Evaluating the Limitations of the EPA's Landfill Gas Emissions Model

TigerGEM Consulting

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SWANA's Young Professionals Present
THE SOLID WASTE STUDENT DESIGN COMPETITION

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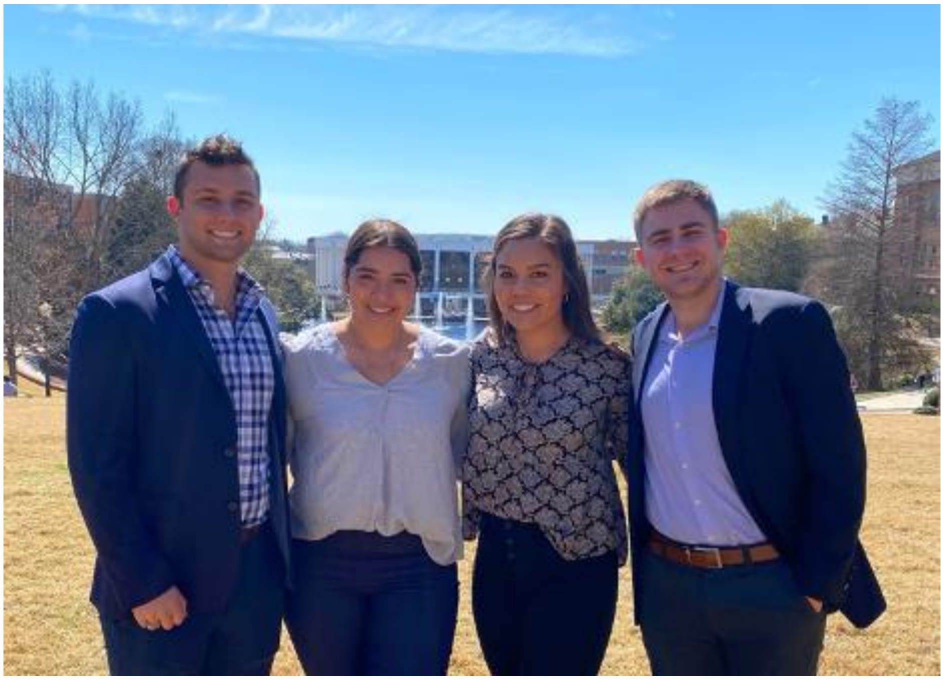
Meet the Team



From left to right: Derek Kosydar, Nina Del Rio, Hope Owens, and Ryan Fisher

Derek Kosydar is an entry-level Environmental Engineer who graduated from Clemson University in 2022 with a Bachelor of Science in Environmental Engineering. Some of his relevant coursework included Solid and Hazardous Waste Management. He has previous consulting experience with Gannett Fleming as an engineering intern where he worked on bridge rehabilitation projects and structural design. Additionally, he has experience in the construction industry with Moss Construction LLC, where he worked as a solar panel construction intern. He is also OSHA HAZWOPER certified.

Nina Del Rio is an entry-level Environmental Engineer who graduated from Clemson University in 2022 with a Bachelor of Science in Environmental Engineering. She has also graduated from Charleston Southern University in 2020 with a Bachelor of Science in Applied Mathematics. During her time at Clemson, she has taken courses in Solid and Hazardous waste Management. She has experience as an engineer for First Quality Tissue and Bowman Consulting. During her time at First Quality, she conducted research for landfill sampling and ensured reports to DHEC were accurate with EPA standards. She oversaw working with operators of the landfill to guarantee compliance with the EPA. Lastly, she has experience in CAD files, communication with clients for environmental reports and cost estimates for projects within the environmental department.

Hope Owens is an entry-level Environmental Engineer who obtained her Bachelor's of Science in Environmental Engineering and minor in Environmental Science and Policy from Clemson University. During her time at Clemson, Hope completed three Co-op rotations at Charleston Water System where she was able to learn more about minimum standards and submittal approvals. She also worked as a natural resource technician for South Carolina Department of Health and Environmental Control where she was able to learn more about the environmental regulation sector. Her relevant coursework includes classes in municipal solid waste engineering, air pollution engineering, and hazardous waste engineering. Her previous experience will be very helpful in communicating with others and researching new methods to solve complex problems.

Ryan Fisher is an entry-level Environmental Engineer who graduated from Clemson University in 2022. During his time at Clemson University, he has taken specific courses in Environmental Engineering Fundamentals, Municipal Solid Waste Management, and Hazardous Waste Management. He has experience as an engineering co-op student at Goodwyn Mills & Cawood, an engineer/scientist at the Savannah River Site, and as an engineering production intern for Kimley-Horn. Within these positions, Ryan has assisted in the design of Water/Wastewater Treatment Facilities, pipe networks, and lift stations. He has had exposure to carrying out numerous projects that included tasks such as CAD files, site investigation reports, communication with clients and sales representatives, asset management, specifications, operations and maintenance manuals, preliminary engineering reports, cost estimates, site plans, life cycle analyses, environmental reports, and various flow measuring, and collection devices used for monitoring tritium contamination in waterways and the air.

I. Executive Summary

Our group, TigerGEM Consulting, has assessed the Landfill Gas Emissions Model (LandGEM) created by the Environmental Protection Agency (EPA) for potential biases, determined the sources of this bias, and has suggested edits to the model to mitigate these biases. It was determined that one source of bias lies in the default values for the methane generation capacity (*k*) and the potential methane generation capacity (L_0). This is because those values are dependent on the moisture content, average temperature, and cellulose content of the landfill, but these factors may be insufficiently accounted for in the current model. To investigate the impact of these factors on landfill gas estimations, the group recreated the model in Python and added a step which calculates values of *k* and L_0 based on user inputs. The new model found that in the current LandGEM model, the lack of options for L_0 , leads to inaccuracies in estimating the total landfill gas emissions with a 70% disparity. Additionally, calculating a *k* value based on the typical precipitation in the area creates a *k* value that may be more precise than using the defaults, leading to emissions estimations that may be more accurate. This eliminates the limitation of only having two choices when selecting a value for k as it is in the current LandGEM model.

II. Objectives

Objective 1: LandGEM

Within objective 1, TigerGEM Consulting will be responsible for learning and understanding how the LandGEM application is a tool of analysis for estimating landfill gas generation under varying waste disposal inputs and model methane generation rates (k) and methane generation capacity (L_o). The team will learn the ins and outs of the model and contact other professionals that are experienced in LandGEM and landfill permitting. Understanding methane as a product of landfills and the LandGEM model will be a crucial first step toward tackling this problem. A sample model in LandGEM has already been run and the firm has connections with professionals experienced in LandGEM to better understand the model. We will analyze each output for total landfill methane gas emissions.

Objective 2: Detailed Analysis of Available Data

Within objective 2, methane generation rates (k) and methane generation capacities (L_o) will be analyzed for different sites to understand the model. Data from the Facility Level Information on Greenhouse Gasses Tool (FLIGHT) and the Landfill Methane Outreach Program (LMOP) will be used to evaluate how waste characterization affects the waste outputs (EPA). These databases will provide the team with proper annual historical waste disposal rates and actual landfill gas recovery data to compare with model results. The team will communicate with local landfills in the South Carolina area to perform potential site-visits to understand landfill gas collection systems where accurate LandGEM results need to be as accurate as possible to calculate profit margins. The team will develop estimates for these landfill site's gas collection systems using publicly available data, such as the reported number of wells on site, intermediate cover, and final cover. Applying knowledge attained of site-specific landfill gas collection systems design and operations will be considered in determining collection efficiency. These estimates along with actual landfill gas recovery rates will be compared to the LandGEM outputs to determine the accuracy of using the model. A Monte Carlo sensitivity analysis will be considered to further evaluate the model and assess potential biases. The team will consider, if necessary, investigating landfills that exist in different climates around the world and if it is necessary to be able to adjust the model for climate.

Objective 3: Assessing Bias

Within objective 3, the team will choose one or a combination of multiple inaccuracies within the current method developed by the EPA for estimating landfill methane. The goal in this task will be to estimate the potential bias within the current assumptions that the EPA makes in the model and how estimating methane generation, oxidation, and emissions may differ at site-specific landfills or regionally.

Objective 4: Literature Review

Within objective 4, the team will review relevant academic literature in order to supplement the project. Some of the relevant topics will include estimating methane generation using the LandGEM program, basics of landfill gas generation, federal regulations, and different methods of modeling landfill gas emissions.

Objective 5: Calculation of Methane Gas

Within objective 5, the team will use knowledge learned from literature review of different studies that have researched and studied different models for estimating methane gas emissions from landfills. We will analyze the components of these other models to discover if the addition of these variables suggests more accurate estimates of methane emissions. One variable we will explore is oxidation assumptions within landfills and if it plays a vital role in the determination of total methane emissions for a landfill. As a part of this task, the team will analyze if waste characterization affects methane gas emissions too. The team will use Python to rebuild the model and then run additional models against the current model for comparison

Objective 6: Technologies

Objective 6 will consist of a discussion of various technologies landfills use for methane gas treatment, recovery, and collection. Within this task, more information will be researched and provided regarding methane gas collection systems that are used as a source and profit of renewable energy. Within this conversation, the team will attempt to get in contact with the Anderson Regional Landfill or another landfill to learn more about the gas collection system on site.

Objective 7: Economic, Regulatory, and Health/Safety Analysis

Upon completion of the other tasks, the team will move into objective 7 where the team will access our findings in a brief economic analysis. For instance, if the team finds that changes are needed to the model and this makes the model more complex, how does this affect those using this model? From here, we will research if making the model more accurate is what is needed for regulatory purposes. Does the model currently serve as a conservative approach that still meets regulatory requirements? If the model is made more accurate, is it possible that landfills will begin to emit as much methane as possible to meet the exact number instead of being conservative and producing much less? This task will also include a review of the health and safety effects of methane emissions and certain processes landfills use for methane gas collection.

III. Introduction

TigerGEM Consulting is participating in the International Solid Waste Design Competition sponsored by The Solid Waste Association of North America (SWANA). SWANA has tasked TigerGEM Consulting with analyzing the Environmental Protection Agency (EPA) model for estimating landfill gas emissions, known as LandGEM. LandGEM is a Microsoft Excel based estimation tool to estimate the emission rate of methane and other air pollutants. LandGEM uses a simple first-order decay equation to calculate emission rates based on a landfill's waste deposition history and future deposition projections. The model can either use site-specific data or default parameters to estimate the emission rate. The model may be biased towards certain sites whose properties fit the inherent assumptions, while other sites have less accurate emission projections. It is TigerGEM's goal to evaluate the inherent biases of LandGEM and offer suggestions for improvements in the landfill gas estimation methods.

Landfill gas is mainly composed of carbon dioxide and methane with a small portion of various other gasses. The production of landfill gasses, specifically methane, can be seen in **Figure 16** and **Figure 17** in **Appendix A.** Methane (CH_4) typically accounts for between 45-60% and carbon dioxide (CO_2) accounts for 40-60% of landfill gas (Gavrelis 2001). Carbon dioxide emissions result in a global warming effect on the atmosphere but methane has 28 to 36 times more global warming potential than carbon dioxide on a per-mass basis. Thus, it is a well-known EPA goal to reduce methane emissions to protect atmospheric temperatures. TigerGEM is continuing to emphasize the importance of methane emission calculations by evaluating the EPA's LandGEM model to ensure the most accurate possible methane emissions are reported and that the potential biases in the model are understood.

Methane is involved in all atmospheric chemistry (Van Amstel 2012). One way it is produced is from anaerobic decomposition of organic waste buried in landfills. As shown in **Figure 15** in **Appendix A**, landfills account for about 17% of the methane emissions, which reveals the importance of regulations of methane produced when reporting and designing landfills (EPA 2015).

Landfill gas collection systems are a common method to reduce methane emissions. Components of a landfill gas extraction system are shown on the cover page; a municipal solid waste facility in Wisconsin uses a piping system to collect landfill-generated methane. To ensure the health of the environment, the EPA has set standards that limit methane emissions. Once the methane is collected, it can be controlled by advanced technologies like flaring or conversion to heat or electricity. However, some of these methods are imperfect and require high capital and operation costs so many landfills do not have optimized gas collection and treatment capabilities.

EPA has a need to predict and monitor emissions from landfill operations. Landfill operators report the amount of emissions using models like LandGEM, yet any modeling approach will have inherent inaccuracies because of the assumptions used in its creation. It is important for the EPA to receive correct methane emissions to ensure safety of humans and the environment. A correct measurement of methane emissions will allow the EPA to create accurate regulations along with an emphasis in the waste to energy industry. When landfills can accurately model the amount of methane generated then owners would be able to make a better decision for the optimal gas collection system. In this report the TigerGEM design team evaluates the LandGEM model and offers ideas for improvements that can give the model more adaptive capabilities for methane emission prediction.

IV. Literature Review

Background information on the LandGEM Model

Most models use first-order decay to estimate landfill gas emissions. **Equation 1** is the most common equation used to estimate the methane generation for a given year from cumulative waste disposal. (EPA 2012).

$$\boldsymbol{Q = \sum_{t=1}^{n} \sum_{j=0.1}^{1} kL_0 \left[\frac{M_i}{10}\right] \left(e^{-kt}{}_{ij}\right)} \qquad \textbf{(1)}$$

Where:

Q = maximum expected generation flow rate (m^3/yr)

i = 1 year time increment

n = (year of calculation) - (initial year of waste acceptance)

j = 0.1 year time increment

k = methane generation rate (1/yr)

L_0 = potential methane generation capacity (m^3/Mg)

M_i = mass solid waste disposed in the i^{th} year (Mg)

t_{ij} = age of the j^{th} section of waste mass M_i disposed in the i^{th} year (decimal years)

Estimating Methane Generation Rate (k, year^{-1})

The methane generation rate constant *k* is an essential variable when using a first-order decay model to estimate methane emissions from landfills (Mou 2015). Most of the models created are based on **Equation 1**, which is a modified form of the EPA’s LandGEM model (Alexander 2005). The value of *k* represents the waste degradation rate. Important parameters in the determination of *k* are waste depth, density, pH, and moisture content (Alexander 2005). Previous studies have shown that a zero-order decay rate leads to inaccurate estimations of landfill gas emissions, but higher-order decay rates make the process more complicated than most users would like (Majdinasab 2017). Some methods for estimating the *k* value include biodegradability tests (Park et al. 2017), linear regressions of actual landfill gas data (Amini et al. 2012), use of EPA defaults, (Thompson et al. 2009), and matrices based on precipitation and climate.

Anaerobic and aerobic biodegradability test

Anaerobic Test (GB21)

An anaerobic test was conducted in Germany (GB21) to test the biodegradability of actual waste samples. The GB21 apparatus consists of a 400 mL gas collection tube connected to a 500 mL glass bottle via a glass-ground connection. The gas collection tube is filled with 25% NaCl and the air-tight glass bottles are filled with 50 g of sample waste shredded to <10 mm particle size. The bottles are then filled with 300 mL of water. After the pH is adjusted to 7.0, the experiment is run for 21 days at 35°C which is the optimal temperature for mesophilic methanogenic bacteria. Biogas production is tracked throughout the experiment and the background methane production from the inoculum is subtracted from the total amount generated. This experiment is able to determine the *k* value based on the biodegradation potential of a sample (Park et al. 2017).

Large-Scale Respirometer (LSR) Test

In the large-scale respirometer (LSR) test a 17.7 L large-scale respirator drum is filled with 5 kg of dry base sample. The sample is inoculated with microorganisms that were extracted from compost added at 1% v/v of the nutrient medium containing various minerals. The moisture content is then adjusted to 50%. To track the consumption of oxygen (O_2) and production of CO_2, the drum lids are fitted with pressure sensors and oxygen meters. The microbes consume O_2 and produce an equivalent amount of CO_2. Sodium hydroxide is used as a "CO_2 trap" to ensure accurate measurements. O_2 consumption is also measured via pressure drop. This test is run for 14 days at 35 °C. A theoretical *k* value is calculated using the composition of the disposed waste to compare the *k* values that were obtained in the biodegradability tests. The *k* value (k_{waste}) of the landfill waste can be calculated from a weighted average (*wt. fraction*$_i$) of the *k* of each biodegradable component (k_i), as described in **Equation 2**:

$$\boldsymbol{k}_{\text{waste}}=\sum_{i=1}^{n} \left(\boldsymbol{k_i x (wt. fraction)_i}\right) \qquad \textbf{(2)}$$

This method differs from the current LandGEM model because of its ability to determine *k* based on waste composition, versus selecting a generic *k* value unrelated to site-specific waste (Park et al. 2017).

Linear regression of actual landfill gas data

The linear regression method includes using the waste composition to create the waste specific methane generation potential (L_o) derived from laboratory results. L_o is determined from a yearly average landfill waste composition for each case-study. The parameter *k* is then determined by fitting a linear regression to fit the actual landfill data. To obtain a linear regression value with the most accurate slope ($R^2 = 1$), a non-zero intercept had to be used meaning there was inherent error in this method. However, forcing the regression to pass through the origin was the only way to accurately compare the actual data to the estimated emissions. It has been reported that the optimum method for calculating *k* is to use the linear regression method for calculating L_o, then using that methane generation potential to estimate *k (Park et al. 2017)*. Because this method requires landfill gas data, the calculation of *k* is not pre-emptive, and when such data are not available, *k* should be selected based on the literature or other site conditions (Amini et al. 2012).

Equation based on EPA defaults

The following equation has been extrapolated based on the EPA LandGEM defaults of *k*:

$$k = 3.2 \times 10^{-5}x + 0.01 \quad \textbf{(3)}$$

where: k = decay rate [year^{-1}], and x = precipitation [in of rain] (Thompson et al. 2009).

Matrices based on precipitation and climate

Another method for determining a proper *k* value is by evaluating existing user guides. Some of these guides include: The User's Manual: Central-Eastern Europe Landfill Gas Version 1.0 ((EPA 2014), User's Manual Colombia Landfill Gas Model (EPA 2010), User's Manual Mexico Landfill Gas Model (EPA 2009), and the Solid Waste Emission Estimation Tool (SWEET) Version 4.0 (EPA 2021). All have tables of *k* values based on the columns categorizing different precipitation (referred to as climate) and rows categorizing waste type where both are defined in their respective manuals based on the region. This method provides more granularity than the LandGEM model because accommodating both precipitation and waste composition develops site specificity (EPA 2014).

Estimating Methane Generation Capacity (L_o)

The methane generation potential considers the composition of waste, and its potential to biodegrade. The main factor that goes into determining L_o is the composition of waste. L_o can be calculated using the **Equation 4**, where DOC is the fraction of degradable organic carbon [Mg C in waste/Mg waste]. Default values for DOC can be found in the *GHG Emissions Estimation Methodologies for Biogenic Emissions from Selected Source Categories*.

$$L_0 = 493 \times DOC \quad \textbf{(4)}$$

Precipitation is not a factor of consideration in the current LandGEM model. For example, celluloses and hemicelluloses, found in food and yard waste, are readily biodegradable under anaerobic conditions, while lignin, found in wood and newspaper, is not (Thompson et al. 2009). The most common method for selecting an appropriate L_o value is by analyzing the average waste composition of the area of interest (Thompson et al. 2009).

V. Assessing Bias

In the current LandGEM model, only two default values are able to be selected for both *k* and L_o based on the waste composition, regulation, and the climate that the landfill is located in. However, this oversimplifies the function of these two important parameters when trying to calculate gas emissions from a landfill. Thus, the TigerGEM group has chosen to assess the LandGEM model bias with regard to determining more accurate *k* and L_o values.

The US EPA LandGEM User's Guide mentions that there are four primary factors which affect the *k* value of a landfill: moisture content, availability of nutrients, pH, and temperature. However, LandGEM only lets a user select a default *k* value based on the type of standard (either Clean Air Act [CAA] or Inventory) as well as the climate (conventional or arid). The New Source Performance Standards define the default for the CAA regulation inputs and the Title V Permit of the Clean Air Act define the default for the Inventory regulation inputs. By limiting users to these few parameters when categorizing their landfill, the group believes that the values of *k* used by LandGEM may lead to inaccurate calculations for some landfills. If more details about an individual landfill could be incorporated into the model, LandGEM may provide a more precise *k* value and estimate of landfill gas emissions (Amy Alexander 2005).

Something that the group found interesting was how the User's Manual defines conventional and arid climates. It states that "Arid area landfills are located in areas that receive less than 25 inches of rainfall per year" (Amy Alexander 2005). Any geography in which rainfall is above this threshold would be considered a conventional landfill area. Since moisture content and temperature are both essential components of landfill gas emissions, the group concluded that precipitation rates and climate should be more heavily considered when selecting a value for *k*. For example, both Washington state and Florida receive high levels of rainfall in a year, and would both be considered a conventional landfill under the current LandGEM standards. However, Florida's average temperature is significantly higher than that of Washington, creating drastically different conditions for landfill gas creation (US Department of Commerce, NOAA, and National Weather Service n.d.). There is currently no way to change the *k* value in LandGEM to account for differences in temperature, so these two theoretical landfills would use the same *k* value and may have similar emissions calculations when in reality that is not the case.

Similarly, having just two categories for landfills and one threshold is not enough to truly capture the impact that precipitation has on moisture content and therefore gas emissions. A landfill in Michigan, which may receive 30-40 inches of rainfall annually, should not be using the same constant as a landfill in Louisiana where it is common to see 60-70 inches of rain in a year (US Department of Commerce, NOAA, and National Weather Service n.d.). Thus, there is potential bias in the accuracy of the *k* values currently being used in the LandGEM model, and TigerGEM will be investigating ways to implement more accurate values for the methane generation rate based on variances in precipitation and temperature across the country.

The same limitations in LandGEM exist when selecting an $\mathrm{L_o}$ value. Users of the model may only select an L_o value based on the standards they want to apply as well as the precipitation at the landfill, but the user is limited to the options of "arid" and "conventional" for L_o as well. This creates the same biases described for the *k* values, possibly leading to further inaccurate gas emission calculations (Amy Alexander 2005).

According to the User's Manual, there is a direct correlation between cellulose content and L_o. If a landfill contains an above average amount of wood, cotton, or other organic matter, then the default L_o will underestimate the potential methane generation capacity. This also works in the opposite way if a landfill is primarily used for inorganic matter such as construction materials, metals, or plastics, then the default value for L_o will be an overestimation. Landfill composition may change over time, so the group believes that being able to change the L_o value to be more accurate based on the updated waste composition would be a good way to more accurately estimate the gas production as well as allowing it to be more accurate based on more specific climatic conditions.

Lastly, some professionals in the field that TigerGEM has spoken to have expressed frustration when applying LandGEM to a landfill separated into many cells (Lamb 2022). Since LandGEM only allows for one general constant to be selected, many professionals find themselves running LandGEM countless times to account for differences in cell compositions. This makes the current model more accurate with regard to each individual cell, but if all the data could be input at once and the model only had to be run once, it would be more efficient for professionals in the industry. It would also eliminate biases created if the user does not separate their calculations by cell and just does one calculation for the entire landfill. Should someone do that, it would calculate an inaccurate value as the moisture and cellulose contents of each cell could be drastically different. TigerGEM aims to examine how skewed the LandGEM calculations are currently and suggest edits to the model that would include more accurate data regarding the climate and contents of the landfill to create more accurate values for k and L_o.

VI. Analysis Using Python

The team redeveloped the EPA's LandGEM in Python for further analysis. The Python-based LandGEM model was run for each landfill in **Table 14**, found in **Appendix A**, using varying methods that are described below: LandGEM - CAA, LandGEM - Inventory, TigerGEM 1, TigerGEM 2, and TigerGEM 3. The landfills investigated were selected based on varying precipitation and temperature data from the last 10 years. These locations are outlined in **Figure 14.** All methods use the First-Order decay equation (**Equation 1**) for estimating methane emissions. Each method includes the average annual precipitation and average daily temperature for the last 10 years for an individual location from the National Oceanic and Atmospheric Administration (NOAA) Climate Database (NOAA n.d.). The code requires three user inputs before running the model: climatological data for the landfill's location over the last 10 years, annual waste acceptance, and the reported value for *k* from the EPA's Facility Level Information of GreenHouse Gasses Tool (EPA 2022). If a landfill is still open, then the waste acceptance amount for years between present day and the estimated closure year is assumed to be equal to the most recent annual waste acceptance. The Python code is presented in **Appendix B**.

LandGEM - CAA and Inventory

These sections of the Python code are approximately equal to the Landfill Gas Emission Model using the defaults for either the Clean Air Act or the Inventory regulation. The code takes into account the uploaded precipitation data from the last 10 years and automatically assigns the default *k* and L_o values for the amount of precipitation the site receives on average in a given year as well as whether CAA or Inventory is selected. The output of the code is a graph depicting methane emissions for the expected lifetime of the landfill and years after closure.

TigerGEM 1, 2, and 3

After making changes to the coded LandGEM Model, the group has renamed our version of the landfill gas calculation model TigerGEM. The main difference between TigerGEM and LandGEM is that TigerGEM uses different values for L_o and k. L_o is calculated using **Equation 4** and the values for waste characterization are representative of waste in North America as described in the SWEET model. TigerGEM runs the model three times, each with a different method for determining k. In TigerGEM 1, the code takes into account the uploaded precipitation data from the last 10 years and calculates k using **Equation 3**. TigerGEM 2 uses the k values listed for each landfill in FLIGHT rather than computing a new value. Lastly, TigerGEM 3 extrapolates k based on a suggested range from the team's mentor, Matt Lamb. He recommended avoiding k values greater than 0.3 year^{-1}, so the team used that as the maximum and the EPA's value of 0.02 year^{-1} from LandGEM as our minimum. We then extrapolated 12 different k values that are proportional for climates of varying temperature and precipitation. These can be found in the *First-Order Kinetic Gas Generation Model Parameters for Wet Landfills (EPA 2005)*. Decay rates found using this method are of greater magnitude than the TigerGEM 1 and TigerGEM 2 models because they are specifically referenced for Wet landfills. The code outputs a graph of methane emissions using each model for the expected lifetime of the landfill and years after closure.

VII. Analysis of Python Results

The written Python code outputs summary **Figures c and d** in **Appendix A** for each location researched which aided the group in evaluating the EPA's current model for estimating methane emissions from landfills. From the analysis of all 12 locations, it is suggested that against all TigerGEM models (TigerGEM 1, TigerGEM 2, and TigerGEM 3), LandGEM overestimates the emission of methane gas from landfills, except for San Diego, CA, where the TigerGEM 3 model is slightly greater than LandGEM - Inventory. San Diego, CA has relatively low precipitation and warmer temperatures. The group found this result surprising because the TigerGEM 3 model is mainly useful for wetter climates, as a higher *k* value is used.

The data also indicates that the value of L_o plays a vital role in determining methane emissions. This is demonstrated by the LandGEM models for Boise, ID, Las Vegas, NV, and San Diego, CA. All three of these cities receive less than 25 inches of precipitation annually, which makes the *k* value the same at 0.02 year^{-1}. The L_o value varies based on the regulation that is being followed so the values vary at 100 and 170 m^3 methane/Mg waste. The change in L_o demonstrates a 170% increase of total methane production at each location.

The different methods used by the team in Python for estimating methane emissions at landfills revealed varying biases from the EPA's LandGEM. The LandGEM model only allows for three separate values for the decay rate (*k*) [year^{-1}]: 0.05, 0.02, and 0.04. For conventional climates, climates that are receiving on average greater than or equal to 25 inches of rain in a year, the decay rate depends on the regulation under investigation for the landfill. For CCA, LandGEM sets *k* to 0.05 year^{-1}. For Inventory, LandGEM has a *k* default of 0.04. For drier climates receiving less than 25 inches of rain in a year, the default *k* value, regardless of the regulation set for the landfill is 0.02 year^{-1}. The data suggests that the decay rate for landfills in wetter climates may be underestimated or not properly distributed for LandGEM. As seen in **Appendix A Tables 1 and 6**, Bismarck, ND receives on average 28.61 inches of rain in a year and New Orleans, LA receives on average 71.94 inches of rain, yet for LandGEM they are assigned the same *k* values (0.02 year^{-1}). This creates a bias towards Bismark, ND because the *k* value of 0.02 year^{-1} for that area would be more accurate for Bismark, ND than New Orleans, LA because although these two locations receive greater than the 25-inch threshold, New Orleans should have a higher *k* value. When looking at the TigerGEM 1 method, the calculated *k* value for using **Equation 3** in TigerGEM 1 is 0.068 for New Orleans compared to the 0.02 year^{-1} default for LandGEM. **Equation 3** calculates a *k* value based on average precipitation; this value is a 136% increase from the LandGEM default. A similar situation occurs in Forks, Washington and can be recognized in **Table 3 in Appendix A**, where average annual rainfall is 97 inches per year and the *k* value is larger than the default *k* when calculated in the TigerGEM 1 method. The *k* value for TigerGEM 1 for Forks is 0.089 year^{-1}. TigerGEM 1 shows a 178% increase in *k* when accounting for the annual precipitation. Both of these situations fall above the LandGEM deciding point (25 inches of rain annually), but a similar situation can be noticed below the range. For example, in **Tables 2 and 5 in Appendix A** Boise, ID and Las Vegas, NV receive considerably different values of precipitation within a year. Boise, ID receives 16 inches and Las Vegas, receives 8.47 inches on average. This demonstrates Boise experiencing double the amount of rain in a year compared to Las Vegas, but in LandGEM they are both defaulted to the same *k* value. In TigerGEM 1, Las Vegas has a calculated *k* value of 0.017, whereas Boise is 0.023. Here, Las Vegas is rounded up and Boise is rounded down to meet LandGEM defaults, but this creates bias because both locations are experiencing different climates.

VIII. Methane Collection Technologies

Organic waste decomposition produces landfill gas that causes many problems for landfills. Some of these issues include explosions, asphyxiation, and odors. Changes in gas content may also prevent ideal conditions for bacterial decomposition of wastes. Various technologies have been developed to not only combat these problems, but also utilize landfill gas emissions to our benefit. Since these devices operate differently for various types of landfills and landfill gas compositions, it is important to have a method of estimating landfill gas that is reliable and accurate.

Each gas collection device has its own set of ideal conditions for optimal operation. Some of these parameters include volume of emissions, types of gas present and costs. The composition of the landfill gas is usually the determining factor for the type of system most effective for operation. One of the most abundant gasses emitted by landfills is methane, which can be harnessed for a plethora of uses, so the solid waste industry is particularly interested in effectively collecting the methane given off by landfills. However, these technologies have a long way to come as many of them still lack practicality and are not economically attractive (Tsatsarelis et. al 2006).

Methane production in landfills typically begins around 6 to 12 months after the first waste disposal. Normally, the methane generation rate increases over the lifetime of a landfill, with its maximum generation rate occurring shortly after capping. Then, the rate of methane production starts to decline over a longer period of time, typically 30 to 50 years. Landfill gas production rates are determined by the speed of degradation processes which are affected by the amount and type of organic matter, moisture content and density. Since gas generation is dependent on multiple factors, technologies need to be complex enough to account for all possibilities (Tsatsarelis et. al 2006).

Technologies without Energy Recovery

Bioxidation

The concentration of methane in the gas emissions is often considered when choosing a gas collection device. If methane content is very low, biofilters are the suggested option. One guideline in the industry states that biofilters can be effective with approximately 2.2% methane content per volume; they are most popularly used in instances where methane emissions to the atmosphere want to be minimized, not harnessed. A biofilter is a pollution control technology consisting of layers of compost, shredded wood, and timber, which can absorb methane and prevent landfill gas emissions. While they were originally intended to mitigate odors and degrade organic pollutants, research has shown that biofilters help to ensure optimal ambient conditions for methanotrophic bacteria within the landfill. However, the industry has mixed feelings about this kind of technology (Tsatsarelis et. al 2006) . Biofilers are efficient in the use of landfill gas management, but operators in the solid waste industry often report that they are difficult to maintain. To promote the most efficient use of biofilters, the optimal temperature should remain around 30℃ with 30-70% humidity of the field capacity and a neutral to slightly acidic pH value. Additional considerations include the type and texture of the filter bed as well as the residence time. In sum, biofilters can control methane production under certain conditions, but they do require an accurate estimate of methane emissions to work successfully.

A biofilter is not efficient in most landfills because it will not work if the methane concentration is much higher than 3% of the total gas emissions. In these situations, a flare system is much more effective. The rule of thumb for flares is that they will operate well with methane contents of at least 15%, though it is noted that there is a direct correlation between higher methane concentrations and greater efficiency of the system. Flares allow for disposal of flammable gaseous components in a safe way. They are effective at reducing odors and lower the risk of health and environmental complications as they drastically lower atmospheric emissions from landfills.

Flaring Systems

There are two main types of flares: open and closed. An open flare is one in which landfill gas is burned in an open flame. Typically, they can operate with a removal rate of 85%, and the remaining gas that makes its way through the system will be released to the atmosphere. One concern with open flares is that they often form dioxins, furans, and polycyclic aromatic hydrocarbons (PAHs) that are harmful to humans (Emam 2015). Conversely, a closed flare is one in which combustion occurs inside a vertical, cylindrical unit and a combustion control technology is present. Closed flare systems are usually insulated with material to reduce heat loss and allow operations to be conducted at higher temperatures (Tsatsarelis et. al 2006)**.** However, it should be noted that the effectiveness of closed flaring is very sensitive to the temperature at which the combustion takes place. At temperatures above the ideal range, nitrous oxides, a category of dangerous air pollutants, may form. At temperatures that are too low, complete combustion may not occur. Flaring has become popular because legal regulations surrounding it are less stringent than other methods and it is effective regardless of the gas composition, making it the optimal choice for landfills. Gas flaring impacts the environment from thermal radiation and increased noise level. These impacts usually affect local populations which have severe health issues. Gas flaring can produce hydrogen sulfide, dioxide nitrogen and particulate matter (Emam 2015). Even though the exact composition of landfill gas may not be pertinent to make flaring effective, it is still important to know the total amount of gas going through the system to determine the efficiency of the flare system. TigerGEM is hopeful that our new method will allow for a more accurate estimate of total gas generation and in turn allow for optimal flaring.

Technologies with Energy Recovery

Flaring landfill gasses is not the only option to safely release emissions, instead they can be collected and used to create energy. Though not practical for smaller landfills, medium size landfills with around 0.5-3.0 million tons of total waste are capable of supporting a gas to energy system and can produce 500-2,000 kilowatts of electric energy (Tsatsarelis et. al 2006)**.**

Reciprocating Internal Combustion Engine

The most popular device for converting landfill gas to energy is a reciprocating internal combustion engine because it is the most economical device available (Tsatsarelis et. al 2006)**.** Typically, the engines are able to generate about 3 megawatts of power, which can be sold for a profit to offset the cost of operation and the cooling system. There are two types of devices that ignite the gas in the combustion engine: spark ignition engines and dual-fuel engines. Spark ignition systems are much more common because they are easier to build and do not require the additional cost of extra fuel. Spark ignitions require a one-week overhaul after every 25,000-35,000 operating hours, but have a lifetime of about 20 years since the engines use a low rpm. They also produce a considerably lower amount of emissions than dual-fuel engines. When all of these factors are considered, dual-fuel engines are perceived to be obsolete. But, reciprocating internal combustion engines are still the most common form of turning landfill gas into energy.

Gas Turbines

The second most common technology for gas-to-energy is a gas turbine. Gas turbines have gained popularity for certain species of landfills, but they are still uncommon compared to spark ignition engines. This is because of the high rate of energetic loss with this kind of device. Gas turbines typically have low performance, especially when working with a relatively small load of landfill gas. The capital cost is high, and it is uncommon to profit off of the energy produced by a turbine since it is extremely sensitive to the supply load and ambient air temperature. One benefit is that gas turbine systems do not require a cooling system which drastically reduces the emissions produced by the device itself. In general, gas turbines are not always realistic for gas to energy projects because of their lower thermal efficiency and the fact that it is difficult to compress the gas to the required pressure.

Other Technologies

A few other gas to energy systems include production of methanol and direct gas use. The conversion of methane to methanol is done in a gas reformer at a high pressure and temperature with the presence of steam and a catalyst. The methanol produced may be used for vehicle fuel or chemical feedstock since it has a lower emission rate than gasoline and diesel fuels. Landfill gas can also be used to displace fuel oil, natural gas and fossil fuels in a boiler. When a landfill is in close proximity to an industrial/utility plant, a piping system can deliver gas directly to their boilers. When the situation is right, these technologies are highly desirable due to their simplicity and practicality.

In conclusion, there are many technologies that can be used to limit emission of methane gas or to produce energy. However, each of these systems require information about the gas influx to optimize their operation. Having knowledge about the gas constituents and the total volume is paramount to choosing a landfill gas emission technology, but there are currently few ways to calculate these emissions accurately. TigerGEM hopes that with our upgrades to the LandGEM model, landfill gas emission calculations will be simpler and more reliable so that gas control technologies can be further developed to lower the impact of landfills on the world around us (Njoku et al. 2018).

IX. Economic, Regulatory and Health/Safety Analysis

The atmosphere is changing with the emission of greenhouse gases and pollutants, and methane emissions are one of the largest contributors to these changes. The concentration of methane in the troposphere is rising, bringing more concern for the health and safety of humans and the environment. The concentration of methane is estimated to have increased due to anthropogenic activity, generating about 340 Tg of methane per year (Van Amstel 2012). If methane from landfills could be handled properly, methane emissions from human activity would greatly decrease.

To ensure the safety of humans and the environment, scientists around the world determine global budgets of greenhouse gasses like methane. Many authors have quantified the global budget of methane using different methods of modeling. In general, the estimated value of the global budget for methane from landfills is 54 Tg of methane per year (Van Amstel 2012). Landfill methane is difficult to predict because landfills have highly variable composition and irregular structure. Therefore, it is important that models that are used for estimating landfill gas emissions, such as LandGEM are accurate and account for this variability. If they are inaccurate, society may not have correct knowledge of how quickly our environment is changing or the best way to mitigate these changes.

An accurate model also has an economic value for landfills that generate methane. Our recommendations to change the EPA's LandGEM will have a positive impact on the economy. If the model is able to estimate emission rates that are more specific to each landfill then there is a more accurate representation of methane generated. The model should allow landfills to have a more accurate parameter for precipitation along with the effect of waste characteristic L0. With these recommendations, the model can give a more accurate analysis of methane generated. When a landfill can accurately estimate their methane generation, it can allow owners to make a better decision about what to do with their methane generation. A more complex model can increase the need for a third party to use the model. Landfill operators that do their own LandGEM analysis might need a third party that can accurately collect all the data. These will increase the cost to maintain the landfill for owners. Yet, making the model more specific to a given landfill will result in an economic shift to more waste to the energy system for profit. If a landfill uses a more specific model and notices that they produce more methane than waste to energy efforts are a viable option.

A cleaner energy source is waste-to-energy (WTE). Currently, the US has about 88 waste-to-energy plants that combust a combined 26 million tons of waste per year. By implementing WTE operations, dioxins and mercury emissions are reduced along with the humans' reliance on fossil fuels. The average WTE plant can generate a net of 600 kWh of electricity (Van Amstel 2012). Additionally, WTE reduces greenhouse gas emissions like methane by using gas for energy instead of releasing it into the atmosphere.

Landfill gas can be attributed to 13.8% of renewable energy generation per year, and there are many benefits to using it as a renewable energy source. It is estimated that WTE plants can last about 30 years without major upgrades and do not require an abundance of land. The capital cost of land can be avoided by updating an existing WTE plant rather than having to build a new one (Epa and OAR 2016)**. Table 15** in **Appendix A** is a developed chart to analyze the economic benefits from using landfill gas for energy production. The table focuses on the direct and indirect economic impacts from different waste to energy projects. In general, there is an economic benefit to using landfill gas for energy by the generation of jobs and other economic ripple effects. WTE plants continue to benefit the community and economy. The largest costs for a WTE facility are the construction, drilling, piping, and operating personnel. If optimized, landfill gas used for energy would save money compared to fossil fuel usage (Psomopoulos et al. 2009). Overall, WTE plants are beneficial for the economy and can reduce the impact on the environment and human health.

All landfills must follow regulations set by the EPA to maintain a clean atmosphere. These regulations vary for different types of landfills. Most of these rules are contained in either the New Source Performance Standards (NSPS), Emissions Guidelines (EG) or the National Emission Standards for Hazardous Air Pollutants (NEHAP). The specific rules and regulations set by the EPA can be seen in **Table 16** in **Appendix B .**

One important rule is the NSPS Part 60 Subpart XXX. This rule applies to all new landfills that are built or modified after July 17, 2014. The owners and operators of municipal solid waste (MSW) landfills that have a design capacity greater than or equal to 2.5 million megagrams by mass or 2.5 million cubic meters by volume must abide by Subpart XXX. Non Methane Organic Compounds (NMOC) emissions are typically used as a baseline to report and calculate total gas emissions. If the NMOC emission rate is less than 34 megagrams per year, the owners must submit an annual NMOC emission rate until the landfill is closed. If the NMOC emissions are greater than or equal to 34 megagrams per year, the landfill operators are required to calculate NMOC emissions rate by submitting an initial and revised collection and control system design (*Standards of Performance for Municipal Solid Waste Landfills* 2016). A collection system must be installed and capture the gas generated if NMOC emissions are above the threshold. All the gas collected must be routed to a control system like a flare system or boiler system for energy production.

Another regulation pertaining to MSW landfill emissions is EG Part 62 Subpart OOO. The standards apply to landfills built or modified before July 17, 2014. Landfills with the design capacity greater than or equal to 2.5 million megagrams by mass or 2.5 million cubic meters by volume are subject to this regulation. Landfills with an NMOC emission rate greater than or equal to 34 megagrams per year must be closed. The rule also states that there must be a gas collection system in place if the emissions exceed 34 megagrams per year. The collection and control system can be removed or decommissioned if the landfill is capped or the collection and control system has been operating for 15 years and the NMOC emissions rate is less than 34 megagrams per year on three successive test dates (*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* 2021)**.**

Emissions Guidelines Part 60 Subpart Cf implement regulations that help the EPA to keep track of landfill gas emissions. Under Subpart Cf, each US state must submit plans for how they will control landfill gas emissions and maintain the quality of air described under the Clean Air Act (*Emission Guidelines and Compliance Times for Municipal Solid Waste Landfills* 2016).

The state plan must be approved by the EPA and meet all the required criteria established under EG Part 60 Subpart OOO.

In NESHAP Part 63 Subpart AAAA, landfills are subjected to comply if they have a design capacity equal to or greater than 2.5 million megagrams or 2.5 million cubic meters. Landfills are subject to this regulation if they have an estimated uncontrolled emission equal to or greater than 50 megagram per year NMOC. Operation of the collection system must be maintained in an area or cell that has been active for 5 or more years or has been capped for less than 2 years (*National Emission Standards for Hazardous Air Pollutants: Municipal Solid Waste Landfills Residual Risk and Technology Review* 2020). The EPA has created a detailed list of regulations that can be applied to every landfill condition to keep owners and operators responsible for landfill gas emissions. These regulations ensure the health of humans and maintenance of a clean environment.

X. Conclusions and Recommendations

After a thorough analysis, TigerGEM has concluded a bias with EPA's LandGEM. With the use of Python software, TigerGEM is able to present different models for various landfill locations. The different methods used suggest that LandGEM does not produce accurate results for specific locations. To create a more accurate model, TigerGEM recommends a greater variety of the *k* parameter based on precipitation. Currently, LandGEM uses the threshold of 25 inches of precipitation at a landfill to estimate the *k* value but many landfills are well above 25 inches. When landfill locations have greater precipitation, it leads to more decay at a faster rate. The faster rate of decay will call for a higher *k* value. Landfills that are well above 25 inches of precipitation, should not be using the same *k* values as drier landfills that are only slightly greater than 25 inches. As seen in the results, there is a disparity calculating total methane emissions when precipitation is accounted for in the TigerGEM 1 method. The selection of a more site specific *k* parameter based on precipitation will produce a more accurate total methane emission rate.

Creating a more accurate *k* parameter based on precipitation will increase the accuracy of the model along with tailoring L_o. The L_o parameter can be better suited for a site's specific waste characterization. The parameter of L_o is based on degradable organic carbon which is characterized by the percent of biodegradable waste. For a more accurate L_o, the user should be able to put in their own waste characteristics in percentage. L_o is affected by categories such as food waste and green waste that changes the amount of degradable organic carbon in the landfill. TigerGEM also recommends that landfills operators should be required to track the percent of waste type along with cells and how full they are. This will give a more accurate representation of waste characteristics to the best suited L_o.

After analyzing the different methods for producing a value of total methane emissions, TigerGEM does not believe that temperature plays a large role in model estimation. As noticed in the results, temperature of a landfill does not have a significant effect on the accuracy of the model. The temperature of a landfill does not necessarily need to be considered when determining the total methane emissions because the temperature within a landfill is independent of the ambient temperature of the landfill. TigerGEM's analysis concluded that temperature does not need to be considered as it does not have that great of an effect on methane production.

Overall, TigerGEM advocates for more user inputs which will allow LandGEM to be more specific to a certain landfill and give a more accurate total methane emission estimation. If a landfill operation is able to put in a precipitation value along with waste characteristics, then the model will be very detailed. TigerGEM's recommendations will allow for a more accurate model that displays a better result for total methane emissions. Currently LandGEM is not completely inaccurate as an estimation for methane emissions, but it does display some bias towards certain landfills. TigerGEM recommendations can be added to LandGEM to increase the accuracy of the model for all landfills in the United States. A more accurate model of methane emissions will have an economic benefit as more methane can be used for waste to energy while ensuring the health of the humans and the environment by releasing less methane emissions.

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XII. Appendices

Appendix A

Appendix B