick win at a very low cost relative to many other climate solutions. Because it also addresses potent methane emissions, it should be a very high near-term priority.

54 https://www.ccacoalition.org/short-lived-climate-pollutants/methane

Horizontal gas collectors with real-time tech at a landfill.
Photo Source: LoCI Controls.

Authored by: Michael S. Lerner

JULY 2025

ENERGY VISION

138 East 13th Street, New York, NY 10003 | 212.228.0225 | www.energy-vision.org

Office of Air and Radiation
December 2024

White Paper Series: Municipal Solid Waste Landfills – Advancements in Technology and Operating Practices

Fenceline Monitoring

Prepared by the
Sector Policies and Programs Division
Office of Air Quality Planning and Standards
U.S. Environmental Protection Agency
Research Triangle Park, North Carolina 27711

December 2024

White Paper for Evaluating Revisions to the Municipal Solid Waste (MSW) Landfills New Source Performance Standards (NSPS) and Emission Guidelines (EG)

- This series of white papers examines ways to improve the NSPS for Municipal Solid Waste (MSW) Landfills using new information and new technology to further control and reduce landfill gas emissions.
- Topics include applicability (size of landfill), controls (emission rate and timing of controls), operating practices (cover practices, active face), waste composition (organics), and emission monitoring (technology).

Topic: The use of fenceline monitoring for early detection of emissions from landfills

This white paper investigates the use of fenceline monitoring as a technique to detect emissions from landfills early such that the landfill owner/operator can take action to address and mitigate the source of the emissions. Fenceline monitoring and associated work practice requirements have been promulgated in other regulations developed by EPA as an important component of mitigating emissions from fugitive and other difficult-to-monitor sources such as equipment leaks, storage tanks, loading operations, and wastewater treatment systems. This white paper explores the feasibility of incorporating a similar fenceline monitoring program in the upcoming NSPS/EG rulemaking.

Rationale and Possible Results

Fenceline monitoring requirements and associated work practice standards have been promulgated in several regulations by EPA. For example, fenceline monitoring and associated work practice requirements have been implemented at petroleum refineries through requirements in 40 CFR part 63, subpart CC. Fenceline monitoring requirements have also been finalized for chemical plants and Group I polymers and resins plants in 40 CFR part 63, subparts H and U, respectively, for coke ovens in subpart CCCCC, and for integrated iron and steel facilities in subpart FFFFF.

The petroleum refinery regulations[1] require owners and operators to monitor benzene emissions at the facility's fenceline using passive diffusive sorbent tubes and Methods 325A and 325B of 40 CFR part 63 (EPA Method 325A/B). Method 325A is used to locate the monitors around the perimeter. Method 325B describes the analysis procedures, uptake rates, and appropriate sorbents for use in the passive monitors for the hazardous air pollutant (HAP) to be monitored.

The passive sampling tubes are left in place for two weeks and then collected and analyzed. When one set of passive sampling tubes is collected, a new set is deployed, providing continuous sampling at the fenceline. For each biweekly sampling period, the facility determines its contribution to the fenceline emissions by subtracting the lowest sample result in the set from the highest sample result. This concentration difference (Δc) is then averaged over a year on a rolling basis (i.e., the most recent 26 results are averaged every biweekly period). If the facility exceeds the threshold specified in the rule (the

[1] Although fenceline monitoring requirements exist for other source categories, the discussion here is limited to the requirements at petroleum refineries because the fenceline monitoring requirements for the other source categories have not gone into effect yet.

action level), the work practice requirements are triggered and the facility must investigate the root cause of the exceedance, and if appropriate, take corrective action to mitigate the emissions.[2]

Fenceline monitoring data have been generated at petroleum refineries for several years. Data show that petroleum refinery fenceline concentrations have dropped by an average of 30 percent since the inception of the monitoring program requirements in the four years beginning in 2018 (U.S. EPA 2023). These results illustrate that fenceline monitoring and the associated work practices are an effective tool in reducing benzene emissions at the fenceline of petroleum refineries. The fenceline monitoring program in refineries added a new layer of monitoring that allowed for the early identification and repair of fugitive sources of emissions.

The fenceline monitoring approach is used to identify areas within the facility that may be contributing to high emissions at the fenceline. The source(s) of the emissions can be subsequently identified and repaired as necessary, or different operational practices may be employed to reduce emissions from intermittent events in the future. Fenceline monitoring has been used to:

1. Measure HAP emission concentration around the fenceline of facilities as opposed to estimating emissions.
2. Identify areas within the facility that may be sources of HAP emissions – these sources could be point or area sources.
3. Manage fugitive emissions by allowing facilities to identify and repair leaking equipment such as pumps, connectors, and valves; implement better control of storage tanks; address emissions from wastewater treatment operations; and innovate or update process operations to reduce HAP emissions.
4. Realize significant HAP emission reductions through ongoing fenceline monitoring.
5. Work with local communities surrounding facilities to illustrate the efforts and work practices that have been implemented to reduce HAP emissions from facility operations and reduce community exposure to HAP emissions.

Although fenceline monitoring at refineries has resulted in reductions in emissions at the fenceline through identification and repair of fugitive sources of emissions, and implementation of different operational practices, it is not as clear whether similar reductions would be realized at MSW landfills. Landfill point and fugitive sources are unique compared to petroleum refineries; many refinery sources can be identified and repaired relatively quickly, or operational practices can be implemented to reduce emissions.

Because of the large footprint of the landfill, the topography encountered at landfills, and the variability of the emissions found at landfills, identifying the sources of elevated emissions monitored at the landfill perimeter is not always straightforward. However, a fenceline monitoring approach could be used to indicate when, and in general where, there are elevated emissions at the landfill. This could allow landfill operators to combine their knowledge of the site with additional monitoring techniques, such as Method 21 of 40 CFR part 60 Appendix A-7 (EPA Method 21) or optical gas imaging, to identify leaking

[2] In certain instances, corrective action may not be warranted because the emissions may be caused by offsite sources and events outside the control of the facility.

wellheads, leachate sources, cover penetrations, cracks or seeps in the landfill cover, or other fugitive sources on the landfill surface and mitigate these emissions.

The use of fenceline monitoring has been implemented at landfills, although in a different way than at petroleum refineries. Because landfills are large facilities, in some cases covering hundreds of acres, and because of the topography of the landfill, the everchanging location of the work face and vehicle traffic, and the operational activities occurring at the landfill, it may not be practical or even necessary to install monitors around the entire fenceline of the landfill. It may be just as effective to install monitors around the facility perimeter along the active area of the landfill. Where fenceline monitoring has been applied at landfills, the monitors have been placed at strategic locations on the landfill perimeter, close to both the active face of the landfill and to the surrounding communities that would be most affected by emissions from the landfill.

Fenceline monitoring for methane and hydrogen sulfide at the Arbor Hills landfill (AHL) in Salem Township, Michigan is instructive in how fenceline monitors could be incorporated into the upcoming NSPS/EG rulemaking. AHL has developed a website that provides background information, a map showing the most recent results for each of the six monitors, a table of results (for both methane and hydrogen sulfide) for each monitor, and the meteorological data from a 10-meter meteorological tower (GFL Environmental, 2024).

Investigations

Since early 2024, EPA has met with MSW landfill stakeholders, including representatives from industry, environmental groups, and environmental justice groups to understand the perspective of the various stakeholders. Based on these meetings, it is clear that the affected communities around the landfills would like to better understand the emissions from the landfills; in other words, they would like to know to what emissions they are being exposed. These groups would like for landfills to conduct fenceline monitoring and would like to see the monitoring results, similar to a landfill in North Carolina.

The Sampson County Disposal (SCD) Landfill (North Carolina), will post data to a community website, providing another example of how communities can be made aware of fenceline monitoring results. Identifying emission events sooner than the quarterly surface emissions monitoring events that are required in the NSPS/EG and requiring the landfill owners/operators to address locations on the landfill surface that require repair (either surface areas or cover penetrations) would be beneficial because it would help address emissions that communities are exposed to in a more expedient fashion.

As discussed in more detail below, in Michigan, AHL entered into a consent decree with the Michigan Department of the Environment, Great Lakes, and Energy (EGLE) to conduct monitoring at the perimeter of the landfill adjacent both to the working face of the landfill and to local communities (State of Michigan, 2024). The consent decree requires that the landfill install six monitors at the northeast perimeter of the landfill to monitor emissions of both methane and hydrogen sulfide (H_2S). The consent decree specifies the installation of six Scentroid CTair monitoring stations, which monitor for both H_2S and methane on a continuous basis using a sampling rate of approximately once per minute. Results are posted using an averaging period of 15 minutes on a rolling basis.

The monitoring system includes a feature that alerts landfill personnel through an app on their smartphones when emissions are detected at levels above specific thresholds for methane or H_2S. The landfill is required to identify the source of the elevated emissions detected at the fenceline and mitigate the exceedance of the perimeter action levels within 48 hours after detection; if AHL cannot mitigate the exceedance within 48 hours, AHL can request an extension of time from Michigan EGLE.

Examples/Case Studies

This section discusses consent decrees for two landfills where fenceline or perimeter monitoring of emissions has been required. These examples illustrate how fenceline monitoring requirements could be implemented at landfills and illustrate some of the challenges inherent in applying fenceline monitoring at landfills.

Arbor Hills Landfill, Salem Township, Michigan

The AHL consent decree originated after residents in the neighborhoods located adjacent to the northeast corner of the landfill complained to EGLE about odors from the landfill. The consent decree was reached between AHL and EGLE as a remedy for the landfill to respond to instances of high H_2S emissions. EGLE viewed the use of perimeter or fenceline monitoring as a way for the landfill to identify odor issues and address the source of the emissions quickly.

Continuously monitoring emissions at the fenceline provides the landfill with an indication of when there is an issue that needs to be investigated and based on the location of the high monitor readings, the perimeter monitoring system incorporates software to help the facility identify the source of high emissions when the perimeter action levels for either methane or H_2S are triggered. However, there have been instances where, upon investigation, it has been challenging for the landfill operators to identify the source of odor; the landfill consists of 337 acres and emissions measured at the fenceline provide only a general idea of where the emissions are coming from.

In developing the consent decree, EGLE worked with AHL to determine H_2S and methane concentrations or perimeter action levels that would trigger an alert to landfill operators' phones. Perimeter action levels of 30 parts per billion (ppb) for H_2S and 40 ppm for methane, based on a 15-minute rolling average were established for the fenceline monitors at AHL. The 30 ppb perimeter action level for H_2S is based on the California ambient air quality standard for H_2S of 0.03 ppm for a one-hour average; the perimeter action level at AHL of 30 ppb H_2S is based on a 15-minute average. To determine the perimeter action level for methane, a consultant conducted perimeter methane monitoring at AHL over a two-week period and correlated emissions measured with emissions events at the landfill; the 40 ppm perimeter action level corresponds to an unusual emissions event at the landfill. Based on their experience in applying this perimeter action level at the fenceline, EGLE contends that this level is the appropriate level to trigger further investigation.

The Michigan-Ontario Ozone Source Experiment (MOOSE) study, a flyover study conducted by EGLE along with other partners including the Ontario Ministry of Environment, Conservation and Parks (MECP), Environment and Climate Change Canada (ECCC), the National Aeronautics and Space Administration (NASA), and the US Environmental Protection Agency (EPA), identified narrow bands of H_2S plumes and the locations where these bands tend to occur (Michigan EGLE, 2021). Using modeling and this flyover study, EGLE determined the number of monitors needed to provide adequate coverage around the northeast corner of the landfill, and the locations that should be monitored to ensure detection of H_2S emissions with a high level of confidence. The northeast corner of the landfill was chosen for monitoring because it is adjacent to the active face of the landfill and is closest to the neighborhoods that have submitted complaints. Figure 1 provides a map of the facility showing the location of the monitors.

Figure 1. Location of the perimeter monitoring stations at the Arbor Hills Landfill, Salem Township, Michigan (State of Michigan 2024).

The AHL also operates a compost facility just to the north of the landfill. The compost facility sometimes receives materials that are in a fermented state, such as yard waste that has already begun to decompose, which causes odor to originate from the compost plant. One monitor is located about 0.3 miles Southeast of the main composting processing area, which has resulted in instances where the methane perimeter action level was exceeded. However, there have not been any exceedances of the H_2S perimeter action level at this monitor due to the composting pile. Nevertheless, the composting area has been and continues to be a significant source of odor complaints. The odor complaints are usually the result of improper composting management or accepting compost loads that are already fermenting upon arrival.

The consent decree also required that AHL use the Sniffer Drone (an unmanned aerial system developed by Sniffer Robotics, Inc.) to conduct surface emissions monitoring as follows:

- Monthly, at 30-meter intervals in areas with final cover or geomembrane temporary cover and at 15-meter intervals in areas with daily and interim cover outside of the working face.
- Quarterly, at 15-meter intervals that traverse the working face after daily cover has been applied and the landfill has stopped receiving waste.

At all locations with methane concentrations greater than 500 parts per million (ppm), a Jerome 631-X meter or equivalent must be used to measure H_2S surface concentrations. AHL is required to submit the surface emissions monitoring (SEM) data in map form, and after four quarters, AHL must submit an annual report to determine whether adjustments must be made to SEM.

Mapping the locations on the landfill surface with high methane emissions provides AHL with data that allow the operators to find and address these emissions. Locating and fixing leaks sooner improves the surface integrity of the landfill and likely reduces the number of alerts received through the perimeter monitoring system. The experience of implementing the consent decree at AHL has included the following outcomes and observations:

- The perimeter monitoring system allows AHL to identify major problems at the landfill that need to be addressed.
- Odors have been reduced, although odor complaints from neighboring communities still occur. AHL believes that the perimeter monitoring system has helped identify possible emission events, correlate these events with complaints received, and subsequently mitigate the emissions events.
- AHL is notified whenever there is an exceedance of the perimeter action level, which allows the operators to take action to address the source of the emissions in an expedient manner. There are times when the source of the emissions cannot be identified. Additionally, the perimeter monitoring system has allowed AHL to identify exceedances in real time so that problem areas can be identified and resolved quickly. Landfill staff are alerted by phone at all hours if an exceedance occurs and have gone onsite in the middle of the night during the worst events. Prior to the implementation of the perimeter monitoring system, problems may not have been identified for days or weeks. The system has allowed the identification of specific issues at the landfill; back trajectory analysis has been used to pinpoint areas with high emissions.
- Weather has affected the perimeter monitoring system. For example, the monitors are solar powered and sometimes there is not enough sunlight to power the monitors. AHL's third-party consultants are prepared to change out dead batteries with charged back-up batteries as needed. Additionally, AHL is investigating the feasibility of connecting each monitoring station to a direct power source, thereby minimizing the need for solar power. While there is no data capture requirement in the consent decree, EGLE and AHL have agreed to an 80 percent uptime averaged over a quarter averaged over all six monitors. In practice, AHL has been achieving a 95+ percent uptime and often 99 percent uptime. Note that AHL has an extra monitor mounted to a trailer and that is sometimes used to maintain measurements at a location if a monitor is down.
- Learning how the SnifferDRONE that is used to conduct surface emissions monitoring operates presented a challenge initially.
- There have been specific instances where odor is caused by leachate when the leachate handling system breaks down. When the system breaks down, H_2S emissions are high enough to be detected. However, H_2S perimeter action level exceedances are rare.
- Exceedances of the perimeter action levels occur almost exclusively between sunset and sunrise. There have been only a handful of exceedances during the day.
- The perimeter monitoring system has allowed AHL to make GCCS adjustments in the localized area next to the fenceline monitors.
- The fenceline monitoring system is relatively new, and it may be that a combination of the fenceline monitoring along with other surface monitoring techniques, or a combined remote

sensing stack would be effective in identifying the source of emissions and mitigating those emissions.

Due to the success of the monitoring program at AHL, EGLE is in the process of requiring another landfill in Michigan to install a perimeter monitoring system similar to the one implemented at AHL.

Sampson County Landfill, Roseboro, North Carolina

The SCD landfill in Roseboro, North Carolina is the largest landfill in North Carolina and has been in operation since 1973. The local residents have made complaints to the North Carolina Department of Environmental Quality and Sampson County about the SCD for many years. The SCD operators entered into a consent decree with the Environmental Justice Community Action Network (EJCAN) on August 30, 2024 (U.S. District Court – Eastern District of North Carolina (2024). SCD agreed to implement specific actions, including perimeter monitoring that could be model requirements for other landfills where neighboring residents have submitted complaints. The consent decree requires the SCD operators to do the following:

- Implement a continuous Emissions Monitoring System at the perimeter of the landfill for one year. The parties to the consent decree will select an independent third-party consultant to design and implement the continuous monitoring system. The consent decree indicates that the parties will agree on the placement of the monitors and the emission standards (emission thresholds). There are no details on the monitoring system at this time.
- The monitoring data from the Emissions Monitoring System is to be posted to a community landfill website.
- The landfill will monitor for a year, then submit a report with recommendations for emissions and odor mitigation, and address complaints.
- Use an EPA-approved drone SEM method, rather than EPA Method 21, to conduct SEM.[3] The use of the drone SEM will allow SCD to reach areas of the landfill that are excluded when a human operator conducts SEM using Method 21.
- Restrict the acceptance of special waste.
- Conduct community engagement through the community website and regular quarterly meetings.
- Develop a community engagement and complaint process, including the establishment of a community hotline.
- Urge local emergency management personnel to develop an Emergency Management Plan and Emergency Alert System to alert the community within two miles of the landfill in the event of an emergency at the landfill that may impact public safety or prompt the need for evacuation.
- Establish a school recycling and composting program at 10 Sampson County schools and fund a public campaign in Sampson County to encourage recycling in order to divert waste from the landfill.

This consent decree was only recently signed in August 2024; therefore, there are no results associated with its implementation to date. However, the expectation is that the implementation of a fenceline

[3] At the time of development of this paper, OTM-51 is the only EPA-approved drone SEM method.

monitoring program at SCD will reduce the emissions from the landfill over time, thereby reducing the residents' exposure to landfill emissions. The pollutants and emission levels will be agreed upon once a third-party consultant conducts an analysis of the site and surrounding hog facilities and provides recommendations on monitors, locations, and perimeter action levels.

Additional Information

This section provides statistical data on the number of people that live in close proximity to landfills and can be exposed to emissions from the landfills; these statistics illustrate the need to reduce emissions from landfills in order to minimize impacts on residents.

Statistical Data on the Number of People That Live in Close Proximity to Landfills Across the U.S.

Industrious Labs (IL) conducted an analysis of the impact of MSW landfills on fenceline communities. IL compiled data from several publicly available data sources and provided the following information:

- There are over 1,200 active MSW landfills in the United States.
- More than 800,000 people live within 1 mile and over 13 million people live within 3 miles of an active MSW landfill.
- There are more than 1,300 closed MSW landfills in the United States. Closed landfills continue to emit gases, including methane, after closure.
- Nearly 2 million people live within 1 mile and 23.5 million people live within 3 miles of a closed MSW landfill.

Regulation Changes and Implementation

The NSPS/EG requires landfill owners and operators to conduct quarterly SEM using EPA Method 21 to monitor the surface of the landfill for high emissions of methane to help determine whether the landfill GCCS is operating effectively. If EPA Method 21 identifies areas on the surface of the landfill with methane emissions higher than 500 ppm, then the landfill owner or operator must address the emissions from that location. SEM is not required at landfills that do not have a GCCS installed. There are no current requirements to conduct fenceline monitoring at MSW landfills.

As described earlier in this white paper, fenceline monitoring has been conducted at the perimeter of AHL in Michigan for both H_2S and methane. When perimeter action levels are triggered, the perimeter monitoring system sends an alert to the AHL staff. AHL staff then investigate the cause of the emissions and address the issue. The implementation of the perimeter monitoring system allows the operator to identify and respond to emission events faster than if AHL were to rely on the quarterly SEM only. In some instances, it has been challenging for AHL staff to identify the triggering event. However, overall, the perimeter monitoring system has allowed AHL to be more responsive to these events. It is important to note that pollutants of interest vary significantly when it comes to ease of detection. Hydrogen sulfide, for example, is more feasible to detect given the lack of natural or expected emissions in the surrounding area. Methane, on the other hand, proves more difficult when considering both the intrinsic sources (e.g., nearby farms, wetlands, compost) and fugitive components that cannot be easily separated with fenceline monitoring alone. Further research and site-specific modeling are needed to better assess fugitive methane emissions.

With the requirement for another MSW landfill in Michigan and one in North Carolina to install perimeter monitors, perimeter monitoring is recognized as a tool that landfills can use to improve and maintain the surface integrity of the landfill and to be more proactive in identifying triggering events. Additionally, as shown with the consent decree for SCD in North Carolina, perimeter monitoring could be a way to work with the communities that reside near landfills to identify emissions events sooner and to mitigate them more quickly.

Implementing a perimeter monitoring program at MSW landfills in the upcoming NSPS/EG rulemaking could be evaluated in an overall monitoring program that could, as an example, include the perimeter monitoring approach plus the use of fixed sensors across the surface of the landfill, sensors attached to drones that can map the surface of the landfill, or the use of sensors fixed to satellites. For example, drone technology could offer a safer and equivalent approach to SEM to identify issues on the landfill surface. However, drone-based monitoring only provides data periodically, such as once per quarter. Perimeter monitoring systems provide the capability to capture data much more frequently, but identification of the exact emissions source generally requires further investigation.

A drone-based system could be used in conjunction with a perimeter monitoring system to identify the locations on the landfill surface that have triggered alerts from the perimeter monitoring system. This combination monitoring approach would need to be evaluated fully before it could be incorporated into the NSPS/EG. This evaluation would need to consider the effectiveness of the current perimeter monitoring programs, the cost of the monitoring systems, and how best to identify the number of monitors and their locations on the perimeter of the landfill. Additionally, EPA would need to evaluate which pollutants to monitor and the concentrations that would trigger alerts, as well as subsequent investigation and mitigation requirements.

Summary and Next Steps

This paper examined the use of fenceline monitoring as a technique to detect emissions from landfills. This paper described the implementation of fenceline monitoring at petroleum refineries using passive diffusive monitors with Methods 325 A/B. Fenceline monitoring at refineries has allowed for early notification of emissions events such that owners/operators can take action to address and mitigate the source of the emissions sooner. This white paper also described the implementation of fenceline or perimeter monitoring at AHL in Michigan where six fenceline monitors were installed at the northeast corner of the landfill to monitor both H_2S and methane emissions. Another landfill in Michigan and one in North Carolina are also set to implement fenceline monitoring in the near future.

EPA will continue to gather information on the effectiveness of perimeter monitoring programs and evaluate whether this type of monitoring could be incorporated into the updated NSPS/EG. Specifically, EPA could:

- Continue to evaluate the effectiveness of the existing perimeter monitoring programs at landfills, especially for early identification of emissions events to inform repair and mitigation of emissions.
- Gather information on monitoring equipment that could be installed at the perimeter of landfills.
- Evaluate the costs of alternative monitoring systems that could be implemented at the perimeter of the landfills.

- Analyze the feasibility of developing an emissions monitoring program that could include the use of multiple monitoring platforms with a view towards:
    - Reducing emissions from the landfill
    - Supporting the efforts of landfill owners and operators in improving the surface integrity of the landfills by establishing best practices
    - Reducing the impacts of landfill gas emissions on residents that live in close proximity to MSW landfills.
- Address the question: Could a perimeter monitoring program enhance the SEM programs that are contemplated for the upcoming NSPS/EG rulemaking?
- Explore the development of a reference test method for fenceline monitoring if EPA decides to incorporate it into the upcoming NSPS/EG rulemaking.

References/Resources

GFL Environmental. (2024). Arbor Hills Landfill Monitoring. https://arborhillsmonitoring.com/

Industrious Labs. (2024). EPA MSW Landfill Data Request- Human Impact of U.S. Landfills (non-EJ data).

State of Michigan. (2024). Circuit Court for the 30th Judicial Circuit Ingham County. (2022). Consent decree between the State of Michigan Department of Environment, Great Lakes, and Energy (EGLE) and Arbor Hills Landfill, Inc. Available at: https://www.michigan.gov/egle/-/media/Project/Websites/egle/Documents/Multi-Division/Arbor-Hills/2022-03-07-arbor-hills-consent-judgment.pdf

State of Michigan Department of the Environment, Great Lakes, and Energy (EGLE). (2024). Michigan-Ontario Ozone Source Experiment (MOOSE) study. Available at: https://www-air.larc.nasa.gov/missions/moose/

U.S. District Court – Eastern District of North Carolina. (2024). Proposed consent decree between Environmental Justice Community Action Network (EJCAN) and Sampson County Disposal LLC and its parent and affiliated companies; Waste Industries, USA, LLC; Waste Industries, LLC; Black Creek Renewable Energy, LLC; and GFL Environmental, Inc. Available at: https://www.southernenvironment.org/wp-content/uploads/2024/09/2024.08.30_DKT012-1_Exhibit-1-Proposed-Consent-Decree-Sampson-County-landfill.pdf.

U.S. EPA. (2023). New Source Performance Standards for the Synthetic Organic Chemical Manufacturing Industry and National Emission Standards for Hazardous Air Pollutants for the Synthetic Organic Chemical Manufacturing Industry and Group I & II Polymers and Resins Industry. Federal Register, Vol. 88, No. 79. Available at: https://www.govinfo.gov/content/pkg/FR-2023-04-25/pdf/2023-07188.pdf (page 25142 describes the impact of the fenceline monitoring program for petroleum refineries).

U.S. EPA. (2024). Email correspondence with Michigan EGLE. (2024).

U.S. EPA. (2019). Method 325A—Volatile Organic Compounds from Fugitive and Area Sources. Available at: https://www.epa.gov/sites/default/files/2019-08/documents/method_325a.pdf

U.S. EPA. (2019). Method 325B—Volatile Organic Compounds from Fugitive and Area Sources. Available at: https://www.epa.gov/sites/default/files/2019-08/documents/method_325b.pdf

RMI

From Waste to Wins: How Orange County’s Smart Landfills Are Slashing Methane

From compost piles to methane-sensing robotic dogs, Orange County is reimagining landfill management to reduce pollution and benefit communities.

January 30, 2025

By Ellie Garland, Tom Frankiewicz, Madison Hall

Orange County Waste & Recycling Smart Landfill Program

David Tieu, deputy director of OC Waste & Recycling (OCWR), has spent years getting up close and personal with what people throw away. He's seen it all — banana peels, broken lawn chairs, last year's holiday fruitcake. But to him, this isn't just garbage — it's an opportunity. "What we're doing is taking the stuff that no one wants. When we started this journey in 2017, the question was…can we take contaminated waste and actually produce a product out of it?"

Deputy Director David Tieu at one of OCWR's compost facilities.

Orange County is California's third-most populous region — home to Disneyland, famous surf beaches, and three active landfills. The American Lung Association gives Orange County and the Southern California Metropolitan area a failing grade for air quality, citing high ozone days and elevated particle pollution levels. For Tieu, rethinking waste can help address this challenge. New initiatives at OCWR's landfills can drive down methane emissions, improve air quality, and deliver real community benefits.

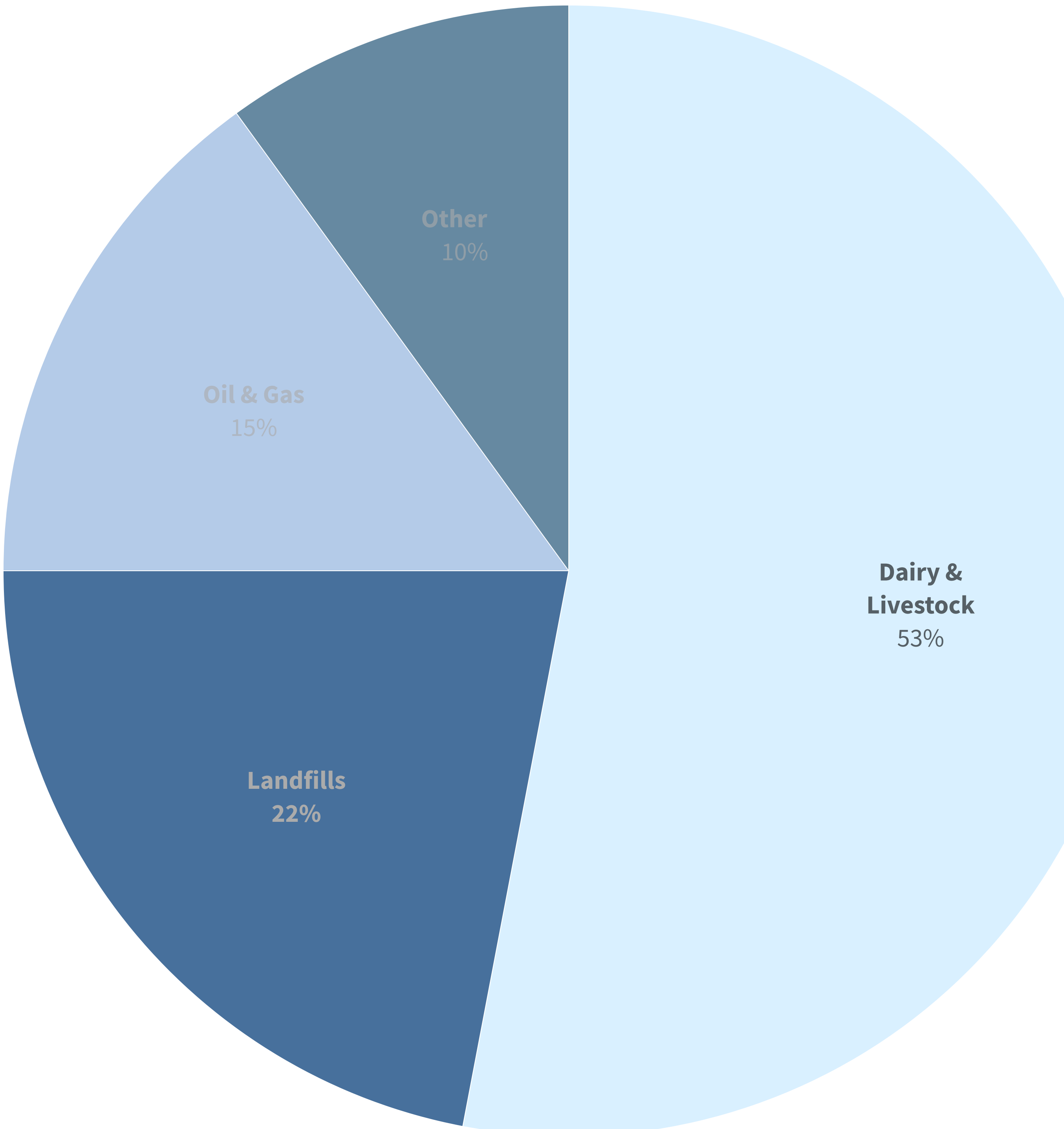
Cutting methane in California

As organic waste such as food scraps and yard clippings decomposes in landfills, it generates methane — a greenhouse gas with over 80 times the heat-trapping power of carbon dioxide in the short term. In California, landfills are the second-largest source of human-caused methane emissions, representing 22 percent of the state's 2022 methane inventory. Airborne studies conducted by the California Air Resources Board — in partnership with Carbon Mapper and NASA's Jet Propulsion Laboratory — have identified large methane plumes over dozens of California landfills.

California Methane Emissions (2022)

36.33 million $MTCO_2e$

Dairy & Livestock **Landfills** Oil & Gas Other



California AB 32 GHG Inventory 2000-2022 (2024 Edition)

Fast action to cut methane is essential to slow warming over the near term. And for hundreds of thousands of Californians living within one mile of these sites, addressing landfill emissions is more than just a climate issue: it's also about minimizing odors, securing clean air and water, and protecting public health. California has developed a comprehensive strategy to address waste sector emissions. The state's Scoping Plan, which targets a 40 percent reduction in methane emissions by 2030, underscores the need to divert organic waste from landfills to prevent future methane generation, while also controlling methane emissions at the source through improved landfill design and operations.

SB 1383, California's landmark law aiming to cut landfill-bound organic waste by 75 percent by 2025, has already diverted 295 million pounds of food waste from landfills, created over 440 jobs in food recovery, and provided millions of meals to those in need. SB 1383 is sparking a statewide shift toward a circular economy, where waste is minimized, surplus food is donated, and the remaining organics are reused to create nutrient-rich products like compost. Nearly 80 percent of California communities are now rolling out organic waste collection programs. The state is also working on critical improvements to its Landfill Methane Regulation, to ensure operators are making use of the latest technologies and best practices to cut methane emissions quickly from waste-in-place.

OCWR is already leading on this two-part solution — turning organic waste into compost while making technology upgrades to boost methane capture at the landfill. "We've been landfilling for 70 years; it's our bread and butter," says Tieu. "(But) this transition is relatively recent, and it's new to our industry."

Compost for the community

Starting in 2020, OCWR developed composting facilities at its landfills to process organic waste separately and prevent future methane generation. "The baseline of what we're doing is to divert organics. I'll say that's the 'low hanging fruit,' just simply because we were already receiving it for many, many years," explains Tom Koutroulis, OCWR Director. "Now, our focus is building out the infrastructure to handle the 1,000–2,000 tons coming in daily from residents."

OCWR diverts organic material from the landfill and turns it into nutrient-rich compost.

To manage this growing volume, OCWR is using windrow composting — a method where organic material is piled and periodically turned — and is developing Covered Aerated Static Piles (CASP) technology. CASP, which Tieu likens to a "set it and forget it" crock pot, involves covering compost piles and using a forced air system to optimize and accelerate the breakdown process, doubling the facility's capacity.

To date, OCWR's composting program has diverted over 64,000 tons of organic waste — and kept 12,400 metric tons of greenhouse gases out of the atmosphere, equal to removing 2,700 cars from the road for a year.

"We're doing this as an essential public service. We don't charge for the compost product. It's free. At this day and age, when inflation is high, it's a great thing we can do for our community," says Tieu.

Compost and mulch are available for residential and community use.

Beyond reducing emissions, composting gives organic waste a second life, transforming it into a resource that sequesters carbon, enriches soil, boosts crop yields, and cuts reliance on chemical fertilizers. It's a simple process with profound impacts, linking waste reduction to stronger agricultural systems and healthier communities.

Successes to date:

64,313 tons of waste diverted

- 12,400 tons of CO_2e eliminated

The Smart Landfill Program

OCWR's Smart Landfill Program (SLP) enhances and automates critical information and equipment to increase landfill gas collection. By incorporating real-time data assessment, drone technology, and infrared imaging, the program monitors and manages the landfill system with precision, improving efficiency and cutting methane and co-pollutants. The SLP can proactively identify leaks and fine-tune methane capture from its landfills, reducing greenhouse gas emissions by up to 15 percent. Deputy director of compliance support, Julian Sabri, describes this technology as "the eyes, ears, and control tool" of landfill operations, emphasizing how it allows OCWR to stay on top of its emissions.

llhead equipped with real-time monitoring and controls.

One standout feature of the SLP is automated well tuning, which makes continuous valve adjustments to boost collection efficiency as temperature, pressure, and weather conditions fluctuate. These systems also provide operators with real-time information on potential issues related to the gas collection system, such as flooded wellheads or cover integrity problems, enabling timely repairs to maintain optimal performance.

"You might not think there's a lot of technology that goes on at a landfill. Matter of fact, there is," Sabri explains. With centralized control and monitoring, OCWR is creating a model for other landfills to follow.

Dogs and drones: boosting methane detection and capture

As part of SLP, OCWR is further enhancing landfill operations by piloting cutting-edge tools to detect, quantify, and mitigate methane emissions and integrating all automation components. Robotic dogs equipped with methane sensors patrol landfill sites, in addition to the drones that map emissions from above. Compared to traditional monitoring, where a technician walks the site for miles, these methods are safer, more efficient, and more economical.

OCWR uses this data to identify leaks and implement targeted solutions, from expanding gas collection systems to improving cover materials. This approach goes beyond compliance, positioning OCWR as a leader in proactive methane management. "We don't just hope to *meet* the standard, but to *be* the standard," celebrates Koutroulis.

> **We don't just hope to meet the standard, but to be the standard.**
>
> **TOM KOUTROULIS, OCWR DIRECTOR**

Additionally, OCWR is utilizing its expansive properties for energy projects, with plans in progress to process excess landfill gas that would otherwise be flared into biomethane for local energy use. OCWR is also researching options such as solar installations on closed landfills that align with California's SB 100 goal of a 100 percent clean energy grid by 2045. "We have a lot of property, and in southern

California, we have a lot of sun. So, we believe this is another great opportunity to take advantage of the infrastructure we currently have to address renewable energy needs," notes Koutroulis.

Methane-detecting drones and robotic dogs efficiently identify leaks for mitigation.

A model for methane mitigation

By diverting organic waste and implementing smart landfilling technologies, OCWR is demonstrating how to comprehensively cut methane emissions while delivering local benefits. These strategies work in tandem: composting improves soil health, creates jobs, and builds resilience, while controlling landfill methane emissions leads to cleaner air, reduced odors, and healthier neighborhoods.

Tackling waste sector emissions is one of the most affordable and impactful ways to advance state and local climate goals. As Orange County continues to make strides, its methane mitigation strategy can serve as a model for other communities across the country and around the world.

For more information on how landfill operators and municipalities can reduce methane emissions see RMI's playbook Deploying Advanced Monitoring Technologies at US Landfills.

Top image: Tom Frankiewicz, RMI's waste sector subject matter expert, and Tom Koutroulis, director of waste & recycling for Orange County, at the Frank R. Bowerman Landfill