DEVELOPMENT OF A DYNAMIC ENERGY BALANCE TO ASSESS OPERATING EFFICIENCY OF THE BURLINGTON COUNTY BIOREACTOR LANDFILL IN NEW JERSEY (USA)

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SUMMARY: Existing operational data from a bioreactor landfill in New Jersey (USA) was used to develop a dynamic energy balance for its associated waste management system. The energy generated and consumed was normalized to the energy density of diesel fuel. The potential energy, defined as the total associated energy of the flared landfill gas (LFG) recovered by the waste management system, was correlated to an associated energy density and normalized to a volume of diesel fuel. The fuel consumed during hauling of municipal solid waste, cover material, leachate and stormwater, as well as operating fuel and electricity consumed to maintain functions at the bioreactor were subtracted from the potential recoverable energy associated with the generated LFG. Transport of cover was the largest consumer of energy and accounted for 53% of the total energy input for the system. The energy balance, the difference between potential recoverable energy and energy consumed by the system, showed that the municipal solid waste system produces more energy than it consumes; however, energy recovery efficiency greatly influences the balance. Electricity generation via an internal combustion engine is currently the most expedient means to utilize the generated energy and would recover 38% of the system energy. However, an interesting alternative is production of liquefied natural gas (LNG) which would recover 30% of the system energy and could also address the increasing cost of diesel and compliance with stricter air emission standards for diesel engines.

1. INTRODUCTION

Higher fuel prices, recent conflicts in the Middle East and greater public awareness of the implications of burning fossil fuels are forcing the industrialized world to reexamine its use of fossil fuel energy sources.

In recent years bioreactor landfill technology has been extensively employed in the US to enhance biodegradation and waste stabilization rates as a means to diminish environmental monitoring costs over the long-term (Reinhart and Townsend 1998). However, recovering the abundant amounts of biogas produced by bioreactor landfills has not achieved the same priority as facilitating waste stabilization. The wasted energy from bioreactor landfills is significant (Barlaz, Ranjithan et al. 1995), and there is an interest in recovering the energy more efficiently. In fact, new regulations expected in New Jersey (USA) as part of its *Energy Master Plan* could require increased biogas energy recovery from bioreactor landfills (BPU 2006), which would establish energy as a control variable to be optimized.

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Previously published studies have utilized life-cycle analysis and linear models to generate theoretical energy balances for various waste-management schemes (Barlaz, Ranjithan et al. 1995; Zacharof and Butler 1999; Solano, Ranjithan et al. 2002). Additionally, numerous studies have been conducted to assess the environmental impacts and energy usage of various waste management options (Thompson and Tanapat 2004; Marchettini, Ridolfi et al. 2007). While these models are useful for considering the design of new systems, immediate energy savings and measures to enhance biogas production for existing bioreactor landfill systems need to be addressed.

The development of a dynamic system-specific energy balance could provide the means to quantify the significance of optimization measures and biogas production enhancements over time. It is important to maintain an energy balance of the waste management system for a number of reasons. First, this balance assesses the whole system including all sectors of the waste management system: from transport of the waste to operation of the bioreactor to generation of methane. Second, the impact of efficiency or operating improvements in one sector of the waste management system can be evaluated against the efficiency of the overall waste management system. Third, relating all sectors of the waste management system to a single control variable, such as energy, allows the system energy to be optimized. The dynamic energy balance can also help landfill operators to assess existing data in a manner that allows a desired parameter, such as energy or the CO_2 footprint, to be maximized or minimized respectively.

Therefore, the objective of this study was the development of a dynamic energy balance for a bioreactor landfill. Existing and readily available data from the Burlington County Resource Recovery Center (BCRRC) bioreactor landfill in New Jersey (USA) was used for this case study.

2. METHODOLOGY

The BCRRC has operated its bioreactor landfill since 1999. The landfill will cover 28 ha, and the final height will be 35 m. Leachate from the bioreactor landfill, an adjacent conventional landfill, and a biofilter from an on-site sewage sludge composting facility are recirculated as liquids. Excess leachate and stormwater runoff that was in contact with the waste are hauled off-site. Municipal solid waste (MSW) transportation, landfill operation, leachate and stormwater removal as well as biogas generation (excluding not recovered biogas) are within the system boundary of the energy balance.

The simplified energy balance can be expressed by Equation 1.

$$\frac{dE_{net}}{dt} = E_{LFG} - E_{transport(in)} - E_{transport(out)} - E_{operation} \qquad \text{Equation 1}$$

dEnet/dt Net energy production rate (L of diesel fuel/yr).

E_{LFG} Energy content of recoverable LFG for a specified time period (L of diesel fuel/yr). This term is a function of many site-specific variables including deposited MSW masses, MSW composition, climate, nutrient availability and moisture content.

$E_{transport(in)}$ and $E_{transport(out)}$ Energy consumption for transportation of incoming and exiting material streams for a specified time period (L of diesel fuel/yr). The incoming streams include MSW and cover material and the exiting streams leachate and stormwater.

$E_{operation}$ Energy expended for landfill operation including waste placement, compaction and electricity use of the landfill for a specified time period (L of diesel fuel/yr).

All energy terms used in this balance were normalized to the energy density of diesel fuel (34.92 MJ/L (Zittel and Wurster 2002)). A positive energy balance indicates that the energy generated from the recovered LFG is greater than the energy required for landfill operation and transportation.

2.1 Landfill gas generation (E_{LFG})

Quantifying the LFG generation term is challenging because there is a time disconnect between LFG generation and waste placement. In real time, the term can be quantified by measuring the actual LFG generation rate. However, a model needs to be employed to predict future LFG generation rates.

Although several complex models have been proposed to predict biogas generation in landfills (Zacharof and Butler 1999), a simple decay model for MSW is currently being used by the BCRRC (Equations 2 & 3). The LFG generation is predicted independently of the energy balance and is based on the Scholl Canyon Gas Generation Model (Thompson and Tanapat 2004; USEPA 2005).

$$Q_1 = \sum_i L_{0i} \cdot R_i \cdot [1 - \exp(-k_i \cdot t_i)] \qquad \text{Equation 2}$$

Where Q_1 is the total LFG generation rate (m^3 LFG / yr) obtained by summing the gas contributions by each considered cell, i, L_{0i} is the LFG generation potential (m^3 LFG / kg refuse) for a specified cell, R is the mass of waste placed in each cell (kg refuse / yr), k is the LFG generation rate constant (yr^{-1}), and t_i is the time in years since initial waste placement began in the cell.

Gas being generated from cells no longer receiving new refuse is predicted using a similar first order decay model given by Equation 3.

$$Q_2 = \sum_i L_{ci} \cdot M_i \cdot \exp(-k_i \cdot c_i) \qquad \text{Equation 3}$$

Where Q_2 is the total LFG generation rate (m^3 LFG / yr) obtained by summing the gas contributions by each considered closed cell, i, Lc_i is the LFG generation potential (m^3 LFG / kg refuse) for a specified closed cell, M is the mass of waste remaining in the cell (kg refuse / yr), k is the LFG generation rate constant (yr^{-1}), and c_i is the time in years since additional waste placement stopped. The total landfill gas Q_{LFG} is the sum of Q_1 and Q_2.

The predicted waste mass was estimated based on population estimates and predicted waste generation rates for the area to be served by the bioreactor landfill. Once waste placement and LFG recovery began, the predicted waste masses were replaced by actual landfilled waste masses.

The associated energy of the LFG, E_{LFG}, for a specified time is obtained by applying Equation 4.

$$E_{LFG}(t) = E_{density} Q_{LFG}(t) \qquad \text{Equation 4}$$

$E_{density}$ is the energy density of the LFG (16 MJ/m^3).

The predicted LFG generation rate, Q_{LFG}, is obtained by summing Equations 2 & 3 was corrected by a factor, C_f, to determine the new predicted LFG generation rate, $Q_{expected}$, and the correction factor is given by Equation 5.

$$C_f = \frac{Q_{observed}(t)}{Q_{LFG}(t)} \qquad \text{Equation 5}$$

Where $Q_{observed}$ is the actual LFG generation rate for a given time period and Q_{LFG} is the previously predicted LFG generation rate for that time period.

2.2 MSW and cover transport to the landfill ($E_{transport(in)}$)

The amount of fuel used to haul MSW from its origin (not including MSW collection) to the landfill was estimated using a ratio that related the MSW mass to fuel consumed. The ratio was derived by analyzing a sample of 5,183 waste deliveries to the BCRRC bioreactor landfill. Various municipalities were assigned an origin code, and the origin of each waste truck was documented.

The distance from each origination point, the average fuel-economy for the waste trucks from this origination point and the total MSW mass per truck were recorded. To obtain the total fuel consumed, $Fuel_1$ (L of diesel fuel), by the 5,183 deliveries considered, Equation 6 was applied.

$$Fuel_1 = \sum_i \frac{2 \cdot d_i \cdot n_i}{F_i} \qquad \text{Equation 6}$$

Where d (km) is the distance from the origination point (2d is the roundtrip distance), i, to the landfill, n is the number of trips from location i, and F_i, is the average fuel economy (km/L diesel) reported by the trucks from the specified origin.

The total mass of waste, $Mass_1$ (kg), is the summation of the total masses from each origination point, $Load_i$ (kg), expressed by Equation 7.

$$Mass_1 = \sum Load_i \qquad \text{Equation 7}$$

The energy needed to transport the MSW to the landfill, $E_{transport(MSW)}$, for a specified time is given by Equation 8,

$$E_{transport(MSW)} = \frac{Fuel_1}{Mass_1} \cdot R \qquad \text{Equation 8}$$

where R is the mass of waste placed in the landfill (kg refuse / yr) resulting from the deliveries for a specified time.

The fuel consumption for transport of the cover material was also determined. For its cover material, the BCRRC uses a mixture of soil, glass cullets and chipped wood, in roughly equal parts by volume. The wood is recovered from the MSW and therefore the energy used to transport this material is accounted for as part of the MSW transport energy expenditure. The energy to chip the wood will be accounted for as part of the landfill operations. The volumetric cover accumulation rate, v_{cover} (m^3 / yr), is known, and the fractional cover material accumulation rates are estimated by Equation 9.

$$v_i = \frac{1}{3} v_{cover} \qquad \text{Equation 9}$$

Where v_i (m^3 / yr) is the volumetric accumulation rate of the soil, glass cullets, and chipped wood fraction, respectively.

The average transportation distance of the soil, d_s, and the glass cullet, d_g, are 50 km and 70 km, respectively. The average volume of cover each truck can transport per trip, V_{Ct}, is 15 m^3. The fuel, $Fuel_2$ (L diesel/yr), required to transport the soil and glass cullet fractions for a specified time period is calculated by Equation 10.

$$Fuel_2 = E_{transport(cover)} = \frac{2}{V_{Ct}} \left(\frac{d_s \cdot v_s}{F_s} + \frac{d_g \cdot v_g}{F_g} \right) \qquad \text{Equation 10}$$

Where F_s and F_g are the average fuel economies (km/L diesel) reported for the transport trucks of the soil and the glass cullet, respectively.

The total energy consumed during transport of materials to the BCRRC for a specified time, $E_{transport(in)}$, is given by Equation 11.

$$E_{transport(in)} = E_{transport(MSW)} + E_{transport(cover)} \qquad \text{Equation 11}$$

2.3 Leachate and stormwater transport from the landfill ($E_{transport(out)}$)

Leachate (65%) and stormwater that came in contact with waste (35%) accumulate in different storage tanks at the BCRRC and are transported to different wastewater treatment facilities. The leachate is transported to a wastewater treatment facility 126 kilometers (d_L) north of the BCRRC and stormwater to a facility 34 kilometers (d_{St}) south east of the BCRRC. The fuel used to haul leachate and stormwater from the bioreactor landfill, $E_{transport(out)}$, is given by Equation 12.

$$E_{transport(out)} = \frac{2}{F \cdot V_{Wt}}\left(d_L \cdot v_L + d_{St} \cdot v_{St}\right) \quad \text{Equation 12}$$

Where v_L and v_{St} are the volumes (m^3 /yr) for leachate and stormwater for a specified time respectively, F is the average fuel economy of the transport vehicles (km/L diesel), and V_{Wt} (m^3) is the volume of the trucks delivering the wastewater to the treatment facilities.

2.4 Landfill operation ($E_{operation}$)

Electricity expenditures of the landfill for a specified time and fuel consumed by landfilling equipment for a specified time were taken into account for the energy associated with landfill operations for a specified time. Electricity consumption was normalized to the energy equivalent of diesel fuel, and $E_{operation}$ is expressed by Equation 13.

$$E_{operation} = (E_{electricity} + E_{fuel}) \quad \text{Equation 13}$$

3. RESULTS AND DISCUSSION

The dynamic energy balance for the BCRRC can help to identify the best energy recovery method, to assess the operating efficiency in real time, and to identify operational problems.

3.1 Energy balance without considering energy loss resulting from LFG conversion

The energy consumed for transportation and operation, the energy recovered via the generated LFG and the difference between both are shown in Figure 1.

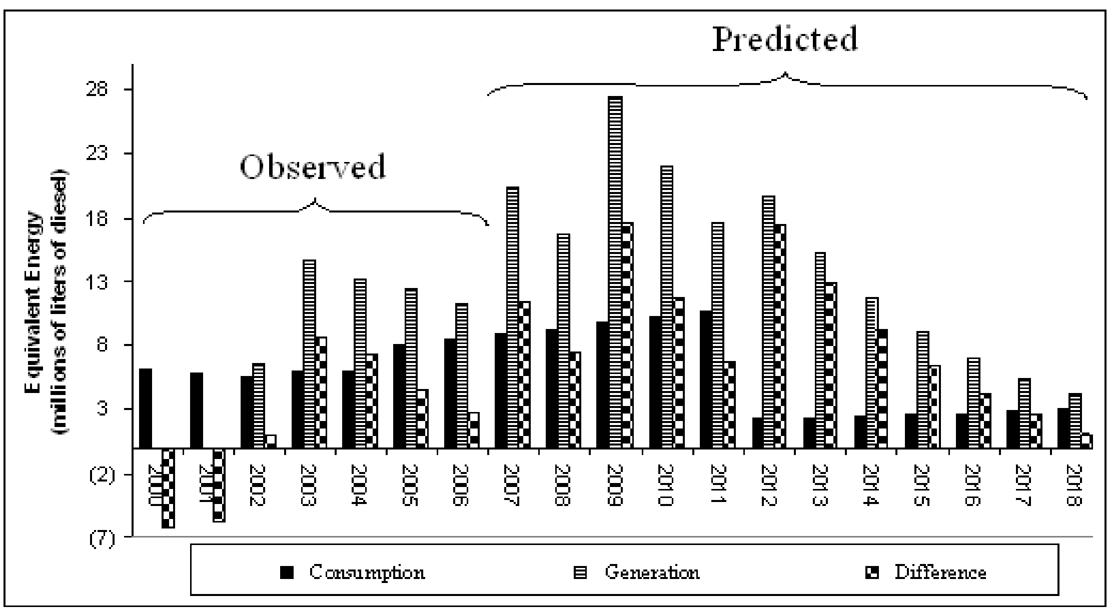

Figure 1 – Energy balance of BCRRC without considering energy loss resulting from LFG conversion

The energy balance from 2000 to 2006 is based on operating data from the BCRRC, while the energy balance for 2007 to 2018 is based on predicted data taking into account a correction factor for the LFG generation based on previous year's LFG generation (Equations 4 & 5). The pattern of peak and decline of LFG generation is caused by newly opened landfill cells coming online (e.g., 2003, 2007, 2009, 2012) followed by a LFG generation decline over time. The energy consumption is expected to decrease considerably in 2012 because the landfill will close at that time.

Assessment of the energy consumption (Table 1) indicates that far more transportation fuel is being and will be used by the BCRRC over the lifetime of the bioreactor landfill than will be needed as electrical energy. The greatest percentage of the energy being consumed by the BCRRC is used to transport cover material to the landfill site.

	Total Expected Consumption	
	[10^6 L diesel]	[%]
Transportation Fuel	**94.84**	**84**
Waste In	13.61	12
Cover In	59.30	53
Water Out	8.08	7
Operation	13.85	12
Electricity	**18.49**	**16**

Table 1 – Distribution of energy consumption at the BCRRC over the lifetime of the landfill (2000-2018)

The LFG at the BCRRC is flared and therefore no energy is currently recovered. The energy of the generated landfill gas in Figure 1 represents the total energy content of the LFG assuming all generated LFG is flared (234.5 10^6 L of diesel from 2000 to 2018). Subsequent to starting LFG collection in 2002, there was excess energy being generated by the landfill compared to the amount of energy used to operate and maintain the waste management system. Although the energy balance was positive at that point (more energy being generated than consumed), the energy balance might be negative if losses from energy conversion to, for example electricity, heat or liquefied natural gas (LNG) were taken into account.

3.2 Energy balance considering energy loss resulting from LFG conversion

The recoverable energy is a function of the efficiency of the conversion technology and the LFG generation. Efficiency, as defined here, is the recoverable energy divided by the energy associated with the total flared LFG (234.5 10^6 L of diesel from 2000 to 2018). Three recovery options are compared in Table 2.

Recovery Method	**Efficiency**	**Recoverable Energy (10^6 L of diesel energy equivalent)**
Liquefied Natural Gas (LNG)	0.305	71.52
Internal Combustion (Electricity)	0.38	89.11
Cogeneration (Electricity, Heat)	0.78	182.91

Table 2 – Recoverable energy at BCRRC of three common LFG energy recovery options (Note: 100% efficiency = no loss of the recoverable energy of 234.5 10^6 L of diesel fuel equivalents from 2000-2018 during LFG conversion)

The recoverable energy is the associated useable (convertible to work) energy to be obtained from recovering otherwise flared LFG. Converting LFG to LNG produces the equivalent of 71.52 10^6 L diesel transportation fuel. It is assumed that 2 L of LNG are equivalent to 1 L of diesel, and that

20% of the LFG is converted to electricity at an electrical efficiency of 0.35. For BCRRC these assumptions were confirmed by data obtained onsite at the BCRRC by Acrion Technologies (Cleveland, OH, USA). Others (Wegrzyn, Litzke et al. 1999; Litzke and Wegrzyn 2001) have determined that the efficiency of the LNG conversion is higher and that 1.33 L of LNG are equivalent to1 L of diesel.

Internal combustion engines (IC) produce electricity to be used onsite and/or sold to the grid, but do not recover heat. This option generates electricity equivalent to 89.11 10^6 L of diesel fuel. This technology will be employed at the BCRRC in late 2007, and the efficiency of this process was confirmed by DCO Energy (Mays Landing, NJ, USA).

Cogeneration would generate electricity equivalent to 75.04 10^6 L diesel fuel and 107.87 10^6 L diesel fuel as useable heat (transmission of electricity and heat not considered). The cogeneration efficiency has not been independently verified at the BCRRC, and assumptions for this paper are based on other findings (USEPA and Group 2002). Although cogeneration would seem to be the best of the three options for energy recovery (greatest recovery efficiency), cost, feasibility, and available infrastructure are major factors and do not always make cogeneration a viable option.

Numerous trade-offs exist when identifying a LFG energy recovery option. Since the waste management system consumes far more energy for transportation needs (83.68%, 94.84 10^6 L diesel fuel) than for electricity needs (16.32%, 18.49 10^6 L diesel fuel equivalents), LNG conversion would do more to offset the system's own energy consumption internally, yet it would not be sufficient to offset all transportation fuel expenditures. An additional 23.32 10^6 L of diesel fuel equivalents would be required from fossil fuel or other sources. However, electricity generation by an internal combustion engine and cogeneration, being more efficient, would easily offset the system's electrical requirements and provide substantial electricity to the grid (70.62 and 56.55 10^6 L diesel fuel equivalents, respectively). Only cogeneration could entirely offset the system's energy consumption (113.33 10^6 L diesel fuel equivalents), but 59% of the recovered energy would be in the form of heat, and would not be useful at the BCRRC because of its location and limited existing infrastructure. In fact, since the internal combustion engine has a greater electrical efficiency than the cogeneration process, it would produce more useful energy in this case. None of the options presented would entirely offset the BCRRC's energy consumption and eliminate its associated carbon footprint unless the heat from cogeneration could be harnessed effectively.

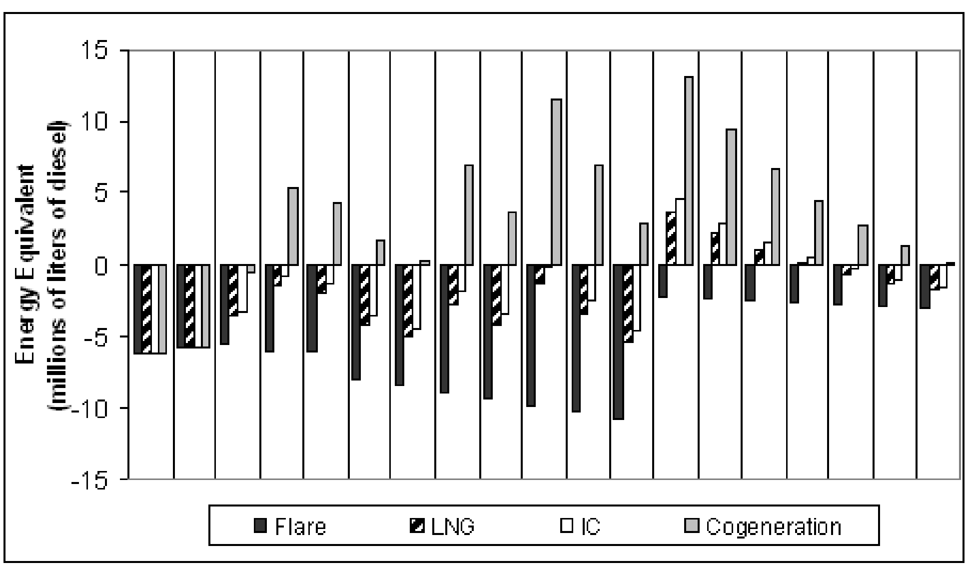

Figure 2 – Energy balance for the flare and the three energy recovery options (LNG, electricity

generation by internal combustion engine and electricity/heat generation via cogeneration. Note: vertical lines separate each year from 2000-2018)

While the energy balance is positive for cogeneration subsequent to LFG recovery commencing in 2002 (Figure 2), and remains positive through 2018, LNG production, and electricity generation by an internal combustion engine are only positive for a short period (2012-2014) following closure of the landfill. As already discussed, cogeneration has the most favorable energy balance, however, in most cases the heat can not be recovered due to the remote location of the landfill, which might exclude cogeneration as a viable option. The energy balance for LNG production and electricity generation via an internal combustion engine are comparable, although electricity generation via an internal combustion engine is most favorable. Although LNG generation might gain a larger market share due to increasing and unpredictable diesel fuel costs as well as interest in reducing air emissions from diesel engines (NSWMA 2006), tax credits seem to favor electricity production (2005; Sissine 2005). Diesel trucks will have difficulties meeting the 2007 and especially the 2010 air emission standards (Golden 2000; Cannon 2006).

The energy balance presented here can also validate public policy decisions. For example, current proposals in New Jersey call for MSW to be transported out-of-state to Pennsylvania for disposal. The energy balance indicates that transporting refuse over a greater distance and effectively eliminating the prospect of New Jersey recovering the valuable LFG would not be favorable especially since the state is seeking policies to increase biofuel generation and decrease fossil fuel CO_2 emissions as part of the new energy master plan (BPU 2006).

3.3 Role of the energy balance in landfill operation

As well as being a tool to assess policy and energy recovery decisions, the energy balance can be used to assess operating efficiency in real time and to identify operational problems. Subsequent to 2003 the net system energy has been declining annually (Figure 1) as a result of increasing system energy consumption (up 41% from 2003 to 2007), and decreasing LFG generation (down 23% from 2003 to 2007). The decreasing LFG generation was not expected to continue beyond 2005. This anomaly presents an opportunity to demonstrate the utility of the energy balance to identify undesirable conditions, propose possible causes, and test applicable solutions. Figure 3 compares LFG generation predictions to observed LFG generation at the BCRRC.

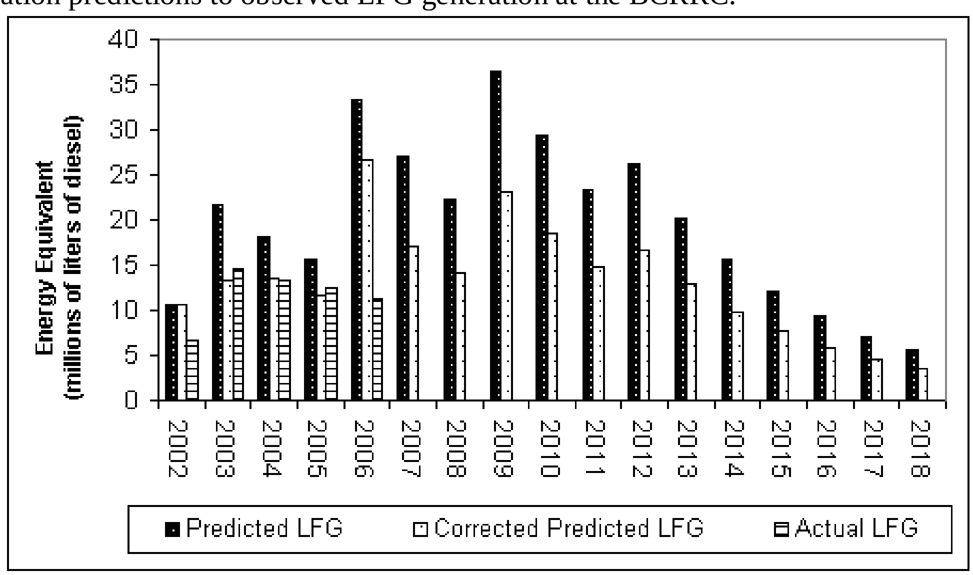

Figure 3 – Predicted and actual LFG energy generation at the BCRRC

The predicted LFG generation is in the same order of magnitude as the observed LFG generation (Figure 3), and was further corrected by the correction factor, C_f (Equation 5). The corrected predicted LFG generation models the LFG generation well from 2003 through 2005. However, a decreasing LFG generation rate has been found to persist unexpectedly into 2006, suggesting that the operation of the landfill should be further evaluated.

Although numerous factors can lead to poor LFG generation, excess leachate accumulation has been a major concern since the inception of the BCRRC bioreactor landfill. The facility's limited leachate storage capacity of only $1.5\ 10^6$ L, is 50% to 60% less than typical design specifications recommended for a landfill of this size and under New Jersey's climate conditions (Reinhart and Townsend 1998). During rain events and rapid snowmelts the leachate storage capacity is rapidly depleted. Problems with excess leachate have prevented the operation of a controlled recirculation strategy. The excessive leachate recirculation may reduce the in-situ temperature of the landfill, and could be the reason for lower LFG generation (Zeiss 2006). The dynamic energy balance will be used to assess the impacts of adding an impermeable synthetic cover to reduce the effects of leachate generation on LFG generation.

With respect to optimization of waste management practices at the BCRRC, the balance can be used to develop strategies to reduce transport fuel expenditures in various areas or minimize overall electrical consumption. The greatest reductions in transport fuel consumption could be realized by reducing the distance the cover material travels by obtaining cover material from locations within a closer proximity to the landfill.

4. CONCLUSIONS

Increasing social and political focus on energy policy and environmental protection necessitates the quantification of energy use and generation, as well as environmental impacts, of large waste management systems. The dynamic energy balance for the BCRRC, presented here, is useful for identifying the amount of energy being generated from LFG versus the amount of energy needed to operate and maintain the waste management system (i.e., the amount of energy put in to the system versus what the system can generate), and has been used to assess energy recovery options. Electricity generation via an internal combustion engine seems, currently, to be the best option for energy recovery at the BCRRC because it produces the greatest amount of useable energy. This option is comparable to LNG generation. Electricity can more easily be provided immediately to the grid, whereas the LNG and cogeneration infrastructures (LNG vehicles, storage, heat utilization etc.) would need to be established. However, considering the increasing costs of diesel and the stricter air emission standards, LNG generation is an interesting alternative.

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