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MSW Landfill Gas Collection and Control System (GCCS) Installation Lag Time and Nonmethane Organic Compound (NMOC) Destruction Efficiency

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

- EPA developed this series of white papers to examine ways to improve the NSPS/EG for MSW landfills using new information and new technology to further control and reduce landfill gas (LFG) emissions.
- Topics include applicability (size of landfill), controls (emissions rate and timing of controls), operating practices (cover practices, working face), waste composition (organics), and monitoring (technology).

Topic: MSW Landfill Gas Collection and Control System (GCCS) Installation Lag Time and Nonmethane Organic Compound (NMOC) Destruction Efficiency[1]

This white paper evaluates the impact of reducing the time required for gas collection and control system installation and the minimum destruction efficiency for GCCS. Specifically, this white paper evaluates the following changes that could be made to the NSPS/EG:

- Allowed time for GCCS installation (i.e., lag time):
  - Maximum allowable time for when landfills must install and operate a GCCS after exceeding NSPS/EG size and emission thresholds and
  - Maximum allowable time for expanding the existing GCCS into new active areas.
- Destruction efficiency criteria:
  - Minimum required destruction efficiency for GCCS and
  - Change from NMOC-based criteria to methane-based criteria.

This paper reviews these requirements in the NSPS/EG and then compares them to similar requirements in several U.S. states and in Canada. This paper then estimates the potential methane emission reductions resulting from reducing the NSPS/EG landfill GCCS installation lag time, increasing the required GCCS destruction efficiency, and switching from a NMOC-based criteria to a methane-based criteria. This paper also identifies possible rule revisions, the benefits and potential drawbacks of such revisions, and next steps for further evaluating changes to the NSPS/EG landfill GCCS installation lag time and destruction efficiency requirements.

Rationale and Possible Results

Current information supports the need to investigate how reducing the landfill GCCS installation lag time and changing GCCS destruction efficiency requirements could further reduce LFG emissions, especially methane. Several states and Canada (Environment and Climate Change Canada [ECCC]) have promulgated or proposed regulations that require LFG collection and control sooner (than the NSPS/EG) after exceeding applicability thresholds or expansion, as well as other requirements for destruction efficiency for GCCS. Implementing a shorter time between threshold exceedances or landfill expansions

[1] The NSPS/EG use the term "reduction efficiency" to describe the required NMOC reduction that must be achieved by a device (i.e., the "control" portion of the GCCS); no reference to "destruction efficiency" is made in the NSPS/EG. The reviewed state rules and Environmental Climate Change Canada (ECCC) rules use the term "destruction efficiency" to describe the required methane reductions; thus, the term "destruction efficiency" is used throughout this paper as an equivalent to the NSPS/EG requirement for "reduction efficiency."

and GCCS installation and operation can result in earlier control of LFG emissions versus the current NSPS/EG requirements.

MSW LFG is approximately 50 percent carbon dioxide (CO_2) and 50 percent methane (CH_4) by volume, along with trace (<1 percent by volume) constituents (e.g., NMOCs, hazardous air pollutants (HAPs), hydrogen sulfide). The NSPS/EG determine timing of controls by evaluating LFG in terms of NMOC emissions; however, this paper focuses on the methane emissions from LFG due to their environmental significance on climate change, and the expected transition from an NMOC-based to a methane-based emission threshold in the upcoming NSPS/EG rulemaking. Increasing the minimum GCCS destruction efficiency requirement and switching to a methane-based standard may also decrease methane emissions that occur post-collection.

The NSPS/EG require MSW landfills to install and operate an LFG GCCS upon meeting or exceeding two thresholds:

- A permitted landfill design capacity of 2.5 million megagrams (Mg) and 2.5 million cubic meters (m^3) of municipal solid waste.
- An estimated emission rate of 34 Mg/yr NMOC, determined using tiered testing.

Once these thresholds have been met or exceeded, the NSPS/EG then require a landfill to:

- Develop and submit a GCCS design plan within 12 months of initially exceeding the NMOC emission rate threshold.
- Install and operate a GCCS within 30 months of initially exceeding the NMOC emission rate threshold.
- For landfills with an existing GCCS under the NSPS/EG, expand the GCCS into each area, cell, or group of cells where waste is placed within 5 years if actively accepting waste, or within 2 years if the area, cell, or group of cells is closed or at final grade.
- Install a GCCS with a minimum reduction of 98 weight-percent of NMOC or reduce the outlet NMOC concentration to less than 20 parts per million by volume, dry basis as hexane at 3 percent oxygen (O_2).

Lag times for GCCS installation provide landfill owners and operators time to develop, permit, and construct a GCCS, which requires working with multiple external entities including consultants, contractors, and state and local regulatory agencies. However, the installation lag time also allows additional LFG emissions to occur, especially from waste streams that degrade at a quicker rate (e.g., organic waste). For example, a recent EPA report quantified landfill emissions specifically from food waste and noted that landfilled food waste has increased steadily since 1990 (U.S. EPA, 2023b). This finding is significant because food waste degrades more quickly than other landfilled materials, and the associated LFG generation can occur prior to GCCS installation.

Earlier GCCS installation could collect and control significant emissions from this accelerated food waste decay pathway, which was estimated to account for approximately 58 percent of total fugitive methane emissions from MSW landfills in 2020 (U.S. EPA, 2023b). Increased LFG collection and control could also assist with meeting the goals in the U.S. Methane Emissions Reduction Action Plan (White House, 2021), which aims to achieve a gas collection and control rate for all landfills of 70 percent nationally by 2030. As of 2022, that figure was 60 percent (U.S. EPA, 2024).

Specifying a minimum GCCS destruction, or reduction, efficiency for NMOC in the collected LFG limits the amount of potential NMOC emissions from a landfill. This percent reduction requirement is important; even if a GCCS is highly efficient at collecting generated LFG, emissions could still occur if the GCCS cannot effectively reduce NMOCs and other constituents in LFG. Additionally, the basis of this percent reduction must be acknowledged. The NSPS/EG specify a minimum GCCS reduction efficiency based on NMOC reduction in LFG—other states and Canada (ECCC) specify a destruction efficiency based on methane reduction in LFG. Increasing this minimum percent reduction/destruction, and changing the basis (i.e., methane vs. NMOC reduction) could decrease the total amount of methane that is ultimately emitted by landfills and assist with meeting the goals in the U.S. Methane Emissions Reduction Action Plan.

When LFG is burned for electricity generation in turbines or engines, some amount of methane is not combusted and passes through in the exhaust gas as "methane slip." Combustion may also generate volatile organic compounds (VOC) and HAP—particularly formaldehyde. In all control systems, but particularly complex LFG processing in renewable natural gas plants, there is potential for collected gas to leak and vent from system components, reducing the overall effectiveness of the collection and control system and creating emissions. Existing federal regulations do not require monitoring for fugitive emissions from landfill control systems. Some EPA inspectors have conducted Method 21 and/or optical gas imaging surveys of landfill gas control systems (including flares, electricity projects, and renewable natural gas facilities) and have documented methane/VOC leaks and venting issues. Similarly, remote sensing data from Carbon Mapper has identified plumes originating from renewable natural gas plants and other control devices complexes, including occurrences of apparent venting from control stacks and of what appeared to be more diffuse fugitive emissions.

Note that this analysis does not attempt to account for emissions beyond equipment subject to the NSPS/EG requirement to reduce NMOC by 98 weight-percent or reduce the outlet NMOC concentration to less than 20 parts per million by volume, dry basis as hexane at 3 percent O_2. Any combustion device used to comply with the NSPS/EG, including engines, boilers, turbines, and microturbines, would need to comply with this requirement in the NSPS. Several state regulations (CA, MD, OR) specify methane destruction efficiencies of 99 percent for LFG routed to energy recovery devices, while Washington requires 97 percent methane destruction efficiency.

States can develop standards for MSW landfills that must be at least as stringent as the NSPS/EG but can be more stringent. Several states and Canada (ECCC) have developed their own standards for the acceptable lag time between threshold exceedance or expansion and GCCS installation and operation—some of which are shorter than in the NSPS/EG. Likewise, these states and ECCC have also specified their own requirements for GCCS destruction efficiencies, some of which are more stringent than the current NSPS/EG. Reducing the lag time for GCCS installation upon emission threshold exceedance or landfill expansion in the NSPS/EG could reduce the amount of LFG emissions, especially methane, emitted prior to GCCS startup[2] while increasing the minimum GCCS destruction efficiency. In addition, defining the destruction efficiency in terms of methane instead of NMOC could reduce methane emissions post-collection.

[2] Note: Some sites may have voluntarily installed a GCCS prior to meeting or exceeding any threshold. A GCCS may be installed earlier than required to mitigate potential odors or to benefit from LFG energy practices. However, additional reductions could be possible if these existing systems do not meet NSPS/EG requirements.

Investigations and Results

This paper investigates how landfill methane emissions could be affected by:

- Reducing the initial and expansion lag times for GCCS installation/operation.
- Increasing the minimum required GCCS destruction efficiency and switching from an NMOC-basis to a methane-basis.

This evaluation includes a review of existing information and regulatory language from U.S. states and Canada (ECCC) that have established their own LFG GCCS lag time and destruction efficiency standards differently from the NSPS/EG. The differing standards were used to estimate the potential methane emission reductions over time if the NSPS/EG GCCS installation lag time were reduced and the minimum destruction efficiency was increased similarly to those in the reviewed regulations. This paper also identifies possible rule revisions, discusses potential benefits and challenges resulting from these changes, and identifies next steps for further assessment.

Review of Existing GCCS Installation/Operation Lag Times and Destruction Efficiency Requirements in U.S. States and Canada (ECCC)

GCCS Installation Lag Time

Several states (California, Oregon, Washington, Maryland, and Michigan) and Canada (ECCC) have promulgated or proposed regulations that specify the amount of time landfill owners and operators have to install and operate a GCCS after exceeding size and emission thresholds or to expand an existing GCCS as the landfill continues to accept waste. Table 1 reviews the installation/operation schedules provided in the states' and proposed ECCC's regulations.

Table 1. NSPS/EG, U.S. states, and Canada (ECCC) lag times for GCCS installation/operation initially and upon expansion.

	Federal	States					Canada
	NSPS/EG	California	Oregon	Washington	Maryland	Michigan[3]	ECCC (Proposed)
Initial	Develop design plan within 12 months of exceedance Submit design plan to the Administrator for approval; Administrator has 90 days to	Develop design plan within 12 months of exceedance Executive Officer[4] must review and approve/	Submit design plan within 12 months of exceedance DEQ must review and approve/ disapprove design plan	Submit design plan within 12 months of exceedance Department or local authority must approve/	Submit design plan within 12 months of exceedance No timeline is provided for the Department review	*Existing landfills*: 12 months for design plan; 6 months to install after design plan approval	Within 4 years[5]

[3] Michigan defines "existing landfills" as those existing prior to the effective date of the amendatory act that created this requirement (Act 245 – Solid Waste Act): March 29, 2023. All new landfills or landfill expansions afterwards are "new."

[4] Defined as Executive Officer of the Air Resources Board, or his or her delegate (see Section 95475 Definitions; California Air Resources Board [CARB], 2010).

[5] This applies to all applicable landfills starting January 1, 2033. There are several potential compliance schedules during the initial implementation period that lasts until January 1, 2033, depending on a landfill's methane generation rate and whether there were existing LFG recovery wells in place prior to January 1, 2017, ranging from 2 years (compliance by January 1, 2027) to 8 years (compliance by January 1, 2033).

	Federal	States					Canada
	NSPS/EG	California	Oregon	Washington	Maryland	Michigan[3]	ECCC (Proposed)
	review (or choose to review) Install GCCS within 30 months of NMOC emission threshold exceedance	disapprove design plan within 120 days Install GCCS within 18 months *after* design plan approval (active sites); 30 months (closed/ inactive sites)	within 90 days Install GCCS within 30 months of exceedance	disapprove design plan within 120 days Install GCCS within 18 months after exceedance (active sites); 30 months (closed sites)	Install GCCS within 30 months *after* design plan approval	*New landfills:* Design plan before construction permit; operation before waste acceptance	
Expansion	5 years if open / 2 years if at final grade or closed	No lag time	No lag time	No lag time	No lag time	Design plan before construction permit; operation before waste acceptance	None specified

The NSPS/EG allow for 30 months from when a facility initially exceeds its emission threshold until it must install and operate a GCCS. For expanding the GCCS, the NSPS specifies that the landfill owner or operator must collect gas from each area, cell, or group of cells in the landfill in which the initial solid waste has been placed for a period of 5 years or more if active; or 2 years or more if closed or at final grade (40 CFR 60.762(b)(2)(ii)(C)(2)).

Before discussing the reviewed states and Canada, it is important to note that the state and ECCC emission standards are based on methane emissions and not NMOC emissions. As discussed separately in the MSW Landfill Size Threshold White Paper, U.S. state emission thresholds for methane are typically exceeded years before the NSPS/EG NMOC emission threshold. This is because of the different emission thresholds established for methane emissions and because methane is produced from the anaerobic breakdown of biodegradable MSW components and is thus more closely related to waste-in-place than NMOC emissions, which can vary depending on specific waste inputs (e.g., wastewater sludge, industrial wastes) and site conditions.

When comparing the initial installation lag times for the NSPS/EG and states/ECCC, it is important to understand that the *total* allowed lag time can vary depending on whether it is based on when the *emission threshold is exceeded* or when the *GCCS design plan is approved*. For the NSPS/EG, Oregon, and Washington, the allowed lag time is based on emission threshold exceedance (in other words, the GCCS must be installed and begin operating within a set number of months after the initial emission threshold exceedance). For California, Maryland, and Michigan[6], the GCCS must be installed and operated within a certain number of months after the design plan has been approved.

Oregon has the same initial lag time for GCCS installation as the NSPS/EG: 30 months after exceeding the established emission threshold. Washington's recent landfill rules require a shorter initial lag time of 18 months after exceeding the emission threshold. California's, Maryland's, and Michigan's[7] rules all include schedules to complete design plan submittals within 12 months of emission threshold exceedance and then require GCCS installation within 18 months, 30 months, or 6 months *after* design plan approval, respectively. These differences mean total installation lag times of more than 30 months, 42 months, or 18 months are possible for California, Maryland, and Michigan, respectively, depending on the length of time the design plan submittal and approval process takes.[8]

California and Washington are the only states to have different initial lag times depending on whether the landfill is active or closed:

- Active Landfills:
  - California: 12 months for design plan, plus 18 months after design plan approval to install/operate GCCS.
  - Washington: 18 months after emission threshold exceedance to install/operate GCCS (with 12-month design plan approval timeline included).
- Closed Landfills:
  - California: 12 months for design plan, plus 30 months after design plan approval to install/operate GCCS.
  - Washington: 30 months after emission threshold exceedance to install/operate GCCS (with 12-month design plan approval timeline included).

Michigan is the only state that explicitly makes a distinction for lag times between "existing" and "new" landfills/landfill expansions instead of "initial" and "expansion" GCCS installation/operation. Existing landfills[9] that exceed emission thresholds have 12 months to submit a design plan and then 6 months after design plan approval to install GCCS; however, new landfills and new expansions at existing landfills in Michigan are required to install GCCS during construction and prior to accepting any waste. As for the other reviewed states (California, Oregon, Washington, Maryland), there are no specific lag times stated in their regulations for expanding the GCCS into new active areas; however, these rules generally prescribe that the GCCS must be able to control fugitive methane emissions from the landfill.

ECCC allows a 4-year initial lag time in their proposed regulations (June 2024); however, they did not specify lag time requirements for expansions. The proposed ECCC regulations do have an initial implementation period that lasts until January 1, 2033, with landfills having shorter or longer lag times to comply based on the type of landfill. These compliance schedules are:

[6] Only applies for "existing" landfills; those in existence after the effective date of the amendatory act (Act 245 – Solid Waste Act): March 29, 2023.
[7] Only applies for "existing" landfills in Michigan; those in existence after the effective date of the amendatory act (Act 245 – Solid Waste Act): March 29, 2023. "Existing" vs. "new" landfills in Michigan is discussed later in section.
[8] This timeframe could possibly be longer depending on the length of time the agencies have to approve/disapprove the design plans (see information in Table 1).
[9] Defined as "existing" as of the effective date of the amendatory act (Act 245 – Solid Waste Act): March 29, 2023.

- By January 1, 2027 (2 years to comply): Open or closed landfills with existing LFG recovery wells in place prior to January 1, 2017, and estimated methane emissions of ≥ 1,000 metric tons per year (MT/yr).
- By January 1, 2029 (4 years to comply): Open or closed landfills with estimated methane emissions of ≥ 1,000 MT/yr (that are not included in the landfills noted in the above bullet).
- By January 1, 2033 (8 years[10] to comply): Open landfills with estimated methane emissions between 664 MT/yr and 1,000 MT/yr.

GCCS Destruction

Table 2 presents the different GCCS destruction requirements in the NSPS/EG, in the reviewed states, and in Canada's (ECCC's) proposed rules. GCCS destruction is typically achieved by using open or enclosed flares. The NSPS/EG allow for open flares if the system is operated in accordance with general control device and work practice requirements (40 CFR 60.18) to achieve a 98 percent reduction in NMOC. For enclosed flares, the NSPS/EG require a 98 percent NMOC reduction or outlet gas concentration of less than 20 ppmv (dry) as hexane at 3 percent O_2. The reviewed states, except Michigan, prohibit open flaring unless specific criteria apply, such as:

- Landfill emission rates are below the emission thresholds used to determine GCCS applicability.
- Open flaring is used as a temporary measure during repair or maintenance of an enclosed flare system.

Meanwhile, ECCC's proposed standard allows open flares if a minimum methane destruction efficiency of 98 percent is achieved. Michigan does not make any requirement on open or enclosed flares for active systems or any other specification on how methane must be flared or otherwise destroyed or reduced.

In contrast to the NSPS/EG, the reviewed states specify methane destruction instead of NMOC reduction and require 99 percent destruction or, if used to power engines, an outlet methane concentration of 3,000 ppmv (dry) at 15 percent O_2. Michigan does not specify methane or NMOC reduction requirements beyond the NSPS/EG.

[10] Upon reviewing ECCC's responses to commentors, this appears to be a concession for smaller landfills that are using their LFG to sell offset credits, which once the regulations come into force will eliminate this market. This longer extension provides these landfills time to adapt to the change.

Table 2. GCCS destruction requirements by NSPS/EG, selected states[11], and Canada (ECCC).

	Federal	States				Canada
	NSPS/EG	California	Oregon	Washington	Maryland	ECCC
Flare/ Destruction Requirements	Open flare or enclosed as long as 98 percent NMOC reduction, or when enclosed flare is used 98 percent or NMOC < 20 ppmv dry as hexane @ 3% O_2	99 percent CH_4 destruction; engines: outlet CH_4 < 3,000 ppmv, dry @ 15% O_2 Open flares only allowed if: - LFG HIC < 3.0 MMBtu/hr - Temporary operation during repair/ maintenance of enclosed flare	99 percent CH_4 destruction; engines: outlet CH4 < 3,000 ppmv, dry @ 15% O_2 Open flares only if: - CH_4 generation < 732 tons/yr - Temporary operation during repair/ maintenance of enclosed flare - Emissions cannot be controlled with enclosed flare/ no feasible alternatives	99 percent CH_4 destruction; engines: outlet CH4 < 3,000 ppmv, dry @ 15% O_2 Open flares only allowed if: - LFG HIC < 3.0 MMBtu/hr - Temporary operation during repair/ maintenance of enclosed flare	99 percent CH_4 destruction; engines: outlet CH4 < 3,000 ppmv, dry @ 15% O_2 Open flares only allowed if: - CH_4 generation < 732 ton/yr - Temporary operation during repair/ maintenance of enclosed flare - Emissions cannot be controlled with enclosed flare/no feasible alternatives	At least 98 percent destruction efficiency

Estimating the Potential Methane Emission Reductions by Changing GCCS Requirements

Potential Methane Emission Reductions from Reduced Initial GCCS Installation/Operation Lag Times

The following analysis estimates the differences in potential methane emissions through 2060 if reduced initial lag times were adopted for installing and operating a GCCS. The methodology and assumptions used to develop these estimates are the same as used for the MSW Landfill Size Threshold White Paper; thus, this paper refers to discussion in that paper for additional details on the dataset, modeling, and post-modeling calculations used to develop these estimates.

This analysis used the U.S. EPA Landfill Methane Outreach Program (LMOP) Landfill and LFG Energy Project Database (U.S. EPA, 2023a) to determine the number of landfills that already are or will likely become subject to the NSPS/EG by 2060 based on the current size and emission thresholds. Methane generation from these landfills was then modeled using the U.S. EPA Landfill Gas Emissions Model (LandGEM), Version 3.03 and other post-modeling calculations were applied to the methane generation outputs to develop emission estimates for each initial lag time scenario. The major difference between this analysis and the MSW Landfill Size Threshold White Paper's analysis is that instead of varying the size threshold, only the initial lag time was varied between installation and operation and threshold exceedance.

[11] Michigan is not included in this table because its rules do not specify requirements on GCCS destruction efficiencies or practices.

Based on the reviewed GCCS installation and operation initial lag times, three scenarios were modeled to examine possible reductions in methane emissions:

- **NSPS/EG Initial Lag Time Estimate (Baseline):** 30-month initial lag time, which is modeled as 36 months (3 years) because LandGEM can only model in whole year increments. This estimate is based on the NSPS/EG and reflects the baseline methane emission reductions expected.
- **State Initial Lag Time Estimate:** 18-month initial lag time, which is modeled as 24 months (2 years) because LandGEM can model only in whole year increments. This estimate is based on the shortest initial lag time observed in the reviewed states and ECCC regulations.
- **Zero Initial Lag Time Estimate:** A hypothetical "zero" initial lag time (0 years) was chosen to represent the maximum potential methane emission reductions possible if a GCCS was installed as soon as an exceedance occurred in the following year. In practice, this scenario is realistic only if permitting, design, and construction were started early in anticipation of the exceedance.[12]

Figure 1 presents the estimated methane captured and destroyed cumulatively by GCCS from 2023 to 2059. In summary:

- **NSPS/EG Estimate (Baseline):** Approximately 31.1 million Mg methane is captured and destroyed by 2060.
- **State Estimate:** Approximately 32.2 million Mg methane is captured and destroyed by 2060, or about 1.1 million Mg methane (3.5 percent) more than the NSPS/EG Estimate (baseline).
- **Zero Estimate:** Approximately 34.4 million Mg methane is captured and destroyed by 2060, or about 3.3 million Mg methane (10.6 percent) more than the NSPS/EG Estimate (baseline).

The additional estimated methane emission reductions from the State and Zero Estimates result from earlier capture and destruction of methane emissions because of reduced initial installation lag time when compared to that of the NSPS/EG. An important caveat to this analysis is that it includes only landfills in the LMOP database as of November 2023. This analysis does not account for existing landfills that are not in the LMOP database or new landfills that will start operation between 2024 and 2060.

[12] Challenges with permitting, design, and construction timelines in practice are discussed in detail in the Implementation section.

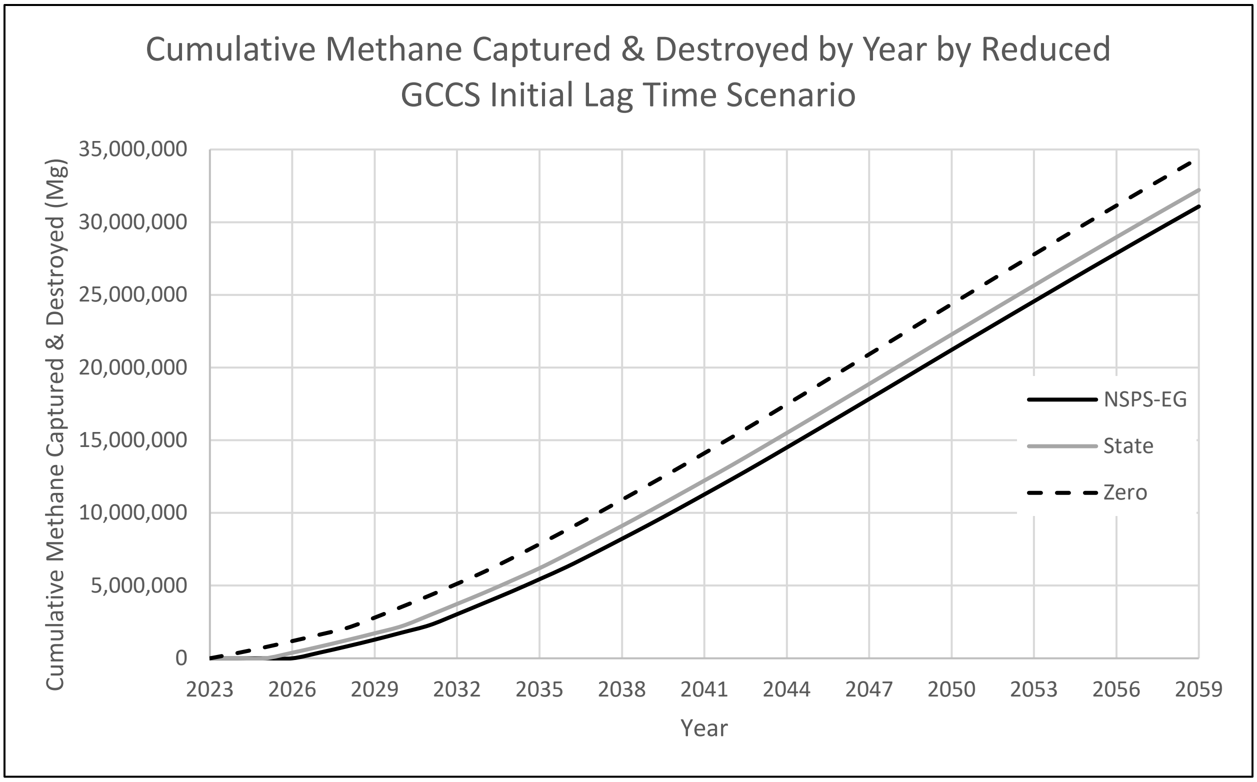

Figure 1. Estimates of cumulative methane emissions captured and destroyed by GCCS by year based on the reduced initial lag time scenarios (NSPS/EG, State, Zero Lag Time Estimates).

Potential Methane Emission Reductions from Reduced Expansion GCCS Installation/Operation Lag Times

One limitation of the estimates shown in Figure 1 is that the impact of GCCS expansion lag time cannot be modeled using the methodology discussed previously. This method assumes that once a GCCS is installed at a landfill that it is expanded as the landfill itself expands with no lag time; however, in practice the NSPS/EG allow up to 5 years for GCCS expansion into active areas and up to 2 years for expansion once the waste disposal area is closed or at final grade to install and operate the GCCS in these areas.

Therefore, a standalone analysis was performed to estimate the potential methane reductions for landfills if they adopted reduced GCCS expansion lag times. An additional LandGEM run[13] was performed to estimate methane emissions generated exclusively from a landfill expansion area per one million metric tons (MMT) of waste accepted annually for a period of 5 years.[14] It is assumed that emissions from all previously disposed waste at a landfill is already controlled by the existing GCCS; thus, the waste disposed for this 5-year period is assumed to be in a new cell or phase of the landfill or otherwise separate from the existing waste-in-place.

[13] Using default LandGEM parameters.

[14] As discussed in the Implementation section, most landfills remain active after 5 years; thus, only this condition for the expansion lag time was modeled.

Figure 2 presents the estimated cumulative amount of methane emissions[15] expected prior to GCCS installation and operation in these landfill expansion areas per one MMT waste disposed each year for a 5-year period. Conversely, Figure 2 also models the possible methane emission reductions achievable if the GCCS is expanded into these areas earlier than the required 5-year horizon. This analysis assumes that no methane generation occurs prior to the end of Year 1, as during Year 1 aerobic conditions in landfilled waste result in a lag time before anaerobic conditions develop and methane generation occurs.

This analysis estimates that approximately 53,000 Mg of methane will be generated over 5 years for every MMT of MSW disposed annually in this timeframe. Thus, earlier installation of GCCS in expanded areas could reduce emissions by up to this amount, per MMT of MSW disposed annually, if implemented at an earlier point in the 5-year period, ranging from approximately 48,000 Mg methane if installed by the end of Year 2, 36,000 Mg methane if installed by the end of Year 3, and 20,000 Mg methane if installed by the end of Year 4. This analysis assumes that a constant amount of waste is disposed of each year during this 5-year period. If waste disposal fluctuates significantly between years within this period, possibly resulting in more or less methane emissions and reductions achievable estimated by year and cumulatively.

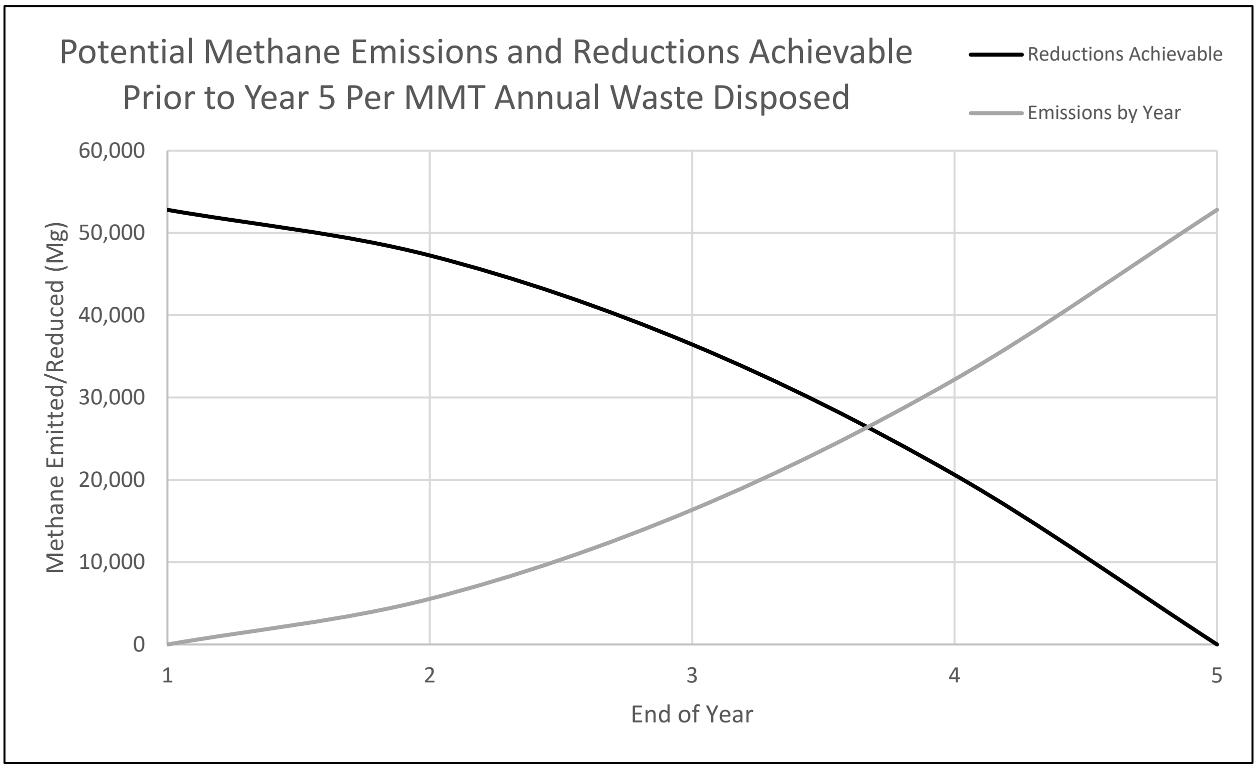

Figure 2. The estimated cumulative amount of methane released per MMT waste disposed annually prior to GCCS installation and operation in new landfill expansion areas.

[15] The previous initial lag time estimate assumed a 25 percent methane oxidation rate to account for cover soil and other subsurface interactions; however, since the expansion lag time estimate considers an area that is strictly active with minimal cover it was assumed that the methane oxidation rate is negligible for this analysis.

Potential Methane Emission Reductions by Increasing GCCS Destruction Efficiency for NSPS/EG

In 2019, EPA performed a technology review for MSW landfills and estimated the expected emission reductions achievable if existing open flares were replaced with enclosed flares. That analysis estimated about 63 percent of landfills that had flares had open flares and 37 percent of landfills that had flares had enclosed flares (U.S. EPA, 2019). That analysis indicated methane emissions could be reduced by approximately 66,000 Mg methane per year if the 63 percent of landfills with open flares replaced them with enclosed flares. That analysis also estimated approximately 6,500,000 Mg of methane per year was flared at U.S. landfills at that time, based on the proportion of open and enclosed flares.

Additional methane reductions could be possible at landfills that will install flares in the next couple of decades if more stringent methane destruction efficiency requirements are implemented. The following analysis estimates the potential methane reductions for increased methane destruction efficiency requirements based on the use of open and enclosed flares.[16] These scenarios include:

- **Baseline (not modeled):** This scenario assumes that the existing ratio of open/enclosed flares in the United States does not change and that all future GCCSs have open flares installed through 2059. No additional methane emission reductions occur.
- **All Enclosed:** This scenario would involve replacing all open flares at U.S. landfills that have open flares with enclosed flares and only installing enclosed flares for all new GCCSs in the future (i.e., all flares 2023 onward would have at least 99 percent destruction efficiency for methane in LFG). This approach assumes that the additional reductions from replacing the existing open flares with enclosed flares (~66,000 Mg/yr) is constant each year through 2059.
- **Existing + New Enclosed:** This scenario assumes that the existing ratio of open/enclosed flares in the United States does not change through 2059, but all future GCCSs have enclosed flares installed through 2059. This approach results in only the new GCCS installations contributing additional methane reductions.

The landfill dataset and methodology described earlier in this paper was used to estimate potential methane reductions by year if the GCCS destruction efficiency requirement were increased for all new future installations. Figure 3 presents the additional methane emissions destroyed (in Mg) by year based on the scenarios listed above (except the "Baseline" scenario).

[16] This analysis assumes that open flares achieve 98 percent methane destruction efficiency, while enclosed flares achieve 99 percent methane destruction efficiency.

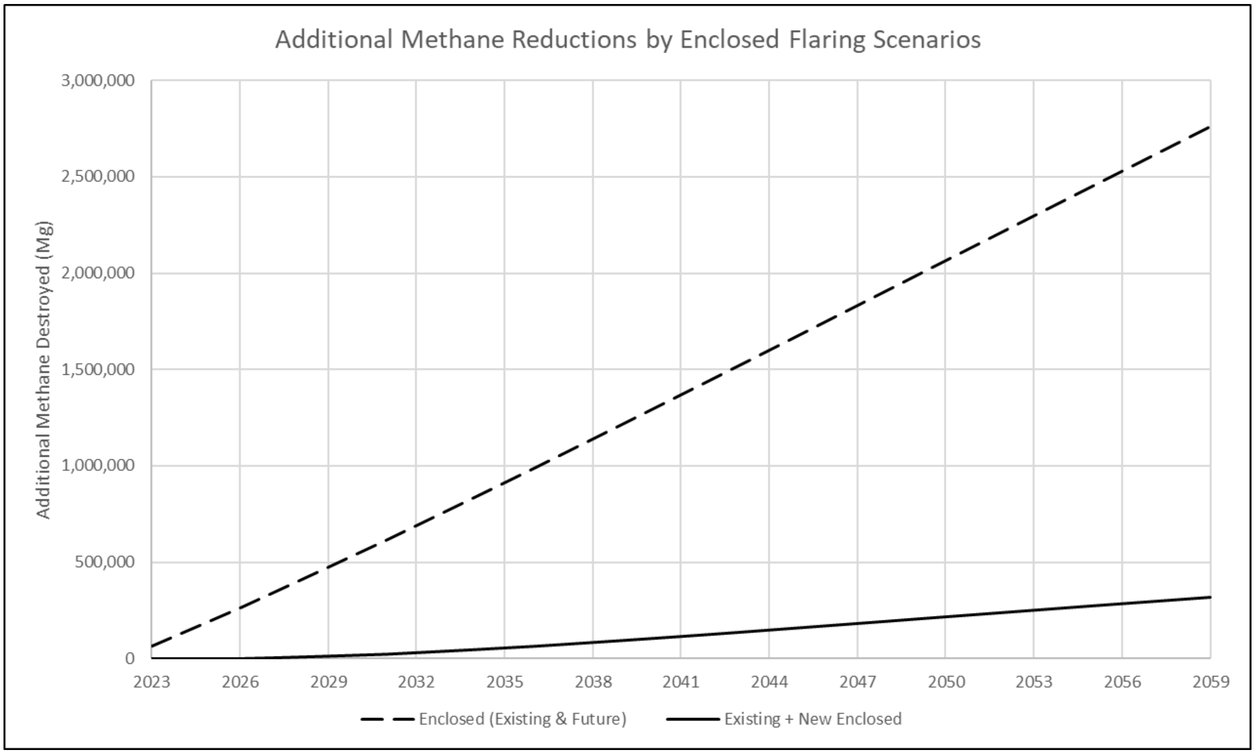

Figure 3. Additional methane emission reductions (in Mg) by adopting enclosed flares, by scenario.

Requiring all flares to be enclosed (both existing and future – the "Enclosed" Scenario), and thus increasing the required destruction efficiency of those enclosed flares to be 99 percent, would result in an estimated additional 2.7 million Mg of methane destroyed by 2060. This reduction is heavily weighted by replacing open flares with enclosed flares at existing landfills, because requiring only new GCCS installations to install enclosed flares (the "Existing + New Enclosed" Scenario) results in about a 320,000 Mg methane reduction by 2060.

This difference may be explained by the following observations. There are currently about 735 landfills with an existing flare (open or enclosed) in the United States, while the estimated number of additional landfills that will be required to install GCCSs (and flares) between 2023 and 2059 is approximately 120. This analysis assumes that the number of existing flares or the overall quantity of methane emissions from these existing landfills remains constant through 2059. The existing landfills are also likely greater sources of methane emissions due to their historical waste-in-place[17] when compared to the newer, smaller landfills that become subject to NSPS/EG requirements between 2023 and 2059 in this analysis. This analysis also assumes that each landfill required to install a GCCS will install one flare.

Regulation Changes

GCCS Installation Lag Time

Revising the NSPS/EG to reduce GCCS installation and operation lag times could involve changing the following:

[17] As most of these are likely already subject to NSPS/EG requirements and have been for years.

- The initial lag time allowed between the time a landfill triggers GCCS requirements and is required to install and operate the GCCS; this initial installation lag time is currently within 30 months in the NSPS/EG.
- The expansion lag time for when a landfill is already required to install and operate a GCCS and must expand the system into new areas where waste is placed; this expansion lag time is currently 5 years for active areas of the landfill and 2 years for closed areas that have reached final grade or have final cover.

The initial installation lag time could be reduced, for example to 18 or 24-months as used currently in some of the reviewed states' rules. The challenges with a reduced initial lag time for GCCS installation and operation for landfills are discussed in the Implementation section of this white paper.

The expansion lag time could be reduced or even eliminated ; however, this approach has challenges and other considerations to evaluate as discussed in the Implementation section of this white paper.

Besides the actual lag time duration, other potential changes that could affect GCCS installation and operation timeframes entail:

- From "when" the lag time begins, such as:
    - When the emission threshold is exceeded
    - When the GCCS design plan has been approved
- Design plan submittal timelines[18], such as details regarding:
    - The length of time a landfill has to submit after an emission threshold exceedance
    - The length of time an agency has to approve or reject the design plan.

GCCS Destruction Efficiency

Revising the NSPS/EG to increase the required GCCS destruction efficiency could involve:

- Requiring the use of enclosed flares or other technologies which can achieve destruction efficiencies of 99 percent and higher
- Changing the "basis" for destruction efficiency from NMOC to methane, which is expected based on EPA's anticipated focus on methane for the upcoming NSPS/EG rulemaking instead of NMOC.

Implementation

GCCS Lag Time

As discussed in the Regulation Changes section, changes to this requirement could involve reducing the lag time for initial GCCS installation/operation, reducing the expansion lag time for expanding areas already required to have GCCS per the NSPS/EG, or both. Reducing GCCS installation and operation lag times in the NSPS/EG would likely not result in major changes to rule structure because timeframes for these actions are already required and written into the NSPS/EG.

[18] Shortening the design plan submittal timeline could possibly expediate the initial GCCS installation process for landfills; however, this would also have logistical and staffing challenges as will be discussed in greater detail in the Implementation section.

Reduced lag times will impact landfill owners and operators nationwide, as these changes will require the permitting, design, and construction processes to occur within a shorter timeframe or be in process before threshold exceedances have occurred. As shown in Table 1, most state and federal agencies are required to approve/reject design plans within 3 to 4 months, although longer approval times are not uncommon. Additionally, the bidding and procurement process for construction can take several months and potentially longer if there is not a large enough pool of acceptable bidders[19]. The design process may be iterative, requiring revisions by both the agency approving the plans and the landfill owner/operator. Lastly, during construction there can be delays due to material shortages, inclement weather, or other site-specific challenges. These challenges apply to landfills expanding their GCCS with reduced expansion lag times as well.

GCCS initial installation and expansion lag time duration has been a topic of ongoing discussion since the original 1996 NSPS/EG rulemakings. The basis for the current 30-month timeline for GCCS installation and operation was chosen based on the following assumed timeline (U.S. EPA, 1999):

- Design plan development submittal: 12 months[20]
- Design plan approval and system installation: 18 months
    - Approval time for design plan: 6 months
        - Agency initial review and comments: 2 months
        - Landfill owner/operator revisions and response: 2 months
        - Agency final review and approval: 2 months
    - Construction and installation: 12 months.

For the GCCS expansion lag times of 5 years for active areas and 2 years for closed areas, a 2-year period was originally proposed for both active and closed areas. EPA later revised the 2-year period for active sites to allow for a 5-year lag time (closed sites remained with the 2-year lag-time) based on feedback from rule commenters. The 5-year lag time was believed to be “reasonable and consistent with common landfill practices” with the rationale that shorter lag times could result in covering over and/or damaging gas infrastructure during filling, resulting in additional costs and inefficiencies; however, lag times exceeding 5 years were deemed unacceptable due to the allowance of additional fugitive emissions and were revised back to 2 years for active areas (U.S. EPA, 1995).

The 2016 NSPS/EG rulemakings revisited the possibility of reducing initial and expansion lag times for GCCS installation. EPA sought comments and feedback from the solid waste community and performed cost-benefit analyses on the potential reductions in NMOC emissions in relation to costs. Feedback revealed that landfills typically do not reach final grade before 7 years; hence, EPA concluded reducing the 2-year lag time for closed areas would likely not achieve significant additional NMOC reductions as most landfills comply with the 5-year lag time. EPA also noted that modifying the 5-year lag time may have limited impacts as many landfills in wet climates install gas collection wells ahead of the 5-year lag time due to odor concerns or for energy recovery (U.S. EPA, 2014). The cost-benefit analyses suggested that reducing lag time compared to the baseline (no reduction to current lag times) resulted in limited

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[19] This can especially be a challenge for public entities as procurement guidelines can often require multiple bidders and rebidding if this condition is not met, possibly adding months to the overall process.

[20] An option for revised NSPS could be to require landfills that are anticipated to exceed design and emission thresholds to prepare their GCCS design plans ahead of time so the plans could be submitted immediately upon exceeding the thresholds.

NMOC reductions relative to the costs that would be required for earlier installation and operation. Cost modeling estimated that the dollar-per-Mg cost to reduce initial and/or expansion lag times in conjunction with reducing the NMOC emission rate threshold (from 50 Mg/yr to 34 Mg/yr) was higher than the option to reduce this threshold without reducing the lag time: $6,900 to $11,300/Mg NMOC vs. $6,000/Mg NMOC.[21] Commenters for the 2016 rulemakings also expressed the following concerns:

- Installing more GCCS equipment in active areas could lead to more frequent equipment damage and replacement due to daily filling operations and equipment movement.
- Waste in active fill areas undergoes significant settlement that could result in more frequent repairs, troubleshooting, and equipment replacement, which can also increase system downtime.
- More gas collection wells located in active fill areas can also increase oxygen levels and increase the potential for subsurface fires due to elevated oxygen and aerobic conditions in the waste.

Horizontal LFG wells were proposed as a possible option that could be implemented sooner than vertical wells (i.e., as soon as a sufficient layer of waste is placed above it) with EPA noting several case studies; however, commenters also expressed that these wells have their own issues such as typically shorter lifespans compared to vertical wells and requiring more frequent replacement (U.S. EPA, 2014).

The solid waste industry has changed significantly since the current NSPS/EG rulemakings and the potential changes in lag times warrant a revised cost-benefit analysis to determine if the conclusions made then are still valid. Additionally, recent work suggests that food waste is being increasingly landfilled and is contributing to methane generation sooner and at a greater quantity than previously anticipated and possibly prior to when GCCS installation or expansion may occur under the existing NSPS requirements (U.S. EPA, 2023b).

EPA is also expected to focus on methane emissions instead of NMOC emissions for the upcoming NSPS/EG rulemaking which will likely result in new conclusions compared to the 2016 analysis. New technologies and new information from case studies on early LFG collection (e.g., horizontal collectors) may also reveal long-term results and conclusions that determine if these strategies are a cost-effective and feasible option or if there may be new options available.

It is possible that reduced lag times may not significantly impact the total cost of GCCS installation and operation; however, these costs could be incurred sooner than a landfill owner or operator anticipated. GCCS design and construction is a major capital investment for a landfill and can be in the range of 1–3 million U.S. dollars (MDE, 2022). This cost does not include the operation and maintenance (O&M) costs associated with a GCCS, estimated at $150,000 to $400,000 per year, and monitoring, recordkeeping, and reporting requirements, estimated at about $60,000 per year (MDE, 2022). The ability of landfill owners and operators to undertake the earlier costs that may result from a potentially shorter timeline for GCCS installation may also be dependent upon whether the affected facilities are owned by a private or public (e.g., a county or municipality) entity.

[21] This difference in cost was due partly to timing of the first round of wellfield expansion at these new landfills, many of which were modeled to expand their systems in 2023 and incurred additional costs in that year to operate both initial GCCS and the first set of expansion wells.

Cost concerns may be mediated with possible options for loans, grants, or tax credits[22] at the federal or state levels or potential options to be exempt from or extend the timeline for GCCS installation/operation for select landfills[23] and by the benefit of additional, saleable methane collected for possible beneficial use. Alternatively, federal assistance with technology guidance to make GCCS installation and operation more fiscally feasible (e.g., LFG energy project assistance) could be beneficial to ease the transition.

Lastly, obtaining the necessary solid waste and air permits (e.g., Title V) in an appropriate timeframe to accommodate reduced GCCS install/operation lag times will require more rapid turnaround times from state and local regulators which may require additional staffing and resources.

GCCS Destruction Efficiency

Like the reduced GCCS installation and operation lag times, increasing the GCCS destruction efficiency would not require major changes to rule structure because a destruction or removal efficiency is already specified in the rules. As discussed in the Regulation Changes section, increasing destruction efficiency can be achieved by requiring the use of enclosed flares, which can achieve destruction efficiencies of 99 percent and higher. Enclosed flares are already used at a significant portion of landfills across the country; however, if landfills are required to convert open flares to enclosed flares there could be some financial and logistical challenges. Strategies to overcome these challenges like those discussed in the previous section (e.g., federal guidance, loans/grants) may be helpful for affected landfill owners and operators and ease this transition.

As for switching the basis of destruction efficiency from NMOC to methane, EPA is considering transitioning the focus of the NSPS/EG from NMOC to methane, which could promote increased methane destruction (emission reductions) from landfills. This new requirement would likely result in some recordkeeping, testing, and reporting changes; however, it is typically assumed that NMOC destruction is associated with the same level of methane destruction (e.g., 98 percent reduction NMOC results in 98 percent reduction of methane).

Summary and Next Steps

This paper reviews GCCS installation and operation lag times used in the NSPS/EG, several U.S. states, and in the proposed ECCC rules, and estimates the potential methane emission reductions that could be possible by reducing lag times for GCCS install/operation. This analysis found that:

- Reducing the current 30-month[24] initial lag time to install/operate GCCS to 18 months[25] could result in a reduction of 1.1 million Mg methane by 2060 (approximately 3.5 percent compared to baseline). A greater reduction of 3.3 million Mg methane by 2060 (approximately 10.6 percent compared to baseline) could be achieved if a hypothetical “zero”-month (immediate) GCCS installation schedule were adopted; however, this immediate GCCS installation after emission

[22] The Inflation Reduction Act established energy production tax credits (PTCs) and investment tax credits (ITCs) that LFG-to-energy projects may qualify for to assist with GCCS installation and operational costs. For additional information, visit: https://www.epa.gov/inflation-reduction-act.

[23] For example, landfills with annual acceptance rates under a certain tonnage, are located in arid climates, or practice organic waste diversion.

[24] Modeled in LandGEM as 3 years due to model limitations (whole year inputs and outputs required).

[25] Modeled in LandGEM as 2 years due to model limitations (whole year inputs and outputs required).

exceedance would be difficult to achieve in practice unless started months or years prior in anticipation of the GCCS requirement.

- Reducing the current 5-year expansion lag time for active landfill areas that are undergoing expansion could reduce methane emissions on a per MMT waste disposed annually basis by approximately:
    - 53,000 Mg methane/MMT waste disposed annually, if installed at the end of Year 1
    - 48,000 Mg methane/MMT waste disposed annually, if installed at the end of Year 2
    - 36,000 Mg methane/MMT waste disposed annually, if installed at the end of Year 3
    - 20,000 Mg methane/MMT waste disposed annually, if installed at the end of Year 4.

As for evaluating potential methane reductions from increasing GCCS destruction efficiency, requiring enclosed flares (and thereby providing a minimum 99 percent required methane destruction efficiency) instead of open flares at all landfills with a GCCS could result in approximately 2.7 million Mg additional methane reduced by 2060 (approximately 1.0 percent compared to baseline). This reduction would be significantly less (only approximately 320,000 Mg methane reduced by 2060 or about 0.1 percent compared to baseline) if only new GCCSs (built after 2023) were required to install enclosed flares and not the existing open flares in the United States (about 63 percent of total existing LFG flares).

These methane reduction estimates are contingent upon caveats and assumptions made in this analysis as described in the Investigation and Results section.

Revising the NSPS/EG to change the allowed lag times could be relatively straightforward. Landfill owners and operators could be required to begin and execute the process for design, installation, and operation of their GCCS, both for initial installation and for expansion areas, more rapidly. This process could be more accelerated than it would have been under the current NSPS/EG, and for some landfill owners and operators, it could cause financial and logistical challenges. Likewise for requiring increased GCCS destruction efficiency, this rule language could be relatively easily implemented in the upcoming NSPS/EG rulemaking but could require retrofitting existing facilities and added costs for landfills installing new or adding additional enclosed flares, which may also cause financial and logistical challenges.

Potential next steps and analyses for evaluating feasibility include:

- Conduct cost and emission reduction analyses that examine the potential costs for both the landfill owner/operators and state and federal agencies from a potential rule change and compare them to the potential methane emission reductions.
- Engage in master planning the logistics for implementing these proposed changes at the state and federal level, both initially and in the long term for both solid waste and air quality disciplines.

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