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Methane Generation and Capture of U.S. Landfills

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Abstract: Analysis of the U.S. EPA (Environmental Protection Agency) database of 2,549 MSW (Municipal Solid Waste) landfills showed that there were 1,164 operating landfills in which 348 million short tons (316 million metric tons) of waste were landfilled in 2017. In total, these landfills occupy about 370 million square meters of land so it is not possible to monitor the generation of LFG (Landfill Gas) generation accurately, or collect most of the LFG generated. This study was based on the hypothesis that, on the average, methane generation is proportional to the tonnage of wastes landfilled annually. The Landfill Methane Outreach Program of the EPA (EPA-LMOP) compiles annual operating data of all methane-capturing landfills. Our analysis of the 2018 data for 396 LMOP operating landfills showed that 210 million short tons of wastes were deposited and 5.06 million short tons of methane were captured, i.e., an average capture of 0.024-ton CH_4/ton waste. On the basis of the anaerobic reaction of the DOC (Degradable Organic Carbon) in landfilled wastes, the average rate of methane generation from all operating U.S. landfills was estimated to be 0.05 ton of CH_4 per ton of annual capacity; this number corresponds to bioreaction of about one half of the total organic carbon in MSW. On this basis, the average rate of CH_4 emission from the 396 LMOP landfills was estimated to be 0.026-ton CH_4 per annual ton of deposition and the average efficiency of LFG capture, 48%. Adding up all 1,164 operating landfills, their total emission of methane was estimated at 11.9 million metric tons of CH_4. At CH_4/CO_2 equivalence of 25, this number corresponds to $CO_{2\text{-eq}}$ emissions of 270 million metric tons, i.e., 5.1% of the U.S. energy related carbon dioxide emissions.

Key words: Wastes, LFG, methane generation, methane capture, methane emissions, carbon dioxide emissions, greenhouse gas emissions, U.S.A..

1. Introduction

Landfilling of post-recycling urban wastes results in significant emissions of methane, a potent GHG (Greenhouse Gas). The U.S. EPA (Environmental Protection Agency) has estimated that landfilling of wastes is the third largest source of methane emission to the atmosphere [1]. Therefore, it is necessary to provide an accurate estimate of the tonnage of wastes landfilled and the associated methane emissions, in order to deploy efficient measures for GHG mitigation. The objectives of this study were to determine:(a) the tonnage of solid wastes disposed at all operating MSW (Municipal Solid Waste) landfills in the U.S., (b) the tons of methane captured at U.S. landfills, as reported by the Landfill Outreach Methane Program) of EPA (LMOP-EPA; [2]); and(c) use this data to estimate the total methane emissions from all U.S. operating landfills.

2. Magnitude of Landfilling in the U.S.

The EPA "Facts and Figures" [3] on MSW generation are based on estimates of annual consumption of various materials and their respective lifetimes. From this amount are subtracted the reported tonnages of recycling, composting, and combustion with energy recovery (commonly called "waste to energy" or WTE). This methodology resulted in the EPA estimate of 146 million short tons landfilled in 2018 [3]. The Columbia-Biocycle surveys (2003-2012) were based on questionnaires sent to the waste management agencies of the fifty states and compilation of the landfilling and other data they provided; the latest Columbia-Biocycle survey (2012; [4]) showed that 250 million short tons (227 million metric tons) of various wastes were deposited in U.S. MSW landfills. Later studies by Powell et al. [5], for 2012, and by

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EREF (Environmental Research &Education Foundation) [6], for 2013, reported total landfilling of 262 million tonnes and 220 million tonnes, respectively; all these numbers were much higher than the EPA Facts and Figures estimate [3].

The present study relied on the 2018 EPA database of 2,549 municipal solid waste (MSW) landfills. Our analysis of this database (7) showed that there were 1,164 operating landfills in which 348 million short tons (316 million metric tons) of waste were landfilled. It is believed that this number is reliable because all U.S. landfills are required by law to report the tons of solids deposited annually in each landfill. The large difference from the "146 million tons" of the EPA "Facts and Figures" [3] is due to the fact that U.S. landfills, in addition to what EPA considers as "MSW landfills", receive industrial and agricultural wastes, as well as roadkill, wastewater sludge, and other residues of human activity. The magnitude of landfilling in the U.S. is illustrated by the fact that, in total, 7.9 billion tonnes of wastes have already been deposited in U.S. operating landfills [7]; 931 of these landfills, containing 7.4 billion tons of wastes, reported using 370 million square meters of land. The total design capacity of 970 US reporting landfills is 20.8 billion metric tons of wastes; assuming current rates of landfilling, the U.S. operating landfills have remaining capacity of at least 40 years.

3. Estimate of Maximum Methane Generation per Ton of Solids Landfilled

Table 1 [8] shows estimates of the atomic composition of various biogenic components of the urban wastes. Sulfur and nitrogen are relatively minor components and occur principally in food wastes.

Excluding the minor elements, the average C,H,O molecular structure in U.S. MSW can be approximated by the molecular composition $C_6H_{10}O_4$, as recommended by Themelis and Ulloain a widely cited publication[9]. This composition corresponds to the C,H,O structural formula of at least ten organic compounds, such as ethyl butanedioic acid, succinic acid, adipic acid, ethylene glycol diacetate, and others.

The complete anaerobic bioreaction of the compound $C_6H_{10}O_4$ is as follows:

$$C_6H_{10}O_4+1.5H_2O=3.25CH_4+2.75CO_2 \quad (1)$$

According to this equation, the concentration of methane in LFG should be 3.25/6 = 54%. However, our analysis of the 2018 LMOP database [12] showed an average concentration of 47% methane in LFG, probably due to partial oxidation of methane in the upper layer of landfills. This concentration was assumed in converting the volumes of LFG, in the LMOP database, to tons of methane.

One metric ton of MSW, excluding moisture, plastics and inorganic materials, contains about 370 kg of $C_6H_{10}O_4$; if completely reacted anaerobically, it

Table 1 Empirical formulae C,H,O components of dry MSW [8].

Component	Percent by weight (dry basis; ref. [9])						Empirical Formula
	Carbon	Hydrogen	Oxygen	Nitrogen	Sulfur	Ash	
Food wastes	48.0	6.4	37.6	2.6	0.4	5.0	$C_6H_{9.6}O_{3.5}N_{0.28}S_{0.02}$
Paper	43.5	6.0	44.0	0.3	0.2	6.0	$C_6H_{9.9}O_{4.6}N_{0.035}S_{0.01}$
Cardboard	44.0	5.9	44.6	0.3	0.2	5.0	$C_6H_{9.7}O_{4.6}N_{0.035}S_{0.01}$
Plastics	60.0	7.2	22.8	-	-	10.0	$C_6H_{8.6}O_{1.7}$
Textiles	55.0	6.6	31.2	4.6	0.15	2.5	$C_6H_{8.6}O_{2.6}N_{0.43}S_{0.006}$
Rubber	78.0	10.0	-	2.0	-	10.0	$C_6H_{9.2}N_{0.13}$
Leather	60.0	8.0	11.6	10.0	0.4	10.0	$C_6H_{9.6}O_{0.9}N_{0.86}S_{0.015}$
Yard wastes	47.8	6.0	38.0	3.4	0.3	4.5	$C_6H_{9.0}O_{3.6}N_{0.37}S_{0.014}$
Wood	49.5	6.0	42.7	0.2	0.1	1.5	$C_6H_{8.7}O_{3.9}N_{0.02}S_{0.005}$

Table 2 Biodegradable carbon in various components of MSW [10].

Component of MSW	kg solids/kg wet component	kg total C/kg solids	kg biodegradable C/kg total C	Wet component as % of MSW	Total C as % of MSW	Readily biodegradable C as % of MSW
Food waste	0.4	0.48	0.8	22	8.8	7
Yard waste	0.5	0.48	0.7	7.8	3.9	2.7
Paper fiber	0.92	0.44	0.5	13.3	12.2	6.1
Cotton, wool, etc.	0.9	0.55	0.2	7.6	6.8	1.4
Wood	0.8	0.5	0.5	8	6.4	3.2
Total				58.7	38.1	20.4

would generate 0.135 tons CH_4 per ton of MSW. However, Cossu et al. [10] estimated that the readily biodegradable fraction of MSW is about one half of the total organic carbon (Table 2).

A more recent study by Staley and Kantner of EREF [11] concluded that the average concentration of degradable organic carbon (DOC) in the bulk waste deposited in U.S. MSW landfills was 16.1%, i.e., lower than the 20.4% of Cossu et al. ([10]. Table 2). Accordingly, the generation of methane from bulk wastes in landfills, at complete biodegradation, is calculated (see Equation 1, above) to be 0.161× (3.25 x 16)/(6 x 12)= 0.116 tons CH_4/ton waste. On the basis of all of the above information, the authors assumed that, conservatively, the <u>average</u> rate of methane generation from operating U.S. landfills is 0.05 ton of CH_4 per ton of wastes landfilled, i.e., only 40% of the total potentially degradable carbon. Nearly one half of this amount is captured at the EPA-LMOP landfills, as discussed in the following section.

4. Methane Capture at 396 U.S. Operating Landfills

Biodegradation occurs over several years after deposition but since the rate of deposition in a particular landfill does not change much from year to year, it was assumed that the rate of methane generation during any year is proportional to the annual rate of deposition. In the LMOP spreadsheet [2], the biogas volume captured was reported in million standard cubic feet per day ("mmscfd"). These numbers were converted to maximum tons of methane captured per year in each landfill, by assuming 365 days/year operation and 47% methane in the LFG. i.e., the average CH_4 concentration in LFG reported in the LMOP database [2]. On the basis of these two assumptions, the methane generation corresponding to 1 million standard cubic feet of captured LFG/day was calculated to be 3,818 short tons of methane per year.

The authors' analysis of the EPA-LMOP database [2] included 396 MSW landfills which received 210 million short tons of waste in 2018. The spreadsheet of the analysis is too large to include in this report but it is available on the web [12]; as an example, Table 3 presents the reported and calculated data for the largest thirty California landfills. Fig. 1 is a plot by the authors of the reported tonnages of methane collected at all EPA-LMOP landfills, as a function of the tonnage landfilled annually in each landfill. As expected, there is substantial variation among these landfills, especially for those of very large capacity (and land area), where collection is more difficult. The average rate of capture was found to be 0.024 ton of methane per ton of solids deposited. In comparison, the average capture of California landfills (Table 3) was 0.027ton methane/ton of annual capacity and of New York landfills [12], 0.023 ton/ton annual capacity.

The results of the authors' analysis [12] of the EPA-LMOP spreadsheet are shown in Table 4.

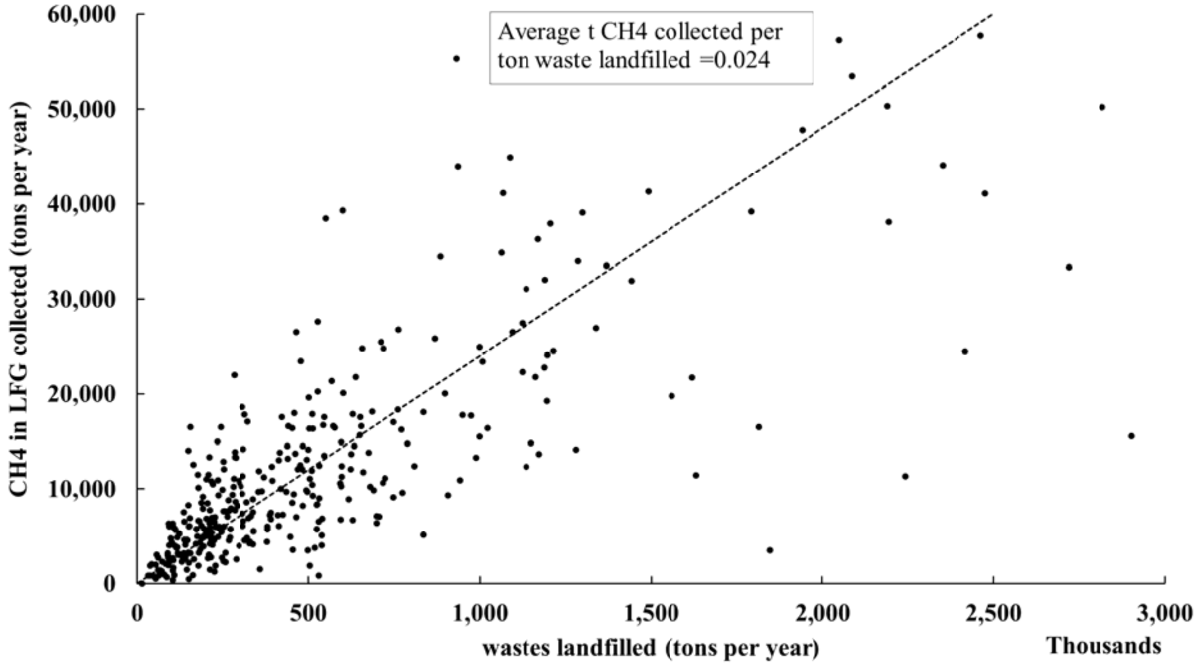

Fig. 1 Tons of methane captured vs. tons of waste landfilled in 2018 (EPA-LMOP database [2], [12]).

Table 3 Methane capture at California landfills in EPA-LMOP database [12].

Landfill Name	Waste in place (short tons)	MSW landfilled (short tons/year)	CH_4 in LFG collected (short tons/year)	Ton CH4 collected/ton MSW landfilled
Acme LF	10,800,000	540,000	6,873	0.013
Altamont Landfill	62,224,563	1,093,632	26,576	0.024
Buena Vista Drive LF	4,111,415	105,869	5,850	0.055
Chiquita Canyon LF	40,308,159	1,491,779	41,304	0.028
Cold Canyon LF	6,317,091	170,123	5,743	0.034
Foothill Sanitary LF	5,599,948	289,351	8,248	0.029
Forward Landfill	27,029,334	897,932	20,073	0.022
Frank R. Bowerman LF	54,928,377	2,461,277	57,734	0.023
Johnson Canyon SLF	3,102,622	208,221	6,377	0.031
Keller Canyon LF	19,935,762	1,123,208	22,326	0.020
Kiefer LF	30,557,161	884,528	34,461	0.039
Neal Road Waste Facility	6,050,515	192,133	5,800	0.030
Olinda Alpha SLF	83,988,930	2,815,733	50,269	0.018
Otay LF	39,827,486	1,619,867	21,765	0.013
Ox Mountain SLF, San Mateo	34,067,875	1,197,053	24,117	0.020
Potrero Hills SLF	18,552,642	1,195,731	19,245	0.016
Prima Deshecha SLF	22,331,121	576,662	16,495	0.029
Recology Hay Road LF	6,506,130	698,308	6,411	0.009
Recology Ostrom Road LF	5,083,592	249,062	7,652	0.031
Redwood SLF	15,768,857	437,994	14,533	0.033
Santa Maria Regional LF	5,817,495	112,182	3,795	0.034
Sonoma County Central LF	not provided	337,517	8,904	0.026

Table 3 to be continued

Sunshine Canyon Landfill	62,900,800	2,018,882	103,417	0.051
Sycamore SLF	not provided	973,826	17,725	0.018
Tajiguas SLF	11,999,911	214,890	6,949	0.032
Toland Road SLF	9,263,676	425,051	7,263	0.017
Vasco Road SLF	27,067,777	774,529	9,607	0.012
West Contra Costa SLF	14,950,000	296,676	10,653	0.036
West Miramar SLF	43,828,172	868,432	25,851	0.030
Western Regional SLF	7,711,744	283,532	8,649	0.031
Yolo County Central LF	8,362,222	204,412	5,208	0.025
Total:	688,993,377	24,758,392	609,874	0.027

Table 4 Results of analysis of 396 operating landfills in LMOP database [12].

Number of operating landfills in LMOP program	396	
Waste already deposited in 396 landfills	5,582	million short tons
Waste landfilled in LMOP landfills in 2018	210	million short tons
Average past life of 396 landfills	27	years
LFG collected, as reported by LMOP (mmscfd)	1,342	million standard ft^3/day
CH_4 collected, for 365-day operation	5.1	million short tons CH_4
Equivalent CO_2 captured (5.1 million/1.1×25)	116	million metric tons CO_2
CH_4 collected per ton waste landfilled	0.024	ton CH_4/ton waste
Total waste landfilled in all U.S. MSW landfills	348	million short tons
Waste landfilled in non-LMOP MSW landfills (348-210)	138	million short tons
CH_4 emitted from LMOP landfills (210×(0.05-0.026)	5.0	million short tons CH_4
CH_4 emitted from non-LMOP landfills (138×0.050)	6.9	million short tons CH_4
CH_4 emitted to atmosphere from all US MSW landfills	11.9	million short tons CH_4
CO_2 emission to atmosphere (11.9/1.1×25)	270	million metric tons CO_2

5. Comparison of Results with Other Estimates of Landfill Methane Emissions

As noted earlier, the complexities of monitoring the enormous surface areas of landfills make difficult the measurement of methane fluxes from landfills. A notable exception is the aerial survey of four Indiana landfills by Cambaliza, Shepson et al. [15]. Table 5 compares the measured emission rates of these landfills with the emission data calculated on the basis that, on the average, landfills generate 0.05 tons CH_4per ton of MSW landfilled.

The estimated methane emissions are based on the assumption that the Indiana landfills generated 0.05 ton CH_4 per ton of annual capacity; from this amount was subtracted the reported amount of CH_4 captured at these four landfills, as per the LMOP database [12]. The measured numbers were obtained by multiplying the reported fluxes [15], in mol/s, by the number of seconds in a year. For two Indiana landfills, there is fair agreement between calculated and measured emissions; for the other two, the measured fluxes are about one half of the estimated emissions.

The U.S. Environmental Protection Agency [14] has estimated that in 2018 the landfill GHG emissions were 110.7 million metric tons of carbon dioxide. This estimate is 41% of our estimate of 270 million metric tons (Table 4) for two reasons:

-EPA assumed [3] that only 146 million short tons were landfilled, instead of the 348 million short tons, as per the EPA inventory of MSW landfills for 2017 [7].

Table 5 Comparison of measured [15] and estimated [12] emissions of CH_4 at four Indiana landfills.

Landfill name	Tons MSW/year	Generated CH_4, t/y (at 0.05/ton MSW)	Captured CH_4, t/y (LMOP database)	Generated-captured CH_4), tons/year	Cambaliza measured CH_4 [15], mol/s	Cambaliza measured CH_4 [15], tons/year
Southside LF, Marion County	1,122,838	56,142	27,492	28,650	45	22,706
Twin Bridges LF, Hendricks County	832,039	41,602	22,477	19,125	17	8,578
Newton LF, Marion County	2,474,239	123,712	41,120	82,592	80	40,366
Randolph Fields LF, Randolph County	379,259	18,963	6,025	12,938	24	12,110

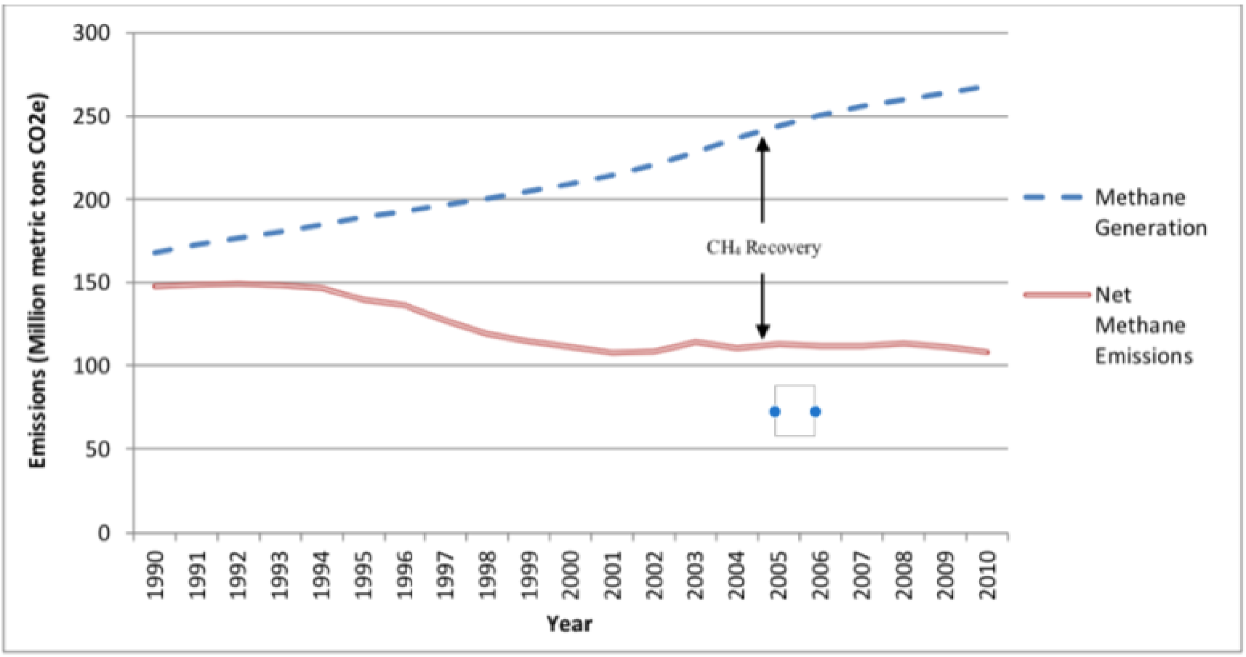

Fig. 2 Generation and capture of CO_2 equivalent by US landfills, 1990-2010 (Bronstein and Coburn [13]).

-Also, EPA may overestimate the amount of CH_4 captured at U.S. landfills. For example, an EPA publication [13] showed (Fig. 2) that in 2010 about 160 million metric tons of $CO_{2,eq}$ were captured, i.e., 160/25 = 6.4 million tons of methane. However, on the basis of our analysis of the EPA-LMOP database [2] the CH_4 capture six years later (2018; Table 4) was only 5.1 million short tons of CH_4, i.e., 126 million metric tons of CO2 equivalent.

6. Conclusions

Despite many technical papers on sanitary landfilling, there is no published information as to the estimated generation of methane per ton of waste landfilled. Yet, in the light of recent catastrophic events attributed to climate change, this information is essential to governments concerned with climate change in deciding whether post-recycling wastes should be disposed in landfills or used as fuel in WTE power plants. Climatic conditions vary widely across the continent and organic carbon can take years to fully decay. Also, it is not possible to monitor or simulate accurately methane generation in landfills spread over hectares of land. For the above reasons, the GHG emissions of landfills have been underestimated. On the basis of the numbers presented in this paper, a conservative estimate of the average generation of methane at U.S. landfills is 0.05-ton CH_4/ton of waste landfilled annually, which is less than one half of the calculated number (0.116-ton CH_4/ton waste) for complete bioreaction of the biodegradable organic carbon contained in the landfilled materials. The average capture and utilization of methane at the 396 operating landfills under the EPA-LMOP program was found to be at 0.024-ton CH_4/ton of waste landfilled, corresponding to an average landfill gas capture efficiency of 48%. It is interesting to note that, on the average, California landfills captured 0.027-ton CH_4/annual ton landfilled and New York landfills, 0.023-ton CH_4/ton, despite the differences in climate and geography.

According to the above data, a landfill of annual capacity of one million tons and assumed life of 40 years is projected to generate, in its lifetime, a total of two million tons of methane (=0.05 × 1,000,000 × 40). When the landfill is equipped to capture and utilize some of this methane, as in the case of the 396 EPA-LMOP landfills, the methane emissions to the atmosphere can be reduced by at least 48%. In total, in 2018, the U.S. landfills emitted 10.8 million metric tons (11.9 million short tons) of methane. On a 100-year horizon, this was equivalent to 10.8 x 25 = 270 million metric tons of carbon dioxide, i.e., 5.1% of the U.S. energy related emissions (5.27 billion metric tons; [16]).

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