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A comparison of greenhouse gas emissions and potential electricity recovery from conventional and bioreactor landfills

Reza Broun [a, *], Melanie Sattler [b, 1]

[a] Graduate Research Assistant, University of Texas at Arlington, Arlington, TX 76019, USA
[b] Department of Civil Engineering, 416, University of Texas at Arlington, Arlington, TX 76019, USA

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ABSTRACT

As methane constitutes about 50% of landfill biogas, reduction of methane emissions from municipal solid waste (MSW) landfills results in climate change mitigation. As such, it is important for a landfill lifetime model to properly reflect the manner in which biogas is managed. The goal of this research is to compare landfill biogas management in a conventional landfill with a bioreactor landfill during a 100-year time horizon. This comparison concentrates on the greenhouse gas (GHG) emissions balances and electricity generation potential from recovered biogas using reciprocating internal combustion engines (RICE), which leads to avoiding GHG emissions due to fossil fuel displacement. The results estimated that the total amount of GHG emissions released to atmosphere, including fugitive methane emissions and the avoided effect of electrical energy production, was 668 and 803 kg carbon dioxide (CO_2) equivalents (CO_2E) per metric ton (t) of landfilled MSW for the conventional and the bioreactor landfill, respectively. This study underscores the importance of installing an aggressive gas collection system early for bioreactor landfills, and for investigating methods of improving gas collection efficiency during active landfilling.

1. Introduction

In 2012, the U.S. Environmental Protection Agency (USEPA) estimated that about 135 million tons of municipal solid waste (MSW) was disposed of in 1908 landfills (USEPA, 2012). Despite best efforts to lower MSW generation and to manage solid waste by recovery, composting and combustion, landfilling will remain a major element of MSW management for the foreseeable future. Hence, it is important to understand the environmental performance of discarding MSW in landfills (Levis and Barlaz, 2011).

After solid waste is buried in a landfill, biogas, composed of methane (45–60% by volume) and biogenic carbon dioxide (40–55%), is generated through the anaerobic degradation of the organic fractions (USEPA, 2014). Release of biogas directly to the atmosphere contributes to climate change, since methane and carbon dioxide are greenhouse gases. Methane in particular has a global warming potential of 25 times that of CO_2 on a weight basis over a 100-year time period. MSW landfills are the third largest source of U.S. anthropogenic methane emissions, contributing 18.2% of total methane emissions. In 2012, landfills emitted approximately 103 million t CO_2E, or 4897 Gg of methane, which constituted 1.5% of total US GHG emissions (USEPA, 2014). In comparison, electricity production from fossil fuels contributes 2068 million t CO_2E to US annual GHG emissions.

Recently, the Environmental Protection Agency proposed a plan that aims to slash carbon dioxide emissions from existing power plants 30% by 2030 and could accelerate the nation's shift away from coal to other renewable energy sources (Cohen et al., 2014). Practices to reduce landfill methane emissions could contribute to this plan. Converting landfill biogas to energy is an opportunity that not only decreases GHG emissions from landfills, but also aims to produce renewable energy for residential sectors near landfill sites.

As of July 2014, there were 636 operational landfill biogas to energy projects in the US, with a collective annual design capacity of 2032 MW of electricity production, powering more than 1.2 million homes (USEIA, 2014). USEPA has identified an additional 440 candidate landfills (with power capacity of 885 MW) for energy projects, which can mitigate MSW landfill emissions up to 40 million t CO_2E (USEPA, 2014). Therefore, an environmental

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* Corresponding author. Tel.: +1 617 803 7727.
E-mail addresses: reza.broun@mavs.uta.edu (R. Broun), msattler@uta.edu (M. Sattler).
[1] Tel.: +1 817 272 5410.

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comparison between two most common types of landfilling techniques is essential to support this effort by identifying the most environmental friendly MSW landfill, before too much is invested ineffectively.

Conventional landfill operation minimizes the amount of moisture entering the waste to minimize leachate production. Recently, an alternative landfill management strategy has gained attention: bioreactor landfill operation, or enhanced leachate recirculation. In bioreactor landfills, faster solid waste decomposition is achieved by addition of supplemental water to the waste and/or to recirculate leachate (Aguilar-Virgen et al., 2014; Niskanen et al., 2013; Ménard et al., 2004). More rapid waste decomposition can produce more favorable economics for landfill gas (LFG) collection and beneficial reuse, and may recover space for additional waste placement. So far, in many studies about landfill-biogas-to energy, landfill biogas collection efficiency was assumed as a single value rather than a temporally weighted collection efficiency depending on the stage of landfill operation (Aguilar-Virgen et al., 2014; Sandip et al., 2011). Additionally, the combination of internal combustion engines that convert biogas to electricity were chosen arbitrarily, so that the effect of upper and lower bounds of required rate of biogas flow entering to run such engines were not taken into account (Johari et al., 2012; Caresana et al., 2011; Tsai, 2007). This research fills the gap and aims to include both approaches to more closely reflect actual landfill gas collection and recovery system operation. The main objective of this study is to compare GHG emissions balance and potential electricity generation from both types of MSW landfills (conventional and bioreactor landfill) within a 100-year time horizon.

2. Methods

A spreadsheet-based model in Microsoft Excel was developed to incorporate environmental factors such as biogas generation from EPA'S LandGEM, impacts of various collection efficiencies, converting the methane portion of biogas to electricity, offsetting fossil fuel based-electricity by burning recovered methane, methane oxidation through the landfill soil cover and emission inventories of biogas control devices. The spreadsheet model was prepared to estimate the GHG emissions from biogas management and energy recovery from both conventional landfills and bioreactor landfills.

For the purpose of this study, a hypothetical MSW landfill was designed. The landfill site was selected for a model city with a population of 1,000,000 in 2014, as at least 50% of the largest 50 cities in the U.S. will reach a population of at least 1 million persons over the next 30 years, based on their current growth rates (U.S. Census Bureau, 2015). The active filling period in each scenario is 20 years from 2014 to 2033 (USEPA, 2014). According to EPA, per capita generation of solid waste is about 2 kg per day, of which 53% is discarded in landfills. For a landfill serving a population of 1 million, this equates to an acceptance rate of 1200 tons per day, 6 days a week, throughout the year. Additionally, as the landfill considered in this study is a non-hazardous solid waste landfill, MSW composition data for this paper came from the nationwide average derived from U.S. EPA (USEPA, 2012). The other assumptions for the model landfill are considering an average height of 28 m and daily cover volume as being 10% of the waste volume (Themelis and Ulloa, 2007; Ménard et al., 2004).

2.1. Methane balance for a MSW landfill

In the United States, MSW is composed of 40–50% cellulose, 9–12% hemicellulose, and 10–15% lignin on a dry weight basis (Barlaz, 1998). Cellulose and hemicellulose (carbohydrates) are the major biodegradable components of MSW, which make up about 90% of the biodegradable fraction, while lignin is considered to be recalcitrant and slowly degradable under anaerobic conditions (Barlaz, 2006). When MSW is disposed of in a landfill, a series of chemical and microbiological reactions is initiated in which anaerobic microorganisms degrade cellulose and hemicellulose, which leads to terminal products of methane and carbon dioxide. The fate of the produced methane was summarized by mass balance developed by Spokas et al. (2006) using (1):

$$\mathrm{CH_{4,Produced}} = \mathrm{CH_{4,Emitted}} + \mathrm{CH_{4,Collected}} + \mathrm{CH_{4,Oxidized}} + \mathrm{CH_{4,Migrated}} + \Delta\mathrm{CH_{4,Stored}} \tag{1}$$

The methane generated may be collected by an active system of wells and pipes and then flared (it is oxidized to biogenic carbon dioxide) or combusted to produce energy in form of electricity. Also, some part of methane is oxidized by methanotrophic bacteria through aerobic biological processes in landfill soil cover. Moreover, the methane quantity within the air-filled porosity of landfill mass does change temporarily. Change in methane storage is estimated from the change in methane concentrations from gas sampling wells or from changing methane concentrations in main header for gas recovery system and does not typically exceed 1% (v/v) in methane concentration (Spokas et al., 2006). Finally, some portion of methane migrates laterally at the cell perimeter based on diffusion flux through the liners. The remaining methane constitutes fugitive methane emissions. In this paper, it is assumed that there is no change in methane concentration in landfill and the extent of methane migrated through the liner is negligible.

2.1.1. Estimation of biogas production from a landfill

Generation of landfill biogas begins shortly after MSW is placed in a landfill. Estimation of landfill biogas is a deciding factor for designing landfill biogas-to-energy projects. To calculate the biogas generation potential from a landfill, this study used US EPA's LandGEM because of its pervasive application in both engineering and regulatory practice. LandGEM predicts biogas generation using a first-order decay model, as represented in USEPA (2008).

$$\mathrm{Q_n} = \frac{1}{\mathrm{C}} \times \sum_{\mathrm{i=1}}^{\mathrm{n}} \sum_{\mathrm{j=0.1}}^{1} \mathrm{k} \times \mathrm{L_0} \times \frac{\mathrm{R_i}}{10} \mathrm{e}^{-\mathrm{k.t_{ij}}} \tag{2}$$

where: Q_n = Biogas generation rate at year n, m^3/yr; C = Fraction of methane in the landfill biogas; L_o = Methane generation potential, m^3 CH_4/ton of MSW (on the wet weight basis); R_i = Annual MSW acceptance rate for year i (on the wet weight basis); k = First-order MSW decay rate, yr^{-1}; t = Time since the initial refuse placement, yr; i = Year in the life of landfill; j = 1/10th year increment in the calculation.

In this paper, MSW decay rates of 0.04 and 0.12 yr^{-1} were used for conventional and bioreactor landfills, respectively (Cruz and Barlaz, 2010). Furthermore, MSW was treated as one substrate, albeit it is not in real world. Hence, a mean ultimate methane generation potential (L_0) of 100 m^3/Mg was assumed as recommended by the US EPA's AP-42 (USEPA, 2008).

2.1.2. Biogas collection efficiency

Although the use of a single biogas collection efficiency would be convenient, it does not reflect reality. Implementing a temporally weighted average collection efficiency that considers changes in collection efficiency over time is needed. Landfill biogas collection efficiencies were varied over the lifespan of a typical active landfill cell. It was assumed that no landfill biogas collection system is installed during first two years of conventional landfill operation, while in the bioreactor landfill, the gas collection system would be