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Landfill Gas To Energy Incentives And Benefits

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LANDFILL GAS TO ENERGY: INCENTIVES & BENEFITS

by

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ABSTRACT

Municipal solid waste (MSW) management strategies typically include a combination of three approaches, recycling, combustion, and landfill disposal. In the US approximately 54% of the generated MSW was landfilled in 2008, mainly because of its simplicity and cost-effectiveness. However, landfills remain a major concern due to potential landfill gas (LFG) emissions, generated from the chemical and biological processes occurring in the disposed waste. The main components of LFG are methane (50-60%) and carbon dioxide (40-50%). Although LFG poses a threat to the environment, if managed properly it is a valuable energy resource due to the methane content. Currently there are over 550 active LFG to energy (LFGTE) facilities in the US, producing renewable energy from LFG.

A major challenge in designing/operating a LFGTE facility is the uncertainty in LFG generation rate predictions. LFG generation rates are currently estimated using models that are dependent upon the waste disposal history, moisture content, cover type, and gas collection system, which are associated with significant uncertainties. The objectives of this research were to:

- Evaluate various approaches of estimating LFG generation and to quantify the uncertainty of the model outcomes based on case-study analysis,
- Present a methodology to predict long-term LFGTE potential under various operating practices on a regional scale, and
- Investigate costs and benefits of emitting vs. collecting LFG emissions with regards to operation strategies and regulations.

The first-order empirical model appeared to be insensitive to the approach taken in quantifying the model parameters, suggesting that the model may be inadequate to accurately describe LFG generation and collection. The uncertainty values for the model were, in general, at their lowest within five years after waste placement ended. Because of the exponential nature, the uncertainty increased as LFG generation declined to low values decades after the end of waste placement.

A methodology was presented to estimate LFGTE potential on a regional scale over a 25-year timeframe with consideration of modeling uncertainties. The methodology was demonstrated for the US state of Florida, and showed that Florida could increase the annual LFGTE production by more than threefold by 2035 through installation of LFGTE facilities at all landfills. Results showed that diverting food waste could significantly reduce fugitive LFG emissions, while having minimal effect on the LFGTE potential. Estimates showed that with enhanced landfill operation and energy production practices, LFGTE power density could be comparable to technologies such as wind, tidal, and geothermal.

More aggressive operations must be considered to avoid fugitive LFG emissions, which could significantly affect the economic viability of landfills. With little economic motivation for US landfill owners to voluntarily reduce fugitive emissions, regulations are necessary to increase the cost of emitting GHGs. In light of the recent economic recession, it is not likely that a carbon tax will be established; while a carbon trading program will enforce emission caps and provide a tool to offset some costs and improve emission-reduction systems. Immediate action establishing a

US carbon trading market with carbon credit pricing and trading supervised by the federal government may be the solution.

Costs of achieving high lifetime LFG collection efficiencies are unlikely to be covered with revenues from tipping fee, electricity sales, tax credits, or carbon credit trading. Under scenarios of highly regulated LFG emissions, sustainable landfilling will require research, development, and application of technologies to reduce the marginal abatement cost, including:

- Diverting rapidly decomposable waste to alternative treatment methods,
- Reducing fugitive emissions through usage daily/intermediate covers with high oxidation potential,
- Increasing the lifetime LFG collection efficiency, and
- Increasing LFG energy value – for instance by producing high-methane gas through biologically altering the LFG generation pathway.

I dedicate this dissertation to my cherished wife, Bahareh Seyfi Nouferest, for her support, for being by my side all along, and for energizing me to do better at every step. I also dedicate my dissertation to my beloved family, my parents, Saddradin and Forough, for showing me the right path of life, my brothers, Ali, Mahmoud, and Hamed, and my sister, Yeganeh, for their guidance and support. Finally, I dedicate my dissertation to my dear in-laws for their support and encouragement, especially dear Behnaz.

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LIST OF ABBREVIATIONS, ACRONYMS & UNITS OF MEASUREMENT

CCX	Chicago Climate Exchange
CEA	Commodity Exchange Act
CFTC	Commodity Futures and Trading Commission
CV	Coefficients of Variability
C&D	Construction & Debris
EPA	Environmental Protection Agency
EU ETS	European Emissions Trading Scheme
FDEP	Florida Department of Environmental Protection
GHG	Greenhouse Gas
GWP	Global Warming Potential
IC	Internal Combustion
IPCC	Intergovernmental Panel on Climate Change
LFG	Landfill Gas
LFGTE	Landfill Gas to Energy
LMOP	Landfill Methane Outreach Program
MOE	Measure Of Effectiveness
MSW	Municipal Solid Waste
NMOC	Non Methane Organic Compound
OTC	Over-The-Counter
PCC	Post Closure Care
PTC	renewable energy Production Tax Credit
PV	Photovoltaic
REC	Renewable Energy Credit
RPS	Renewable Portfolio Standard
SWICS	Solid Waste Industry for Climate Solutions

C	Carbon
CH_4	Methane
CO_2	Carbon dioxide
H	Hydrogen
N	Nitrogen
N_2O	Nitrous oxide
O	Oxygen
O_3	Ozone
S	Sulfur
CO_2eq	CO_2 equivalent
mm	Millimeter
cm	Centimeter
m	Meter
m^3	Cubic meter
m^3Mg^{-1}	Cubic meter per mega gram

m^3hr^{-1}	Cubic meter per hour
m^3yr^{-1}	Cubic meter per year
Mg	Mega gram
MJm^{-3}	Mega joule per cubic meter
MW	Mega Watt
MWh	Mega Watt hour
kW	Kilo Watt
kWh	Kilo Watt hour
$kWhyr^{-1}$	Kilo Watt hour per year
$kWhm^{-3}$	Kilo Watt hour per cubic meter
Wm^{-2}	Watt per square meter
kgm^{-3}	Kilograms per cubic meter
yr	Year
yr^{-1}	1/Year
°C	Degrees Celsius
\$/tonne CO_2eq	US dollars per tonne CO_2 equivalent emissions

CHAPTER ONE – INTRODUCTION

Municipal solid waste (MSW) is composed of different types of waste material usually coming from household and commercial sources. A typical MSW stream includes material such as food waste, yard waste, paper, aluminum, plastics, wood, construction-demolition, and textiles. Managing high quantities of MSW coming from multiple sources has always been a challenge for communities. Several methods have been suggested for managing MSW from easier solutions (such as dumping) to more complicated solutions (such as sending waste into space). As time has passed and different methods have been applied, only a few solutions remain feasible, including landfilling, incineration and recycling. These waste management solutions are being used to different extents. However, landfilling is the most favorable solution worldwide. In the US approximately 54% of the generated MSW is landfilled (US EPA, 2008a). Strict regulations oblige landfills to use new technologies to reduce their potential threat to the environment. However, landfills remain a major concern for environment protecting organizations due to their potential to generate odors, leachate, and landfill gas.

Landfill gas (LFG) is generated from the chemical and biological processes occurring in the disposed waste. The main components of LFG are methane (50-60%) and carbon dioxide (40-50%). The fact that methane and carbon dioxide are two main greenhouse gases (GHGs) enhances the importance of studying LFG. Although LFG poses a threat to the environment, if managed properly it is a valuable energy resource, with an energy value of 18-22 MJm^{-3} due to the methane content (Spokas et al., 2006). Consequently, efforts have been made to collect and produce energy from LFG. As of April 2011 there were 551 active LFGTE projects across the

US, with an annual design capacity of about 1700 MW of electricity production and about three billion m^3 of direct thermal use. The US EPA estimates that there are an additional 510 candidate landfills in the US which could feasibly operate a LFGTE facility (US EPA LMOP, 2011). However, producing electricity from a LFG to Energy (LFGTE) plant is just one means of beneficial LFG usage. The rising carbon market provides an important economic incentive as well. Recent trends toward trading carbon emissions suggest that collecting LFG can have significant economic benefits for landfill owners.

In order to environmentally and economically benefit, landfills should first design and apply a proper LFG collection system. However, a major problem in designing a LFGTE plant is the uncertainty of predicting LFG generation rates. This is mainly because of the effect and interactions of several factors that are difficult to predict. These factors include the amount of disposed waste, waste composition, moisture content, temperature, landfill cover material, and LFG collection system efficiency. Furthermore, operational approach affects the economics of LFGTE projects. In order to increase the number of LFGTE projects, owners and designers should have a better understanding of which operational model is best for those conditions and what are the benefits for these projects. The objectives of this research were to:

- Evaluate various approaches of estimating LFG generation and to quantify the uncertainty of the model outcomes based on case-study analysis,
- Present a methodology to predict long-term LFGTE potential under various operating practices on a regional scale, and
- Investigate costs and benefits of emitting vs. collecting LFG emissions with regards to operation strategies and regulations.

A detailed literature review is presented on the science, methods, and technologies related to LFG estimation, LFG collection, and LFGTE production in Chapter Two. The approaches in using the LFG generation models are evaluated in Chapter Three and uncertainties in the model outcome are quantified. Finding from this Chapter have been submitted in the form of a technical research article to Waste Management journal.

The methodology to predict long-term LFGTE potential on a regional scale is presented in Chapter Four. This methodology has been submitted as a research article to Waste Management journal and has received proof of publication. Chapter Five of this dissertation consists of an economic analysis on the costs and benefits of emitting vs. collecting LFG emissions. A research article on this Chapter has been prepared and will be submitted to Journal of Environmental Economics and Management shortly. Finally, summarized conclusions and future research recommendations are presented in Chapter Six. Detailed information from case-study landfills and example calculations are presented in the Appendices.

CHAPTER TWO – LITERATURE REVIEW

2.1. Landfill Gas

LFG is generated from the chemical and biological processes occurring in the disposed waste. The components of landfill gas are methane (50-60%), carbon dioxide (40-50%), nitrogen, water vapor, and numerous trace gases. The fact that methane and carbon dioxide are two of the main GHGs makes the study of landfill gas very important. GHGs are components in the atmosphere potentially contributing to climate change. The main compounds in the atmosphere causing the greenhouse effect are water vapor, carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and ozone (O_3). The concept of the greenhouse effect is that long-wave length radiation from the sun is reflected on the earth and should exit the atmosphere; whereas, high quantities of GHGs in the atmosphere re-reflect these waves downwards again, preventing them from leaving the atmosphere. This action is believed to be the reason of an increase in global temperature and the cause of the greenhouse effect. However, the effects of different GHGs are not equal; some components are of more concern due to higher contributions to the greenhouse effect. For instance, although the portion of methane gas in the atmosphere is lower than carbon dioxide, its high global warming potential (GWP) makes it of more importance. The GWP is a measure of how much a specific compound contributes to global warming, scaled to an equivalent carbon dioxide contribution. The GWP of methane is 21, meaning a specific amount of methane has 21 times the contribution to the greenhouse effect of the same amount of carbon dioxide. Also important to note is that methane has an atmospheric lifetime of nine to 15 years and is reported to be responsible for approximately 40% of the global warming over the past 150 years.

One of the main advantages of LFG is its high methane content. During biodegradation in landfills, methane is formed by methanogenic microorganisms under anaerobic conditions, either through the direct conversion of acetate into methane and carbon dioxide, or through carbon dioxide reduction by H_2.

2.2. LFG Generation Modeling

In order to plan for the recovery of LFG, the first step involves estimating the amount of gas generated in the landfill. For this purpose, many LFG generation models have been applied with different approaches. However, maximum accuracy of the model outcomes is the ultimate goal. Generally, landfill gas generation can be modeled using zero-order, first-order, second-order, and/or multi-phase generation models. Studies have shown that zero-order model outcomes are not reliable due to relatively high inaccuracies. Higher order models have relatively lower inaccuracies when comparing model outcomes to actual measurement data (Oonk, 1994). Considering the fact that moving from a first-order to a second-order or a multi-phase model makes the modeling procedure much more complicated, most users stick with the first-order model.

Over the years a large number of numerical and mathematical models have been developed based on different approaches. However, the fact is that these models are not commonly used because they are often only accessible to the developers. The required parameters in each model are often so uncertain that they negatively affect the accuracy of the model outcomes. Because of the complexity of numerical and mathematical models, some simplified empirical models have been developed. These models are all based on the same general facts as the numerical and mathematical models, but some processes have been simplified in order to make modeling easier. The uncertainty in several affective parameters in numerical models makes them no more accurate than the simplified models. Some of these models have been presented as computer software programs to make it even more user-friendly, including the US EPA LandGEM, the E-PLUS, the IPCC, the Dutch Multiphase (AMPM), and the French ADEME models (Table 1).

Table 1. Empirical LFG generation models (Thompson et al., 2009; Machado et al., 2009; Faour, 2003)

Model	Order / Main Parameters	Reference
LandGEM, E-Plus	First order model / Methane generation potential (L_0) and methane generation rate constant (k)	US EPA (2005a); US EPA (1997)
IPCC Model	First order model / Decomposable degradable organic carbon ($DDOC_m$) and k	IPCC (2006)
Triangular Model	Zero order model / Methane generation potential (L_0) and peak rate of methane generation	Tchobanglous et al. (1993)
Scholl Canyon Model	First order model / Volume of methane remaining to be generated (G) and gas generation rate constant for submass (k)	EMCON (1980)
Palos Verdes Model	First order model with two phase generation / Methane generation potential of organic component (L_{0j}) and methane generation potential of the whole waste (L_0)	US EPA (2005b)
GASSFILL	Two phase model / Methane generation rate (Q) and peak methane generation rate (Q_p)	Findikakis et al. (1988)
GasSim	First order multi phase model / Waste input carbon content and degradation rate constant (k)	Gregory et al. (2003)
AMPM	First order multi phase model / Disposed waste type	Fredenslund et al. (2007)
ADEME	First order model / Methane generation potential (FE) and degradation rate fraction (k)	French Agency for the Environment and Energy Management

For instance the US EPA LandGEM model estimates emission rates from landfills for methane, carbon dioxide, non-methane organic compounds (NMOCs) and other toxic air pollutants (Pierce et al., 2005). The E-PLUS model, also presented by the US EPA, is used to estimate the costs and benefits of LFG recovery projects, also projecting methane flow, LFG flow and NMOCs emissions (Pierce et al., 2005); The Triangular model assumes that waste degradation takes place in two phases. The first phase starts after 1 year of deposition, and the rate increases linearly from zero at year 1 to a maximum value at 6 years. It then decreases linearly to zero at 16 years after deposition (Mor et al., 2006). The EMCON model allows input of specific refuse environmental conditions relating to the overall moisture conditions, specific moisture input for individual waste streams, and temperature. It also utilizes the extraction efficiency (EMCON Associates, 1980). Almost all these empirical models are based on first-order modeling. The LFG generation models presented by US EPA and the Intergovernmental Panel on Climate Change (IPCC) are the most widely used models by operators, designers, and evaluators. These models may differ in some minor approaches, but the main parameters have very similar definitions in both methods.

Thompson et al. (2009) studied 35 Canadian landfills collecting LFG, considering only landfills with sufficient waste data and eliminating outliers. Five LFG generation models have been applied to all 35 landfills to study the accuracy of the model outcomes compared to actual collected LFG records. A 20% loss factor was applied in the studies to account for collection inefficiency. The five studied models where the zero-order German EPER model, the TNO model, the Belgium model, the Scholl Canyon model, and the LandGEM version 2.01 model. The German EPER and the TNO models generally overestimated LFG generation by two to six folds. The Belgium, the Scholl Canyon, and the LandGEM version 2.01 models had a standard error of less than 100%. According to the outcomes of this study, only the LandGEM model underestimated gas generation and the other four models overestimated gas generation.

Willumsen and Terraza (2007) studied six landfills in South America and Europe. The main objective of this project was to compare the LFG collection rates estimated using different models during the project design to the actual performance. Results showed that some models provided better outcomes, including the IPCC First-order Model, the US EPA LandGEM Model, and the Dutch Multiphase First-order Model, with a difference in model vs. actual LFG of -44%, -15%, and -14%, respectively. Other models resulted in outcomes that were significantly different (up to 100%) from actual data, such as the Rettenberger First-order Model, the E-PLUS Model, and the Scholl Canyon First-order Model.

Modeling LFG generation allows forecasting of gas generation and collection based on waste disposal history and operational conditions. Accurate modeling is important because of the need to use results to design a new, expand an existing, or evaluate an active LFG collection system. A major challenge in modeling is estimating the many factors which affect LFG generation. A discussion of major factors follows.

- **Amount of Disposed Waste:** The amount of disposed waste can directly affect the amount of LFG generated. The more waste disposed, the more possible sources of generation of LFG become available.
- **Waste Composition:** The composition of the waste can affect the gas generation potential and the lag time prior to LFG generation. In this respect, disposed waste can be categorized into inert, poorly, moderately, and highly degradable material. Disposed waste consisting mainly of food waste is highly degradable. Hence, it is favorable for generating more LFG, compared to disposed waste containing more non- or poorly-degradable material such as plastics, paper, and wood.

- **Moisture Content:** Up to a specific optimum point, higher moisture content results in a higher rate of LFG generation. Moisture content can vary based on waste composition and climatic conditions. Increasing moisture content in a landfill (bioreactor landfills) can lead to faster generation of LFG, making it possible to recover the LFG in a shorter time period. In recent years, this parameter has proven to be so important that many landfills collect the leachate and re-inject it into the landfill. This will cause a noticeable acceleration in LFG generation (Reinhart and Al-Yousfi, 1996; Bergin et al., 2005). In these bioreactor landfills, LFG generation peaks much sooner and LFG is generated over a much shorter time period. A study by Corti et al. (2007) showed that in a bioreactor landfill, 95% of LFG is produced 10 years earlier than in a conventional landfill.
- **Temperature:** Generally, changes in temperature can affect microbial activities. A rough estimate regarding the effect of temperature on microbial activity is to assume that microbial activity doubles for every 10°C increase in temperature (Pierce et al., 2005). However, this behavior is valid only up to a certain temperature, optimally in the range of 30 to 40°C. From there on, microbial activity declines as temperature increases (Gebert et al., 2003).
- **Time:** The matter of time is of concern from two view points. First, the lag time prior to starting of LFG generation; and second, the overall duration of LFG generation. These can both affect design concepts. Oversight on lag time and LFG generation period allows operators to estimate when the gas collection system should start working with full capacity and for what duration can they be collection LFG beneficially.

In empirical models, these factors are combined into a small number of derivative parameters. The most important derivative parameters used in first-order modeling are the gas generation potential (L_0) and the gas generation rate (k).

2.3. LFG Modeling Parameters

The methane generation potential (L_0) represents the potential of a waste stream to generate a specific amount of methane per unit mass. Consequently, it is mainly a function of the waste composition. Whereas the gas generation rate (k) is a value that ultimately defines the time span of methane generation from a waste stream under specific site conditions. The k value may be affected by waste moisture content, temperature, oxidation potential, waste depth, pH, alkalinity, waste density, and waste particle size (Machado et al., 2009; Garg et al., 2006). For instance, in a deep landfill the waste retains more moisture at depth, providing better conditions for increasing LFG generation rate (Garg et al., 2006). Also Huitric and Rosales (2005) hypothesize that deeper inside a landfill, the insulation improves and temperature increases, therefore accelerating the rate of methane generation (Huitric and Rosales, 2005). Considering all the uncertainties with each of these effective factors, selecting a correct value for L_0 and k may be one of the most significant and challenging tasks of LFG modeling.

The methane generation potential is sensitive to major changes in the composition of the waste stream (Huitric and Rosales, 2005). The waste stream composition can change over the lifetime of a landfill as a result of community lifestyle change and/or expanding recycling programs. Furthermore, different waste components degrade at different rates over time (Machado et al., 2009), and the portion of each component in a waste stream affects the methane generation potential. Waste can be defined in four major categories, considering the composition and degradability:

- Readily biodegradable waste components, such as food waste and some types of green waste,
- Moderately biodegradable waste components, such as paper waste and remaining portions of green waste,
- Slowly biodegradable waste components, such as some type of paper waste and wood waste,
- Non- biodegradable waste components, such as glass, plastics, metal, concrete, etc.

Landfilled waste is composed of different fractions of cellulose, lignins, hemicelluloses and proteins which are the main organic components converted to methane via physical, chemical and biological processes (Barlaz et al., 1989 and 1997). The degradation rates of cellulose and lignins vary considerably under changing landfill conditions. For example, lignins are thought to be recalcitrant under anaerobic conditions. Temperature and pH affect the bacterial activities in the waste (Mc. Bean et al., 1995). These facts have resulted in the adjustment of waste quantity by a biodegradation factor to specify L_0 under different conditions by different researchers (Table 2). Also, moisture content controls the methane generation through microbial activities by providing better contact among microorganisms (Barlaz et al., 1990).

Table 2. Biodegradable fraction values suggested by different researchers (Machado et al., 2009)

Author	Biodegradable Fraction					
	Paper	Cardboard	Food waste	Garden waste	Wood	Textiles
Tchobanoglous et al. (1993); Bonori et al. (2001)	0.44	0.38	0.58	0.45	0.61	0.40
Barlaz et al. (1997)	0.19-0.56	0.39	0.70	0.70-0.34	0.14	N/A
Harries et al. (2001)	0.30-0.40	0.44	N/A	0.20-0.51	0.30-0.33	0.17-0.25
Lobo (2003)	0.40	0.41	0.64	0.35	0.17	0.32

The values of L_0 and k can be derived either from laboratory experiments, theoretical predictions or using collected LFG data. As Machado et al. (2009) state, in laboratory experiments one of the main challenges is to simulate real conditions of landfilling at lab-scale. On the other hand, theoretical predictions result in maximum values for L_0, while in reality these are never reached. One of the main reasons is that not all of the organic waste is biodegradable, requiring a biodegradability-factor which is an unknown parameter itself (Machado et al., 2009). Most simplified models have a similar first-order based formula (Equation 1) to predict LFG generation but use different L_0 and k values.

$$Q_g = \beta k M L_0 e^{-kt} \tag{1}$$

where:

Q_g = Annual generated LFG, m^3yr^{-1}

β = Inverse ratio of fraction of methane content

k = Methane generation rate constant, yr^{-1}

M = Tonnage of waste disposed, Mg

L_0 = Methane generation potential, m^3Mg^{-1}

t = Age of disposed waste, yr

Different organizations including the US EPA and the IPCC, have proposed default values for L_0 and k. For example, k values in the open literature generally range from 0.01 to 0.21 yr^{-1} with 0.04 yr^{-1} being a commonly applied value (Pierce et al., 2005; Garg et al., 2006). But values of 0.30 yr^{-1} and 0.50 yr^{-1} have also been reported under specific conditions such as for bioreactor operating landfills or for rapidly degradable fractions of waste (Faour and Reinhart, 2007; Ogor and Guerbios, 2005). The suggested default value by US EPA is 0.04 yr^{-1} for areas receiving 63.5 cm (25 inches) or more of rain per year, 0.02 yr^{-1} receiving less than 63.5 cm (25 inches) of rain, and 0.30 for wet landfills (US EPA AP-42, 1997; US EPA, 2008a). Although the values recommended by US EPA are based on a best fit for 40 different landfills, the predicted methane emissions ranged from 30% to 400% of actual measurements (US EPA AP-42, 1997; US EPA, 2008a). According to Machado et al. (2009), high rates of k, about 0.20 yr^{-1}, are associated with higher fractions of readily biodegradable waste and higher moisture content values. On the other hand, lower rates, about 0.02 yr^{-1}, are associated with higher fractions of slowly biodegradable waste and lower moisture content values. Some values for k suggested by the IPCC are presented in Table 3.

Budka et al. (2007) compared methane generation rate for a conventional cell and a bioreactor landfill cell based on the type of waste received. Results are presented in Table 4. As seen below, there are considerable differences based on the type of waste and the operational conditions. The waste in the conventional cell consists of 40% readily biodegradable, 34% moderately biodegradable, and 26% slowly biodegradable waste. For the bioreactor cell, 34% were readily biodegradable, 38% were moderately biodegradable, and 28% were slowly biodegradable waste.

Table 3. Values of k (yr^{-1}) suggested by the IPCC (Machado et al., 2009)

Type of waste		Dry boreal and temperate climate		Wet boreal and temperate climate		Dry tropical climate		Wet tropical climate	
		Default	Range	Default	Range	Default	Range	Default	Range
Slowly degrading waste	Paper/textiles waste	0.04	0.03-0.05	0.06	0.05-0.07	0.045	0.04-0.06	0.70	0.06-0.085
	Wood/straw waste	0.02	0.01-0.03	0.03	0.02-0.04	0.025	0.02-0.04	0.035	0.03-0.05
Moderately degrading waste	Other (non-food) organic putrescible/ garden and park waste	0.05	0.04-0.06	0.10	0.06-0.10	0.065	0.05-0.08	0.170	0.15-0.20
Rapidly degrading waste	Food waste/ sewage sludge	0.06	0.05-0.08	0.185	0.10-0.20	0.085	0.07-0.10	0.400	0.17-0.70
Bulk waste		0.05	0.04-0.06	0.09	0.08-0.10	0.065	0.05-0.08	0.170	0.15-0.20

Table 4. Outcomes of k from study by Budka et al. (2007)

Cell Type	k values (yr^{-1})		
	Readily biodegradable	Moderately biodegradable	Slowly biodegradable
Conventional	0.35	0.23	0.07
Bioreactor	1.73	1.62	0.42

Likewise, L_0 values vary from case to case. In different studies, L_0 values in the range of 6 to 270 m^3Mg^{-1} have been reported (US EPA, 2008a). The default value suggested by US EPA is 100 m^3Mg^{-1} of "as received" waste. Results from a study by Machado et al. (2009) specified an L_0 of 70 m^3Mg^{-1} for tropical landfilling conditions from both laboratory and on-site measurements. In another study, Bentley et al. (2005) calculated L_0 and k for seven case study landfills using baro-pneumatic pressure measurements. The results from this study are presented in Table 5. The mean methane generation potential and generation rate from this study are approximately 107 m^3Mg^{-1} and 0.153 yr^{-1}, respectively. Budka et al. (2007) also reported LFG generation potential values from their studies (Table 6). Recent studies have also reported an inverse relationship between L_0 and k (Budka et al., 2007; Huitric and Rosales, 2005).

Table 5. Parameters values from the Bentley et al. (2005) study

Landfill	L_0 (m^3Mg^{-1})	k (yr^{-1})
N. Shelby Memphis TN	103	0.078
Georgia	108	0.086
Decatur County, GA	115	0.179
St. Landry Parish, LA	104	0.237
Louisiana	110	0.238
Houser’e Mill Road, GA	102	0.148
St Landry parish, GA	112	0.104

Table 6. Outcomes of L_0 from study by Budka et al. (2007)

Cell Type	L_0 (m^3Mg^{-1})		
	Readily biodegradable	Moderately biodegradable	Slowly biodegradable
Conventional	30	84	42
Bioreactor	35	77	38

The amount of generated LFG should be derived from available data. This information can be provided from different sources, including:

- If the landfill has a gas collection system, the collected gas can be measured and records can be made by considering approximate values for collection efficiency, oxidized, emitted, stored, and migrated gas.

- By using different methods, such as the flux chamber, to measure the emitted LFG, the approximate amount of generated LFG can be derived.
- Installing continuous emission monitoring sensors in the gas collection system can also provide good data on the approximate amount of LFG generated in the landfill.

One method to derive the L_0 value for a specific waste is based on its composition. The chemical formula of a waste stream is derived from knowledge about the physical composition of the waste. Based on the chemical formula of the waste stream, the methane generation potential can be calculated (Budka et al., 2007). By inserting the values of L_0, collected LFG, and landfilled waste tonnage data in the first-order model, the k value can be calculated.

Another method proposed by Bentley et al. (2005) to calculate the derivative parameters of LFG generation is to use barometric pressure data. This method estimates LFG generation by measuring pressure responses under the landfill cover compared to atmospheric pressure changes (Bentley et al., 2005). Pressure changes are monitored above and under the landfill cover using implanted sensors at different depths and in different areas for several days. In a recent study, measurements showed that under the landfill cover, the barometric pressure was higher than the atmospheric pressure, and it continued to increase with depth. The results of tests carried out by Bentley et al. showed that the pressure inside the landfill ranged from near atmospheric pressure (163 mm H_2O) to 8.6 atm (1400 mm H_2O) (Bentley et al., 2005). Bentley et al. state two main advantages for this method:

- The interpretation can be accomplished using a quantitative gas flow equation based on continuity and Darcy’s law equations.

– The barometric response data result from pressure changes imposed over a large area.

Garg et al. (2006) presented a model to calculate k based on a fuzzy synthetic evaluation method. They compared the outcomes from their model to k values used in 32 different studies or estimated using EPA's 2E method from LandGEM for different case studies. The results showed that their fuzzy-based model outcomes for k ranged from 43% below to 287% above, with a mean of 79% above the given or estimated k value and a regression coefficient of 0.79 (Garg et al., 2006). Garg et al. (2006) did a sensitivity analysis regarding k values and reported that the methane generation rate constant is more sensitive to biodegradable waste fraction and depth than average precipitation and temperature (Garg et al., 2006).

2.4. LFG Collection

Landfill gas extraction and utilization plants have been developed in the US since the mid 1970s; although, some of the early plants have been closed. Shortly thereafter, this technology started to appear in other places, particularly in Europe. In 2005 there were approximately 1150 LFG extraction/utilization plants active worldwide (Willumsen, 2005). The primary reasons for recovering LFG are odor control, GHG emission control, environmental and safety protection, energy recovery, and subsurface migration prevention. Extraction of gas reduces the emission of methane from landfills into the atmosphere, which would otherwise contribute to the greenhouse effect. Furthermore, landfill gas substitutes for fossil fuels such as oil, coal, and natural gas, which all contribute to the greenhouse effect. The risk of fire and explosion hazards in surrounding facilities is also minimized when the gas is recovered.

As noted earlier, the main components of landfill gas are methane and carbon dioxide. Considering the GWP and energy potential of methane, it is of more concern than CO_2 in landfill gas collection projects. The generated LFG has multiple fates, including recovery, emission, and oxidization, as presented in Equation 2 where all units are volume/time.

$$Q_g = Q_c + Q_{em} + Q_{ox} \tag{2}$$

where:

Q_c	=	Annual collected LFG, m^3yr^{-1}
Q_{em}	=	Annual emitted LFG, m^3yr^{-1}
Q_{ox}	=	Annual oxidized LFG, m^3yr^{-1}

Overall, collection and utilization of LFG can have several direct and indirect benefits, including:

- Reducing gas emissions, odors, and gas migration
- Providing a reliable, uninterruptible energy source
- Creating new jobs at the landfill site or related industrial sites
- Providing additional local capture and separation technology development, manufacturing, and marketing as well as potential associated businesses
- Developing new markets for LFG

2.4.1. LFG Collection Technologies

A passive landfill gas collection system relies on pressure or concentration gradients to function using vertical wells and gravel trenches open to the atmosphere. After the landfill has reached its final capacity, wells and trenches are installed and the landfill is covered. The generated gas moves through the wells and trenches by means of natural pressure gradient forces. On the other hand, an active landfill gas collection system uses a mechanical pump, creating a vacuum in the vertical and/or horizontal well network.

The passive system has low operation and initial costs; however, gas collection is inefficient. The active system, on the other hand, has higher initial and operation costs; but advantages include greater collection capacity and higher efficiency. These advantages have led to active systems becoming more favorable and used by most landfill owners.

2.4.2. LFG Collection Hardware

A LFG collection system generally consists of an extraction system, a flare, and a utilization system. The extraction system generally consists of vertical pipes (wells) and horizontal pipes (trenches). The LFG is extracted from the landfill by means of a vacuum induced by a compressor. The gas is collected and sent to be either flared or utilized. The designer must determine if the gas conveyance system will be installed over or under the final cover, taking into account cost effectiveness and suitability terms. Several design and cost consideration factors affect collection system hardware selection, including waste composition, density, precipitation, maintenance, settlement, liquids management, and construction costs. The US

EPA's regulations specify whether or not the installation of a landfill gas collection system is required, but do not dictate specific installation designs and procedures.

2.4.2.1. Installation Sequences

The LFG collection system hardware can be installed before or after the final cap is placed. Installing the collection system hardware, such as pipes and control gauges, before placing the final cap may increase costs and construction time (Lebron et al., 2007). This procedure allows the evaluation of the LFG production parallel to the construction phase and as waste is being landfilled. This way it will be easier to correct any possible problems. On the other hand, installing the collection system after the final cap is placed can reduce cost and time and are easily accessible for future maintenance. A new procedure has been developed by HDR Engineering Inc., Jacksonville, FL, that entails construction of certain portions of the LFG collection system below the final cap (including the header line, valve box) and other portions (particularly laterals, wellheads, and air/condensate lines) above the final cap (Lebron et al., 2007).

2.4.2.2. Vertical Wells and Horizontal Trench Systems

The most common method of LFG extraction is the installation of vertical wells and application of a vacuum to the wells. This approach is the simplest way of installing the system, as the waste is already in place. The use of vertical wells is most effective when a landfill reaches the final grade and is equipped with a low permeability cap (Townsend et al., 2005). Vertical gas wells are typically spaced one in each 0.4 hectare (one acre). By 2007 with the onset of over 150 leachate recirculation projects in over 20 bioreactor landfills in the US, an increase in maintenance costs in the vertical well fields and a potential for increased surface emissions had been reported (Harter et al., 2007). A main problem in this system is that vertical wells fill with water and leachate, requiring extraction pumps to be installed in each well. This increases the operating costs and frequency of maintenance. Water accumulation in vertical wells becomes an even greater challenge for landfills in wet climates.

Water accumulation may be a reason why landfill owners have been applying horizontal extraction wells (trenches) in recent years. The main advantage of horizontal collectors compared to vertical wells is that they can be installed and operated within the active waste disposal zone; whereas for vertical wells, the landfill should first reach its final elevation before the wells can be drilled in the landfilled waste. There are other situations in which landfill operators prefer to start collecting LFG earlier such as in bioreactor landfills. Bioreactor landfills are required by federal regulation to operate the LFG collection system much sooner than a traditional landfill. Current regulations require LFG collection within five years after initial waste placement or two years after closure for traditional landfills (depending on the amount of waste placed). For bioreactor landfills, LFG should be collected after 180 days, although this varies from one state to another (US EPA, 2004). Also, US EPA Emission Guidelines and New Source Performance Standards require large landfills (at least 2.5 million Mg of waste and/or 2.5 million m^3 in size) with estimated non-methane organic compound (NMOC) emissions at or above 50 Mg NMOC per year to control landfill gas within 30 months of the date when the specified limit of NMOC emission is exceeded (US EPA, 1996). In most sites, horizontal gas extraction pipes or trenches are installed as the waste is being placed in the landfill. With this system, LFG can be extracted soon after gas generation beings, which can be fairly soon if the waste stream consists of high percentages of readily biodegradables. Soon after each layer of waste is placed, a trench is excavated and a pipe is placed inside the gravel-filled trench. The pipes are connected to one another and eventually connected to a vacuum compressor system.

The Los Angeles County Sanitation Districts (LACSD) pioneered the use of horizontal collectors to maximize LFG collection and control (Kong and Chung, 2005). The primary design was based on a pilot scale experiment in 1980 at the LACSDs Puente Hills Landfill. Later in 1985, the first field-scale LFG trench system was constructed in the same landfill. Initially, PVC pipes were being used; however, the PVC pipes did not seem to have enough bearing resistance under site conditions; therefore, they were soon replaced by steel pipes.

On the other hand, a problem with the horizontal trench system is that a long length of pipes may be connected to a single vacuum compressor, hence causing a large headloss and resulting in reduced efficiency in LFG collection. The system should be designed to minimize headloss along the length of the collection trenches. One solution for the problem is using several vacuum compressors at smaller distances, increasing capital, operational, and maintenance costs.

2.4.2.3. Landfill Covers

The type of material used as temporary and permanent covers and the point in time a landfill is capped can greatly affect the amount of collected and emitted LFG. Different cover material can be used for different purposes. For instance, specific cover soils create oxidation conditions for methane by containing methanotrophic bacteria (De Visscher et al., 1999). Methane oxidation can greatly benefit the environment as CH_4 emissions are converted to carbon dioxide, thus reducing the GHG effect. Landfill cover soils also have a significant potential for degradation of trace gases present in the LFG (Scheutz and Kjeldsen, 2004) which can also help eliminate odors from landfills. Many landfills use a tightly sealed geomembrane cover above the soil cover to control emissions which also increases the efficiency of the vacuum system. Although geomembrane covers are expensive material, they are widely used in countries which have strict regulations, including the US.

2.4.2.4. Extraction Compressors

LFG is extracted from the landfill by a compressor, directing the gas toward the utilization equipment by applying a negative pressure in the transmission pipes. There are several manufacturers that provide these compressors in the market, including Becker, Busch, Edwards, Gast, Rietschle, Siemens, and many other companies.

2.4.2.5. Pipes

Connecting the wells and trenches to a main collection pipe is the most common way to get the LFG to the utilization system. The pipe may be perforated or built-up of overlapping sections of smaller and larger diameter corrugated PVC or HDPE. Potential problems with the piping system could include headloss due to long branching networks and breaks or leaks in the network. To save operation costs and to maintain safe conditions for the workers, the best solution may be having single pipes from each well to a pump and regulation facility (Willumsen, 2005); although this approach increases capital cost significantly.

2.4.2.6. Gauges and Control Devices

In order to be able to control and analyze the effectiveness of the gas collection system and to measure fugitive gas emissions, the quantity and quality of collected LFG should be measured, including flow, temperature, pressure and methane content. Collected LFG flow, temperature, and pressure can be measured by installing gauges on well heads. The quality of LFG can be defined using measure tools such as GEM 2000 by from LANDTEC.

2.4.3. LFG Collection Efficiency

The performance efficiency of a LFG collection system is usually evaluated by measuring the collected gas and comparing the results to gas generation model outcomes. Although LFG collection systems have improved during the years, there still seems to be inefficiency due to operational and design flaws. The US EPA uses a default LFG collection efficiency value of 75% (US EPA, 2008a). However, this default value seems to be based on results from a survey, asking experts in the area for a proper LFG collection efficiency and coming to an average figure of 75%. Although few research studies have been done at field-scale regarding LFG collection efficiency, mostly due to high costs, these few studies state higher collection efficiencies for landfills with proper cover, capping, and collection system. For instance, in a study by Huitric et al. (2007) two methods, the ISM/ISC (integrated surface methane concentration data and Industrial Source Complex air dispersion model) and the flux chamber methods were used to measure the gas collection efficiency in Palos Verdes Landfill, Los Angeles, CA. Both methods measured collection efficiencies above 99% (Huitric et al., 2007).

LFG collection efficiency is highly variable depending on the design, installed hardware, and operational conditions. For instance, material used and timing of covering disposed waste can significantly affect the collection efficiency. Field studies suggest that capture with a geomembrane cap significantly exceeds 90% (Spokas et al., 2006; Ogor and Guerbois, 2005). Outcomes from a study by Spokas et al. (2006) on three landfills propose 35% collection efficiency for an operating cell with an active LFG collection system but with no cover; 65% collection efficiency for a cell with an active LFG collection system and with a temporary cover; 85% collection efficiency for a cell with an active LFG collection system and with a final clay layer covering; and 90% collection efficiency for a cell with an active LFG collection system and with a final geomembrane covering (Spokas et al., 2006). Also, in a report prepared by SCS Engineers for the Solid Waste Industry for Climate Solutions (SWICS), the proposed collection efficiencies were 60% (range 50 to 70%) for an active landfill with an active gas collection system and under daily soil cover; 75% (range 54 to 95%) for an active landfill with an active gas collection system and intermediate cover material; and 95% (range 90 to 99%) for an active landfill with an active gas collection system and final soil and/or geomembrane cover (SCS Engineers, 2008).

2.4.4. US Regulations

The 1996 US EPA Municipal Solid Waste Landfill New Source Performance Standards (NSPS) require landfill gas recovery for air quality purposes. Current regulations require gas collection within five years after initial waste placement or two years after closure for traditional landfills and 180 days for bioreactor landfills, although this varies from one state to another (US EPA, 2004).

On December 12, 2007, the carbon market publication Point Carbon reported that the federal budget passed for 2008 will provide $3.5 million to create a mandatory GHG emissions registry. At the present time, California is probably the front runner in the fight against global warming. AB-32 set goals to reduce carbon emissions to 1990 levels by the year 2020 and 80% below 1990 levels by 2050. Other states are also doing serious work in this regard, including Florida. For instance, a new direction for Florida's energy future was established by the Governor, when he signed a groundbreaking set of Executive Order 07-126 in July 2007. According to the Executive Order, agencies and departments under the governor's purview should reduce GHG emissions from current emission levels by targets of 10% by 2012, 25% by 2017, and 40% by 2025. Also in California AB-32 was signed into law by the Governor in 2006 where it sets regulations to reduce GHG emissions to 1990 levels by 2020, meaning reducing emissions by approximately 30%, and then reducing emissions by 80% below 1990 levels by 2050. Other states have also executed similar action order individually or group wise. For instance the Regional Greenhouse Gas Initiative (RGGI group) consisting of 10 north-eastern states, i.e. Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Rhode Island, and Vermont, have set goals to develop a multi-state Cap-and-Trade program covering GHG emissions. Their goal is to reduce CO_2 emissions from the power sector 10% by 2018. Another regional regulating act is the Western Climate Initiative (WCI group) consisting of several US and Canadian states, Arizona, British Columbia, California, Manitoba, Montana, New Mexico, Ontario, Oregon, Quebec, Utah, Washington, launched in February 2007 aiming to identify, evaluate, and implement collective and cooperative ways to reduce greenhouse gases in the region, focusing on a market-based Cap-and-Trade system. The WCI regional greenhouse gas emission reduction goal is an aggregate reduction of 15% below 2005 levels by 2020.

2.5. Landfill Gas to Energy

Florida Orange County Landfill LFGTE system, for example, consists of 40,000 lineal feet of collection pipe, a gas transmission pipeline, and a pump station. LFG is collected from the 200 acres of waste that have been deposited at the Orange County landfill since the early 1990s. After collection, the gas is sent to the Stanton Energy Center where it is used to generate electricity. The waste at the landfill, in addition to the waste expected to be deposited over the next 20 years, will be the source of more than 10,000 m^3hr^{-1} of LFG, or enough fuel to generate electricity for 13,000 homes. The project takes advantage of $4 million in federal funding and tax incentives allowing replacing finite fossil fuel with the cleaner burning, renewable energy source. This project benefits Orange County and its partners both financially and environmentally. Orange County receives a monetary benefit of $400,000 per year for rights to the LFG, in addition to the $5 million system purchase price. The Orange County LFGE project will reduce methane emissions by almost 30,000 tonnes per year at capacity, improving the global environment and ensuring that the citizens of Central Florida have a healthier environment in which to live and work (US EPA LMOP, 2008).

Selling electricity is one means of converting waste to cash. The rising carbon market provides an important economic incentive as well. The value of the US carbon market more than tripled from 2006 to 2007 (Lynch, 2008). The carbon market at the present time is based on two main scenarios: Taxing and Cap-and-Trade. The more carbon emitted from a plant, the higher its carbon tax bill, and vice versa. The second scenario, Cap-and-Trade, is based on setting a cap on carbon emission for any emission source. As a consequence, the plants will have to obtain permits for any carbon emitting source and limit their emissions to the cap. If they are not below the cap, they can buy extra emission capacity from other sources, which will build a trading market. The costs from this Cap-and-Trade system will motivate many plants to limit their emissions to the permitted cap and other plants to develop technologies which give them extra credit and allow them to trade their carbon permits.

In the United States, although the federal government is still discussing these scenarios, individual states have already set carbon taxing legislation in motion for some industries, and are expanding the field. Others have practiced limited voluntary carbon trading, for example the Chicago Climate Exchange (CCX) Market has been actively trading for some time. Recent trends toward trading carbon emissions suggest that collecting methane from landfills can have significant economic benefit. If there is a carbon cap established for landfills, the cost of extra emissions may be a significant factor in the continuing profitability of landfill operation. But with LFGTE, landfill owners are able to sell their gas reductions on the carbon market. Depending upon the projected price of carbon, the economic benefits may be significant. For example, the market price of CO_2 in the CCX market has varies between $1 and $6 per tonne in the past. However, many predict much higher CO_2 prices in near future, especially if the US signs onto a global climate change treaty in some form.

Further, the carbon market provides other incentives for LFGTE operators, i.e. Renewable Energy Credits (REC) and renewable energy Production Tax Credits (PTC). Each REC represents one MWh of electricity produced from renewable resources and PTC is the tax credit awarded for producing one kWh of electricity from renewable resources. R.S. Lynch & Company, Inc., established in 1987 and active in the carbon market, studied the City of Albany, NY, landfill and reported annual potential carbon values of over $1.6 million in carbon offset credits, over $1.5 million in RECs and over $0.3 million in PTCs for a duration of 10 years from its 33,000 MWh LFGTE plant (Lynch, 2008).

Perhaps one of the main issues for landfill owners associated with LFG collection projects is economics. Showing proof that installation of a LFG collection and utilization system is economically feasible and beneficial can easily convince any landfill owner to install a plant. Such a plant will collect LFG and use the collected gas to generate some form of energy. Presently most LFGTE projects are using LFG to generate electricity via an IC engine or a gas turbine. The generated electricity is then sold to other companies or used to run the operational plants inside the landfill. LFG can also be utilized to other economically beneficial forms, e.g. LNG, or used for other purposes, e.g. gas burning motor vehicles. All these can economically benefit the landfill owners.

The matter of proving the feasibility of a LFGTE project becomes more challenging when it comes to small landfills. LFGTE project developers have not shown much interest in small landfills (1-5 million tonnes) because they think it is not economically feasible. On the other hand, some landfill owners and operators are beginning to discover that small LFGTE projects can provide big benefits to the environment and surrounding community. They can be economically feasible if resources are leveraged properly, new methods of landfill gas extraction are utilized and project plans are realistic (Byam and Schuller, 2005). Even in cases where the profits may be small, regulatory requirements will result in the installation of LFG collection systems. As for relatively larger landfills, a typical US landfill disposing 450 million tonnes of waste annually can produce approximately $50,000 per year of electricity from a LFGTE project based on $0.10 per kWh average electricity price.

In 2005, after investigating different costs around the world, Willumsen stated that the average range of investment per kW power installed for LFG collection and utilization system can be summarized in Table 7. Revenue from LFG collection is significantly dependent on the type of energy produced. Willumsen (2005) showed that the price for selling electricity from LFGTE to the grid ranged from one country to another, but was normally in the range of $ 0.01 per kWh (off peak hour) to $0.10 per kWh (peak hour) with an average of $0.04 per kWh. While as, in 2006, the average price for electricity was approximately $0.10 per kWh in the US (michaelbluejay.com/electricity/cost.html). In the same research, Willumsen states that in order to make LFGTE feasible in the US, the generated electricity should be sold at a price of some $0.030 per kWh or higher in typical landfills. As for small landfills the generated electricity should be sold at $0.055 per kWh or higher to make LFGTE feasible (Willumsen, 2005).

Table 7. LFG collection and utilization system investment costs (Willumsen, 2005)

Component	Collection system	Extraction system	Utilization system	Planning and design	Total
Costs in $/kW	200-400	200-300	850-1,200	250-350	1,550-2,250

Electricity generating LFGTE plants also benefit the environment as they are considered a renewable energy source and a replacer for a portion of fossil fuel burning in power plants. This renewable energy source can take advantage of a number of tax credit and other economically beneficial programs. New carbon trading markets are vastly growing for direct or indirect subsidizing renewable energy sources. According to Willumsen, in 2005 subsidies for selling electricity may have approximately been \$0.004 per kWh in the US and for plants that could receive CO_2 credit there would be an extra income of approximately \$0.023 per kWh, assuming a market price of \$5.00 per tonne of CO_2 (Willumsen, 2005). Although, economic benefits from a LFGTE plant is site specific and a function of many factors, including the quality and quantity of generated (collected) LFG, forecast product prices, and proximity to pipelines and end users (Byam and Schuller, 2005).

2.6. Necessity of Research

As presented, many researchers have used various approaches on empirical models to estimate LFG generation. Furthermore, due to the nature of empirical models, outcomes will be associated with inevitable uncertainties. It is necessary to compare the viability of the various modeling approaches and facilitate choosing best-approach-modeling. Quantifying the LFG generation potential and uncertainties ranges is required for landfill owners, operators, and regulators when design a new or evaluating the performance of an existing LFG collection and/or LFGTE production facility.

Energy policies are generally long-term regional policies and consider all sources of supply and demand. LFGTE is considered a renewable energy resource in most renewable portfolio standards and can contribute to the energy supply policies. However, landfills are long-term project with typically over 30 years of lifetime. Changes in landfilling and energy production practices are expected over such time period. Most published literatures have quantified energy production from LFG for a limited number of landfills and for current capacity. A methodology is necessary to estimate regional LFGTE production with respect to current waste generation, landfilling, and energy production practice, and also have the capability to incorporate changes in practices and energy policies over long-term periods.

According to the reviewed literature, landfills are considered major potential contributors to the climate change. With the growing level of GHGs in the atmosphere, more strict regulations on LFG emissions are inevitable in the near future. Yet, under current regulated practices, many US landfills claim they are collecting most of the generated LFG. The validity of such claims should be evaluated. Nevertheless, any regulatory action with respect to GHG emitting sources, including landfills, could significantly affect the economy of these projects. Therefore, research is necessary to study the environmental and economic impact of various regulation scenarios, and whether it is more beneficial to operate landfills and collect LFG under such regulation or consider other waste management alternatives.

CHAPTER THREE – DETERMINATION OF LANDFILL GAS MODEL PARAMETERS AND UNCERTAINTIES

3.1. Background

A major challenge in planning and designing a LFG collection and LFG to energy (LFGTE) facility is the uncertainty in LFG generation rate predictions. LFG generation rates are currently estimated using mathematical models that are dependent upon the amount of disposed waste, waste composition, moisture content, landfill cover material, and LFG collection system efficiency. Because these factors are generally poorly defined, there is significant uncertainty in model results. Quantifying model uncertainty is also essential to estimating LFG collection efficiency. Some researchers base collection efficiency on modeled LFG generation; while others calculate LFG collection efficiency from mass balances which also have inherently great uncertainties because of the challenges associated with measuring fugitive emissions and methane oxidation. The objective of this chapter is to evaluate several approaches of estimating LFG generation using the first-order model and to quantify the uncertainty of the model outcomes, based on the analysis of case-study landfills with long-term availability of LFG data.

3.1.1. Generation Models

Landfill gas generation can be modeled empirically using zero-order, first-order, or second-order generation models. Studies have shown that zero-order model outcomes are not reliable due to relatively high errors; higher order models have lower errors when comparing model outcomes to measured data (Oonk et al., 1994). Increasing from first-order to second-order makes the modeling procedure more complicated and is not justified by the increase in accuracy (Oonk et al., 1994), therefore most models are based on a first-order equation, such as that shown in Equation 1. Two important parameters used in modeling LFG generation based on a first-order equation in Equation 1 are the methane generation potential, L_0 (m^3/Mg), and the methane generation rate constant, k (yr^{-1}). L_0 represents the total volume of methane generated from a specified quantity of disposed waste, i.e. ultimate yield. The methane generation rate constant controls the predicted time over which methane is generated from the specified waste stream. Also, to estimate the overall LFG generation (methane plus carbon dioxide plus trace gases) a methane content factor, β, is applied. These parameters lead to the first-order generation model shown in Equation 3, which is a modified form of the US Environmental Protection Agency (EPA) LandGEM model (US EPA, 2008a; US EPA AP-42, 1997).

$$Q_g = \sum_{i=1}^{n} \sum_{j=0.1}^{1} \beta k (\frac{M_i}{10}) L_{0_i} \, e^{-kt_{zj}} \quad (3)$$

where:

i	=	Time period of waste disposal, yr
j	=	1/10 time increments, yr
n	=	(Last calendar year of waste disposal) - (Calendar year of initial waste disposal)+1, yr
z	=	Time period of LFG generation from waste disposed in year i, yr
β	=	Inverse ratio of fraction of methane content
k	=	Methane generation rate constant, yr^{-1}
M_i	=	Tonnage of waste disposed in year i, Mg
L_{0i}	=	Methane generation potential of waste disposed in year i, m^3Mg^{-1}

t_{zj} = Age of j^{th} section of waste M_i in year z, yr

The quantity of LFG that can be collected is affected by cover material type, cover material installation timing, and gas collection system design and timing of installation. The quantities of generated and collected LFG are related by the collection efficiency as shown in Equation 4. In this study, a corresponding η value was applied for each year of the lifetime of waste disposed.

$$Q_c = \sum_{i=1}^{n} \sum_{j=0.1}^{1} \eta_{iz} \beta k (\frac{M_i}{10}) L_{0_i} e^{-kt_{zj}} \qquad (4)$$

where:

η_{iz} = Collection efficiency in year z from waste disposed in year i, fraction

3.1.2. Model Parameters and Model Accuracies

The value of k reflects the rate of degradation and is affected by waste depth, density, pH, and other environmental conditions (Machado et al., 2009; Garg et al., 2006). Generally, each waste component degrades at a different rate (Machado et al., 2009), however most models assume a single overall value for k. The value of k can be defined through laboratory studies, pilot-scale cells, or by comparing measured LFG from full-scale sites to model outcomes. The degradation rate is also affected by moisture content, for example increased moisture content results in faster waste degradation, therefore generating a higher k value (Machado et al., 2009).

The value of L_0 is a function of the waste composition. L_0 values reported in the literature vary considerably, ranging from 6 to 270 m^3Mg^{-1} of waste, as received, depending on the composition of the waste stream and the ultimate methane yield of each component (US EPA, 2008a; US EPA AP-42, 1997). L_0 can be defined using waste degradation stoichiometry, laboratory values, or model fitting using full-scale data. Eleazar et al. (1997) measured methane generation potential for biodegradable components using laboratory tests. The accuracy of applying results from laboratory studies with well-defined wastes and environment to full-scale landfill conditions has not yet been evaluated. The default value suggested by US EPA is 100 m^3Mg^{-1} (US EPA, 2008a; US EPA AP-42, 1997).

Research groups have applied various models to predict LFG generation, however, few have compared model outcomes to actual collected LFG data. A summary of some of these studies is presented in Table 8. These studies were generally based on short-term data and default model parameters. Most of the models tended to overestimate LFG generation (sometimes by as much as an order magnitude), however, the LandGEM model was reported to generally underestimate gas generation (Thompson et al., 2009; Ogor and Guerbois, 2005).

Table 8. Summary of empirical landfill gas generation model applications

Study	Years of data	Models	Landfill characteristics	k, yr^{-1}	L_0, $m^3 Mg^{-1}$	Error[1]	Reference
Validating LFG generation models based on 35 Canadian landfills	N.A.	Zero-order German EPER TNO Belgium Scholl Canyon LandGEM version 2.01	35 Canadian landfills	0.023 - 0.056	90 - 128	(-81%) – (+589%)	Thompson et al., 2009
The CDM landfill gas projects by the World Bank	1 - 3 years	IPCC First-order Rettenberger First-order E-PLUS US EPA LandGEM Dutch Multiphase Scholl Canyon	Six landfills in South America and Europe	0.014 - 0.28	68 - 102	(-3%) – (+1109%)	Willumsen and Terraza, 2007
Comparison of landfill methane emission models: A case study	N.A.	US EPA LandGEM French ADEME UK GasSim IPCC Tier 2	Four French landfills	0.04 – 0.50	44 - 170	(-65%) – (+140%)	Ogor and Guerbois, 2005
Landfill gas energy recovery: Economic and environmental evaluation for a case study	N.A.	Scholl Canyon	Casa Rota Landfill, Tuscan, Italy	0.07 - 0.36	13 - 30	+5%	Corti et al., 2007

[1] The error comparing model estimations to actual data, with negative indicating model estimation is lower than actual
N.A.: Not Available

3.2. Methodology

Historically, LFG generation modeling was based on a limited number of field observations or an incomplete description of the landfill and LFG collection system. In the present study, detailed field records were collected from Florida case-study landfills, described in Section 3.2.3. These records covered three to 16 years of landfill operation. The data collected from landfill officials and the Florida Department of Environmental Protection (FDEP) (FDEP, 2009) included waste disposal history, waste composition, waste disposal and LFG collection operating methods, and collected LFG quantity and methane content.

3.2.1. Model Parameter Determination Approaches

To optimize model parameter selection, various modeling approaches were evaluated for the case-study landfills based on Equation 3 (example calculations provided in Appendix A). The model outcomes representing the generated LFG, Q_{mg}, were converted to modeled collected LFG, Q_{mc}, by applying collection efficiency factors (Equation 4) on a year-by-year basis to each year's portion of disposed waste. Collection efficiency factors were derived from commonly applied values reported in the literature related to landfilling operating conditions and LFG collection methods (Table 9). Q_{mc} outcomes from each approach were compared to actual LFG collected from each landfill. The approaches that were used to evaluate LFG generation model parameters were (1) Fixed AP-42 Default Parameters, (2) Calculated L_0-Variable k, and (3) Simultaneously Variable L_0 and k. The parameter k was assumed to be a single value for each operating method (traditional vs. wet cell) representing the entire waste stream. Each approach is described further in the following sections.

Table 9. Average LFG collection efficiency based on operation methods (compiled from US EPA, 2008a; SWANA, 2007; SCS Engineers, 2008; Spokas et al., 2006)

Description	Average collection efficiency
No LFG collection system	0%
Active landfill with active LFG collection system of vertical wells and daily cover only	67%
Active landfill with active LFG collection system of vertical wells and intermediate cover or active LFG collection system of horizontal trenches and daily cover	75 %
Active landfill with active LFG collection system of vertical wells and engineered final soil cover or active LFG collection system of vertical wells and horizontal trenches and intermediate cover	87%
Closed landfill with active LFG collection system and geomembrane, subtitle D or equivalent cover	95 %

3.2.1.1. Approach 1: Fixed AP-42 Default Parameters

US EPA default values were used for k and L_0 to calculate Q_{mg}. L_0 was set at 100 m^3Mg^{-1} and k at 0.04 yr^{-1} for traditional landfills as Florida has annual precipitation greater than 635 mm (Florida Precipitation Map, 2009) and 0.30 yr^{-1} for the wet cell (US EPA, 2008a; US EPA AP-42, 1997).

3.2.1.2. Approach 2: Calculated L_0-Variable k

In Approach 2 L_0 was calculated and set and the calculated value, while k was considered as an adjustable variable for best fit. Two methods were used to calculate L_0:

- Approach 2.1: Based on waste composition, and
- Approach 2.2: Based on Landfill 3 data

Approach 2.1: Composition Calculated L_0-Variable k

L_0 was calculated using the waste composition and waste-component specific methane generation potential (Table 10) derived from laboratory measurements (Eleazar et al., 1997; Staley and Barlaz, 2009). L_0 was determined from a weighted average of yearly landfilled waste composition for each case-study landfill (example calculations provided in Appendix B). Waste composition data were available for years 1996 to 2006 (average values are shown in Table 10, details provided in Appendix C, Tables C1-C5). The calculated L_0 for the years 1996 to 2006 was applied to the model directly; for the years prior to 1996, the average L_0 calculated from 1996 to 2006 waste composition was applied, and for the years after 2006 the L_0 calculated for 2006 was used, representing the most recent waste composition data available.

The parameter k was determined through linear regression of actual LFG collection data, Q_{ac}, vs. Q_{mc}, by adjusting k to obtain best slope (i.e., closest to 1.0). When adjusting k for each landfill, as the intercepts were significantly different from zero, the Q_{ac} vs. Q_{mc} trendlines were forced to pass through the origin. This approach was the only way to consistently compare Q_{ac} vs. Q_{mc} over the entire data range (non-zero intercept meant accepting a constant error between modeled and actual data). In addition, by definition, Q_{ac} and Q_{mc} equal zero at t=0.

Table 10. Waste properties used to calculate methane generation potential, L_0, for Approach 2.1

	CH_4 Yield mLg^{-1} (dry)[1]	Typical Moisture Content[1], % (weight)	10-year averaged composition, % (weight)					
			Landfill 1-Phase 1 [2]	Landfill 1-Phase 2 [2]	Landfill 2 [2]	Landfill 3 [2]	Landfill 4 [2]	Landfill 5 [2]
Food waste	300.7	70	8.1	7.2	15.7	6.6	7.3	7.3
Yard trash	72.0	60	6.0	2.8	8.0	6.5	4.7	7.9
Newspaper	74.3	6	5.5	4.8	3.9	5.1	5.0	3.6
Other paper [3]	145.8	6	25.3	23.3	32.8	34.1	27.4	27.3
Textiles	14.8	10	3.5	3.2	3.4	3.7	3.2	6.7
Metals	0	3	28.0	39.5	16.5	18.2	15.3	23.2
Plastics	0	2	3.2	4.8	7.2	12.4	9.8	6.4
Glass	0	2	3.8	1.2	3.4	2.1	3.6	2.7
Tires	0	2	0.3	1.0	0.2	1.6	0.3	1.3
C&D	0	6	4.8	5.0	4.0	5.0	14.8	5.0
Miscellaneous [4]	72.6	5	7.1	7.2	4.9	4.7	8.6	8.6
Biosolids	27.8[5]	87[6]	4.4	-	-	-	-	-

(1) Source: Staley and Barlaz, 2009; except for biosolids
(2) Source: FDEP, 2009
(3) Considered to be a mix of 58% office paper (L_0=217.3 m^3Mg^{-1}) and 42% other paper (L_0=145.8 m^3Mg^{-1})
(4) Assumed to be 50% organic (L_0=145.1 m^3Mg^{-1}) and 50% inorganic material (L_0=0 m^3Mg^{-1})
(5) Source: Reinhart et al. (2005)
(6) Source: Landfill 1 data, personal communication (2008)

Approach 2.2: Landfill 3 Calculated L_0-Variable k

Approach 2.2 utilized data from one of the case-study landfills (Landfill 3) that had been operated for over 20 years and had sufficient LFG data to permit a field-based estimation of L_0. L_0 was calculated from the cumulative methane generation from Landfill 3 divided by total waste disposed (calculation details provided in Appendix D). L_0 was assumed to be applicable to all case-study landfills because waste placed in all cases was largely domestic with similar composition, as can be seen in Table 10. Fixing L_0 to this value, the first-order model was applied and k was adjusted to obtain the best slope for the Q_{ac} vs. Q_{mc} regression for each landfill. Similar to Approach 2.1, the Q_{ac} vs. Q_{mc} trendlines were forced to pass through the origin when adjusting k.

3.2.1.3. Approach 3: Simultaneously Variable L_0 and k

In this approach the first-order model equation (Equation 3) was expanded as shown in Equation 5, and collection efficiencies were applied. Equation 6 was solved for k and L_0 to minimize the residual (*r*) using a nonlinear regression algorithm. Q, M, and β from the landfills data and η values based on operation practices and values presented in Table 9 were provided, and a best-coupled solution for k and L_0 for each landfill was determined. Note that in Equation 5, the 1/10 of year increments from Equation 3 were not included because the actual LFG collection data were based on annual values and would not improve the final outcome.

$$Q_{mc} = \left(\eta_{11}\beta M_1 L_{0_1} e^{-k}\right) + \left(\eta_{12}\beta M_1 L_{0_1} e^{-2k} + \eta_{21}\beta M_2 L_{0_2} e^{-k}\right) + \cdots$$

$$\ldots + \left(\eta_{13}\beta M_1 L_{0_1} e^{-3k} + \eta_{22}\beta M_2 L_{0_2} e^{-2k} + \eta_{31}\beta M_3 L_{0_3} e^{-k}\right) + \cdots$$

$$\ldots + \left(\eta_{1n}\beta M_1 L_{0_1} e^{-nk} + \eta_{2(n-1)}\beta M_2 L_{0_2} e^{-(n-1)k} + \cdots + \eta_{n1}\beta M_n L_{0_n} e^{-k}\right) \qquad (5)$$

(terms defined in Equations 3 and 4)

$$Q_{mc} - Q_{ac} = r \qquad (6)$$

3.2.2. Data Analysis

The following measures of effectiveness were used to evaluate the modeling approaches:

- The slope of the Q_{ac} vs. Q_{mc} regression line showing the accuracy of each approach (over or underestimating LFG generation); a non-biased model would result in a regression line that passes through the origin with a slope of 1.0. An alternative statement is that the residuals (as defined in Equation 6) follow a normal distribution with zero mean.
- The Q_{ac} vs. Q_{mc} regression correlation coefficient (R^2); R^2 varies from 0 to 1.0 and ideally would be equal to 1.0. An R^2 greater than 0.80 was considered an indicator of a statistically significant approach.
- The analysis of residuals, calculated based on Equation 6 under each approach, and the standard error of residuals, calculated as the standard deviation of residuals over the square root of number of observations under each approach.

3.2.3. Case-Study Landfills

The selected case-study landfills were all located in central and northern Florida, where rainfall ranges 1000 to 2000 mm per year (Florida Climate, 2009), and had active LFG collection systems. Further details on each case study landfill are provided in the followings.

Landfill 1 was an active traditional landfill with a LFG collection system consisting of a network of vertical wells and horizontal trenches. Nine years of collected LFG records were available. Landfill 1 was operated in two phases. Phase 1 consisted of two closed cells from which the collected LFG was transferred to a nearby coal-fired power generating facility and Phase 2 was an active cell, partially closed, where the collected LFG was flared. An engineered intermediate cover overlain by a geomembrane was applied to closed areas of both phases. Total waste-in-place in Phase 1 was over 14 million tonnes and about 3.2 million tonnes of MSW was disposed in Phase 2 by 2008 (details provided in Appendix C, Table C6).

Landfill 2 was an open traditional landfill with an on-site LFGTE facility equipped with internal combustion engines. Vertical wells were installed in intermediately closed areas, where MSW had been placed more than five years ago. The landfill consisted of two approximately equal sized cells. The closed areas were covered with an engineered soil layer. Cell 1 received MSW from 1978 to 1994, while Cell 2 opened in 1995 and more than 50% of its area was closed at the time of this study. Eight years of collected LFG records were available. Annual MSW disposal tonnages from 1992 to 2008 were available; whereas, waste disposal tonnage records prior to 1992 were not available for Landfill 2. Therefore, 1978-1991 annual disposal tonnage values were estimated based on 1992 per capita MSW disposal rate and regional population, as well as annual population data for 1978-1991. The overall MSW disposed by the end of 2008 was about 6.9 million tonnes (details provided in Appendix C, Table C6).

Landfill 3 received MSW since 1972 until 1999 and consisted of two cells, one operated traditional and one operated with leachate recirculation. The traditional cell (Phase 1) opened in 1972 and was closed with a clay final cover in 1988. The wet cell (leachate injected by ponds and horizontal injection wells, Phase 2) opened in 1988 and was closed with a geomembrane cover system in 1999. An active LFG collection system with vertical wells was installed in Phase 1 in 1992 and a Phase 2 gas collection system was added in 2000. Collected LFG records starting from 2000 were available; however, separate records for each phase were not available. Gas collected from Phase 1 and Phase 2 was initially flared then used to generate electricity on-site from 2003 to late 2008. Annual waste disposal tonnage data were available from 1988 to 1999 (details provided in Appendix C, Table C6). Annual waste disposal tonnages for 1972-1988 were estimated based on total landfilled waste up to 1988 with consideration to the annual service population. Approximately 2.2 million tonnes of MSW has been disposed in the two cells, overall. Different k values were determined for each phase in Approaches 2.1, 2.2, and 3.

Landfill 4 was an active traditional landfill receiving a mix of MSW and construction and debris waste and with an on-site LFGTE facility. Vertical wells were installed as the disposal areas reached final elevation and horizontal trenches were used in active areas. Each closed area was covered with an engineered intermediate cover layer and a geomembrane had been applied to some closed areas. Thirteen years of collected LFG records were available. By 2009, about 14 million tonnes of waste had been disposed in Landfill 4 (details provided in Appendix C, Table C6).

Landfill 5 was an active landfill that was operated as a traditional landfill until early 2006, when leachate recirculation was initiated. However, it is unlikely that an effect on gas generation by leachate recirculation could be detected in the data set available. Therefore Landfill 5 was treated as a traditional landfill. Landfill 5 had a network of vertical gas collection wells. Closed areas were covered with an engineered intermediate cover layer, and a geomembrane had been applied to almost 33% of the surface of the cell at the time of this study. Eleven years of collected LFG records were available. Total MSW-in-place by 2008 was approximately 8.6 million tonnes (details provided in Appendix C, Table C6).

3.2.4. Model Uncertainties

An uncertainty range was estimated for Q_{mg}, using recommended modeling approach parameters for case-study landfills. A Monte Carlo computational method was used to determine uncertainties of output values at each year, t, by generating numerous scenarios using randomly selected values from a specified range and probability distribution for input parameters, i.e. L_0 and k. Due to a lack of information regarding future collection efficiencies, uncertainty in Q_{mc} was not estimated.

For each case study, a range for the methane generation rate constant, k, was determined. The parameter k was adjusted to minimum and maximum values so that when applying those values to Equations 3 and 4, actual data points fell within the modeled LFG range of values. Parameter k was assumed to have a triangular distribution around the likeliest value and in the minimum and maximum range. The range and distribution for L_0 for input into the uncertainty estimation were calculated using the Monte Carlo method by assuming a uniform distribution of each waste component value with a ±30% range. The applied component ranges resulted in annual waste compositions with overall degradable material varying from 20% to 80%. A mean value and distribution range for L_0 was calculated for each waste composition data set (95% confidence level). The Monte Carlo analysis was executed using a Pentium 4 Dell PC with a 3.0 GHz CPU and 2.0 GHz RAM. By applying probability distribution ranges to input parameters in the model (Equation 3), a range of possible values was generated annually for Q_{mg}. The Coefficient of Variation (CV, the ratio of standard deviation over the absolute value of the mean), representing the uncertainty range for Q_{mg}, was calculated for each data set.

3.3. Results and Discussion

3.3.1. Calculated Parameters and Model Evaluation

The L_0 and k values for all approaches are summarized in Table 11 and Q_{ac} vs Q_{mc} values for each approach are presented in Table 12. Graphical fits and values of measures of effectiveness are presented in Table 13 and Figures 1 and 2. In Approach 1, the US EPA default values were used for k and L_0. The calculated L_0 values in Approach 2.1 were lower than the US EPA default value for all case-study landfills (average L_0=67 m^3Mg^{-1}, standard deviation = 6.8). The k values in Approach 2.1 for the traditional landfills were generally higher than US EPA default values. Approach 2.2 also had lower L_0 values compared to US EPA default values. Approach 3 did not result in a solution (coupled k and L_0 value) for Landfill 1-Phase 2 due to an insufficient number of data points. Also, the results for Landfill 5 under Approach 3 were unreasonable compared to values reported in the literature.

Table 11. Summarized k and L_0 values for each approach

		Landfill 1 Phase 1	Landfill 1 Phase 2	Landfill 2	Landfill 3 Phase 1	Landfill 3 Phase 2	Landfill 4	Landfill 5
	No. of data points (years)	9	3	8	9		13	11
Approach 1	L_0, m^3Mg^{-1}	100	100	100	100		100	100
	k, yr^{-1}	0.04	0.04	0.04	0.04	0.15	0.04	0.04
Approach 2.1	L_0, m^3Mg^{-1}	62	56	77	70		63	61
	k, yr^{-1}	0.08	0.04	0.08	0.04	0.10	0.13	0.13
Approach 2.2	L_0, m^3Mg^{-1}	93	93	93	93		93	93
	k, yr^{-1}	0.04	0.02	0.08	0.04	0.14	0.04	0.05
Approach 3	L_0, m^3Mg^{-1}	68	No results; insufficient number of data points	175	153		69	3844
	k, yr^{-1}	0.07		0.24	0.10	0.31	0.09	0.001

Table 12. Q_{ac} vs. Q_{mc} values from each approach

Landfill	Q_{ac}, m^3yr^{-1}	Q_{mc}, m^3yr^{-1}			
		Approach 1	Approach 2.1	Approach 2.2	Approach 3
Landfill 1 – Phase 1	55,244,966	51,535,157	51,670,558	46,350,523	52,272,668
	50,845,262	54,368,386	53,772,487	48,933,385	54,568,047
	56,409,072	57,058,042	55,459,735	51,391,092	56,659,146
	68,373,041	60,300,251	57,241,541	54,341,588	59,418,172
	61,169,602	64,000,986	59,513,299	57,702,231	62,707,546
	54,516,735	61,491,471	54,937,699	55,550,685	58,228,900
	40,967,907	59,080,356	50,713,888	53,479,363	54,070,124
	39,290,509	56,763,782	46,814,819	51,485,275	50,208,372
	44,305,436	57,556,448	43,229,036	52,308,743	49,202,748
Landfill 1 – Phase 2	3,629,882	11,584,555	6,308,658	6,324,276	N.A.
	7,392,060	16,798,238	9,084,353	9,247,941	N.A.
	14,072,389	20,065,551	10,826,657	11,162,397	N.A.
Landfill 2	20,273,439	12,466,454	12,054,805	14,550,093	17,030,376
	20,707,565	13,070,980	12,612,607	15,067,979	17,295,420
	20,613,768	13,650,248	13,045,211	15,542,232	17,498,801
	26,085,070	14,244,569	13,330,305	16,036,630	17,792,884
	26,571,499	14,809,635	13,928,669	16,482,523	18,003,572
	18,616,655	15,348,942	14,515,147	16,887,377	18,156,862
	19,160,664	16,030,209	15,057,743	17,510,129	18,855,506
	18,530,358	16,682,139	15,374,042	18,079,255	19,396,828
Landfill 3	17,155,971	12,993,075	9,202,877	13,055,968	19,224,608
	13,244,657	10,141,126	8,387,305	11,536,316	14,684,964
	10,280,261	8,008,133	7,648,268	10,208,019	11,290,166
	8,033,537	6,408,548	6,978,380	9,046,278	8,743,977
	6,102,210	5,204,883	6,370,977	8,029,539	6,827,540
	5,108,154	4,295,254	5,820,045	7,139,068	5,379,098
	5,164,177	3,604,156	5,320,159	6,358,579	4,279,032
	3,463,662	3,075,626	4,866,420	5,673,915	3,438,832
	2,228,569	2,668,176	4,454,411	5,072,768	2,792,952
Landfill 4	3,398,471	5,600,029	6,654,657	5,418,710	6,488,483
	3,313,509	5,586,097	6,679,290	5,401,191	6,361,415
	5,409,233	5,566,295	6,710,068	5,378,094	6,233,831
	13,877,089	5,281,589	6,334,977	5,099,051	5,811,834
	13,254,036	5,295,186	6,534,694	5,109,040	5,752,456
	13,877,089	5,102,018	6,160,847	4,919,690	5,474,772
	13,423,959	5,158,949	6,081,611	4,972,333	5,491,317
	12,659,303	5,026,569	5,758,282	4,842,429	5,303,993
	7,890,116	11,393,062	12,479,874	10,975,281	12,031,893
	27,315,208	28,873,492	29,851,444	27,810,455	30,451,231
	32,996,318	30,238,282	29,666,643	29,113,376	31,659,005
	31,750,212	36,100,875	34,159,630	34,817,893	39,754,032
	33,395,639	39,149,184	34,991,064	37,759,990	43,234,668
Landfill 5	16,179,836	16,094,572	20,889,619	13,869,553	13,594,946
	17,375,437	15,463,495	18,379,802	13,790,722	13,585,524
	16,263,127	14,857,163	16,171,531	13,712,338	13,576,108
	14,440,187	14,274,605	14,228,576	13,634,400	13,566,699
	14,430,473	17,698,838	19,881,581	16,665,968	16,558,683
	15,939,479	17,004,857	17,492,877	16,571,242	16,547,208
	16,755,735	16,338,087	15,391,167	16,477,055	16,535,739
	16,234,353	15,697,461	13,541,970	16,383,403	16,524,279
	17,166,072	15,836,053	12,510,695	17,104,797	17,338,469
	17,876,749	15,215,112	11,007,578	17,007,577	17,326,452
	15,504,390	14,618,519	9,685,054	16,910,910	17,314,444

N.A.: Not Available

Table 13. Summarized k and L_0 values for each approach

	Q_{ac} vs. Q_{mc} graph		Analysis of residuals		
	R^2	Slope	Mean	St. Dev.	Standard Error
Approach 1	0.89	1.1	$0.4x10^6$	$6.3x10^6$	$8.6x10^5$
Approach 2.1	0.91	1.0	$1.9x10^6$	$5.0x10^6$	$6.8x10^5$
Approach 2.2	0.90	1.0	$1.3x10^6$	$5.2x10^6$	$7.1x10^5$
Approach 3	0.93	1.0	$0.2x10^6$	$4.8x10^6$	$6.8x10^5$

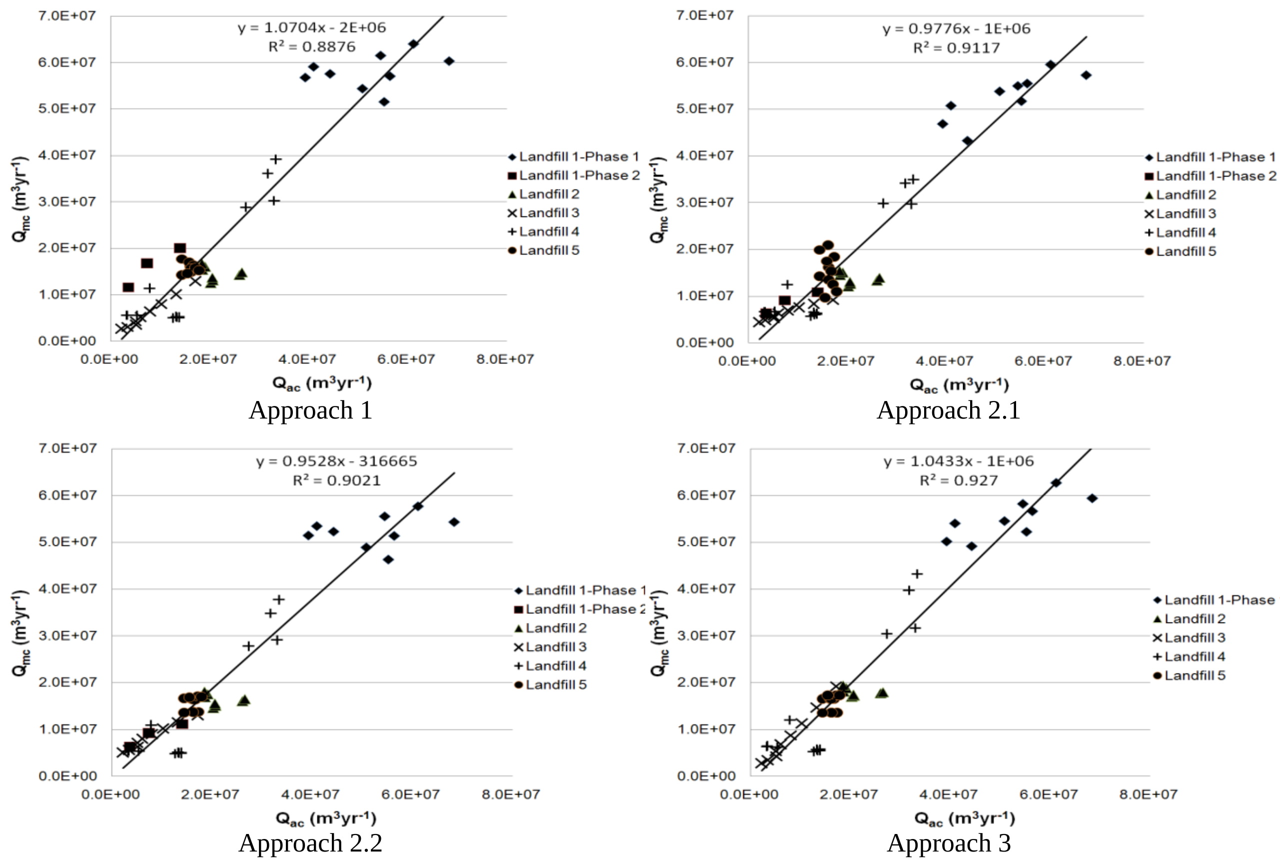

Figure 1. Statistical analysis for each Approach

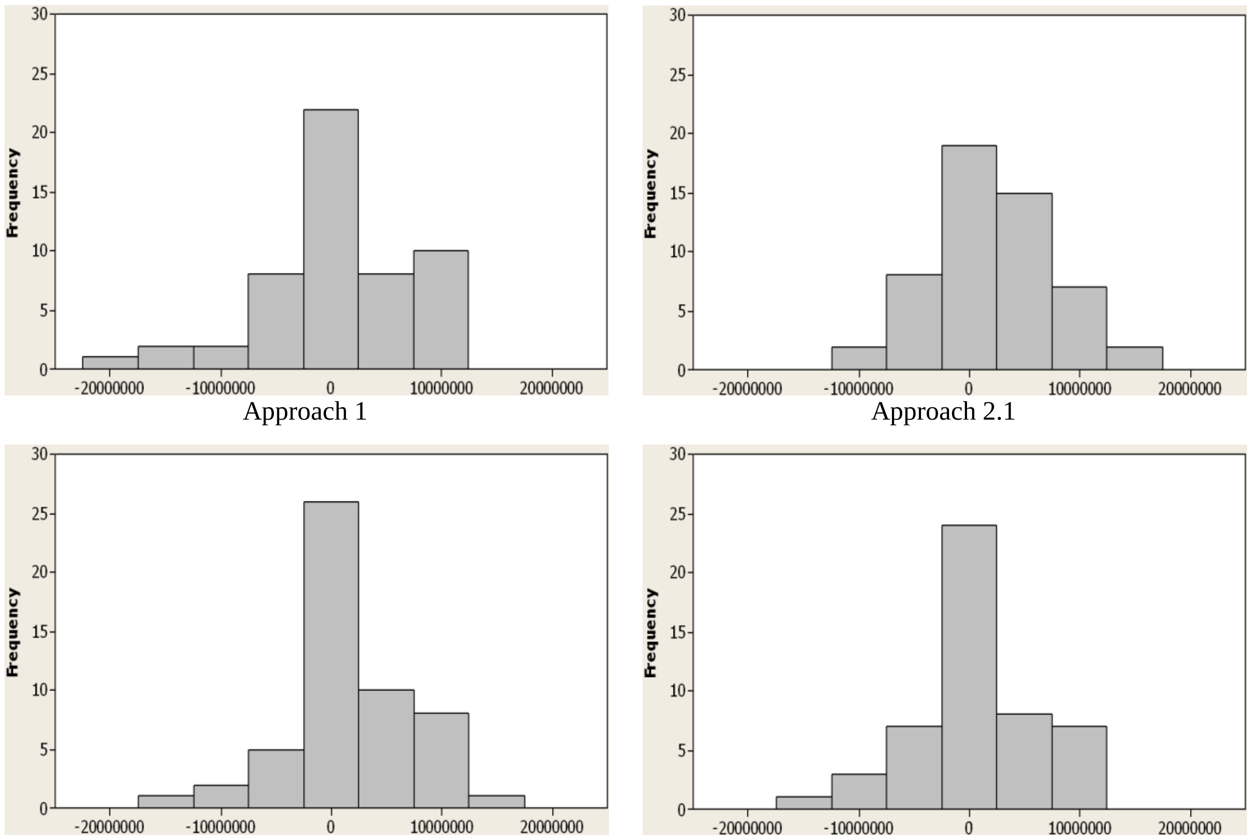

Figure 2. Frequency distribution, %, of residuals results for each approach (each group range $\pm 2.5x10^6$)

Figure 1 show that plotted Q_{ac} vs. Q_{mc} points are normally distributed about a line with slope of 1.0 under all approaches. There was large variability among the $Q_{ac}:Q_{mc}$ ratios determined in each approach, presumably due to the uncertainties associated with LFG generation model input data. The median, mean, and standard deviation of all $Q_{ac}:Q_{mc}$ ratios are summarized in Table 14.

Table 14. Mean and median of all $Q_{ac}:Q_{mc}$ ratios

	Median	Mean	St. Dev.	CV, %
Approach 1	1.0	1.1	0.6	55
Approach 2.1	1.0	1.2	0.5	42
Approach 2.1	1.0	1.2	0.6	50
Approach 3	1.0	1.1	0.5	45

Figure 3 provides frequency histograms for Q_{ac}:Q_{mc} ratios for all data within each approach. The median range of the Q_{ac}:Q_{mc} ratios was around 1.0 ± 0.125, accounting for 34% to 50% of the data. Q_{ac}:Q_{mc} ratios of 1.0 occurred most frequently in Approach 3, accounting for 50% of the data; however, one case-study did not yield solutions under Approach 3. The Q_{ac}:Q_{mc} ratios, trendline intercepts (Figure 1), and the frequency of Q_{ac}:Q_{mc} ratios greater than 1.0 (Figure 3) suggested that the model was underestimating LFG generation for all approaches. Model underestimation was generally in agreement with other research findings (Thompson et al., 2009; Ogor and Guerbois, 2005). The inaccuracy may have been caused by incorrect estimation of collection efficiencies, applying a mathematical model and laboratory measured L_0 values to real-world cases, unaccounted for changes in landfilling operation procedures over time, seasonal climatic changes, and inaccuracy in waste composition and collected LFG flow rates.

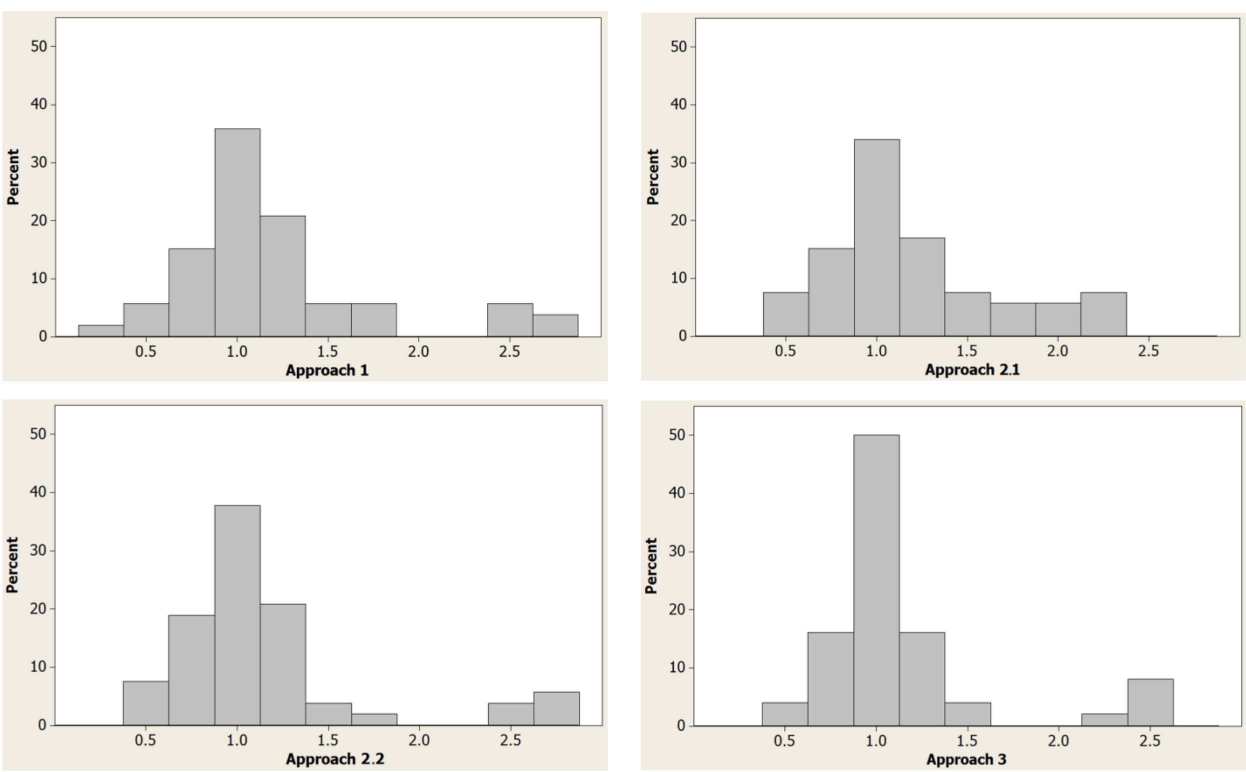

Figure 3. Frequency distribution, %, of Q_{ac}:Q_{mc} ratio results for each approach (each group range ±0.125)

3.3.2. Recommended k and L_0 Calculation Approach and Values

The evaluated approaches showed to be fairly similar based on measures of effectiveness. However, Approach 1 resulted in the lowest R^2 and highest standard error of residuals; Approach 2.2 had a high R^2, but it would only be applicable to landfills with conditions similar to Landfill 3. Approach 3 yielded solutions for only five case studies, which in some cases resulted in unreasonable k and L_0 values. Approach 2.1 resulted in lower standard error of residuals than Approaches 1 and 2.2 (Table 12). Furthermore, Approach 2.1 is the only approach that allows calculation of one of two main modeling parameters (L_0) based on site-specific landfill characteristics. Therefore, calculating L_0 from waste composition and adjusting k for best slope of the Q_{ac} vs. Q_{mc} plot is recommended as the best modeling approach. For Approach 2.1, the average $Q_{ac}:Q_{mc}$ ratio was 1.2 (std. dev. of 0.5), which was considerably improved over many of the other estimations of LFG flow rates reported in the literature (Table 8).

Approach 2.1 is particularly advantageous when modeling LFG generation in landfills where composition differs significantly from the US average and as well as those in regions where LFG generation data are not available. The average model parameters from Approach 2.1 were L_0=67 m^3Mg^{-1}, k=0.08 yr^{-1} for traditional landfills, and L_0=70 m^3Mg^{-1}, k = 0.10 yr^{-1} for the wet cell (Table 10). The LFG generation and collection modeling outcomes for Approach 2.1 are presented in Figure 4 along with actual collected LFG. Note that while L_0 can be calculated for any landfill with known waste composition, the k values determined may be applicable only to landfills with similar conditions to the case-study landfills.

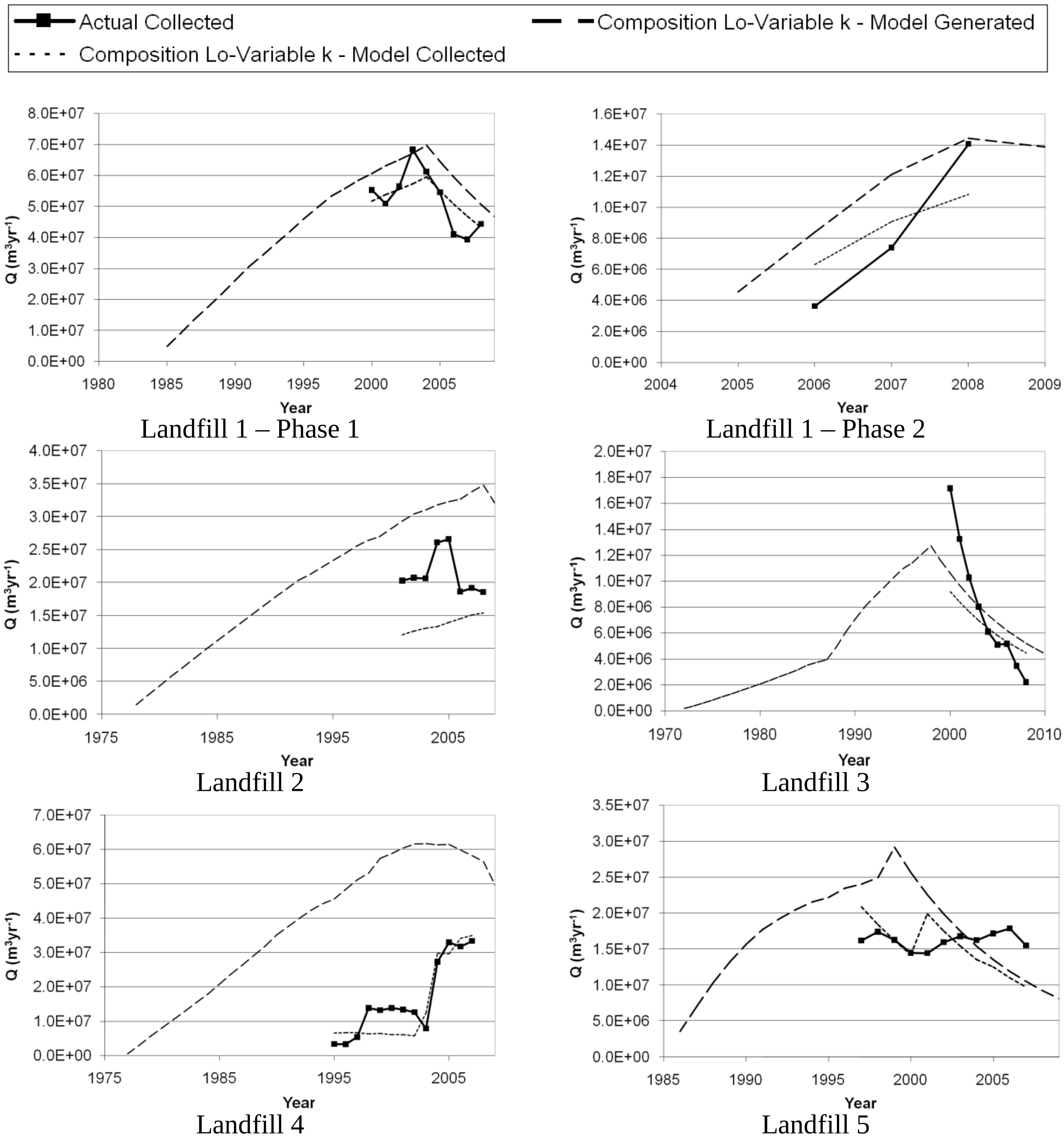

Figure 4. Q_{mg}, Q_{mc}, and Q_{ac} results for Approach 2, Composition Calculated L_0-Variable k

The methane generation rate constant for the wet cell and traditional case studies were similar, perhaps because all landfills were located in Florida which has relatively high annual precipitation rates. Since none of the traditional landfills were fully covered with impermeable material, high precipitation rates may have increased waste moisture content. Additionally, leachate recirculation at Landfill 3 (wet cell) was initially accomplished with ponds which have limited wetting ability, therefore the Landfill 3 recirculation cell may have been only partially wet. Overall, the average k value for traditional landfills was in agreement with values applied to model LFG generation in areas with tropical climates (Machado et al., 2009; US EPA LMOP, 2009).

3.3.3. Estimating Uncertainty in LFG Generation Modeling

The range in Q_{mg} from initial waste placement to 50 years after closure was estimated. Estimates were made considering waste disposed through 2008 for active landfills. L_0 had a normal distribution with the mean values and applied ranges as presented in Table 15. Parameter k was assumed to have a triangular distribution over this range, with the most likely value being the k value presented under Approach 2.1 in Table 9 for each landfill. Figure 5 illustrates the capture of actual data by assumed k minimum and maximum values (Table 15). Minimum/maximum k values could not be determined for Landfill 2; varying k did not capture all data points due to the poor model fit, perhaps as a result of inaccuracy in input data, including waste composition, disposal rate, and landfilling operations. Therefore, the uncertainty in modeling LFG generation for Landfill 2 could not be determined.

Results from the Monte Carlo analysis are presented in Figure 6 showing mean Q_{mg} and 95% confidence bands about the mean, Q_{lower} and Q_{upper}, using k and L_0 values from Table 15. The range of Q_{mg} declined as the landfills were filled and until a few years after the end of waste placement, thereafter the differences in maximum and minimum values increased over time.

Q_{lower} before the peak LFG generation and Q_{upper} after the peak were controlled by minimum k values; likewise, Q_{upper} before the peak and Q_{lower} after the peak were controlled by maximum k values. For each landfill, the annual CVs were calculated as standard deviation over mean value of Q_{mg} (Table 16). The CVs varied from 11% to 17% in the early active years and, in general, declined to their lowest values within five years after waste placement ended. In other words, the uncertainty in estimating LFG generation was lowest around the time of maximum generation.

Table 15. L_0 and k distributions used in uncertainty analysis

Landfill	L_0, m^3Mg^{-1}			k, yr^{-1}		
	Mean	Minimum	Maximum	Likeliest	Minimum	Maximum
Landfill 1-Phase 1	62	57	68	0.08	0.05	0.13
Landfill 1-Phase 2	56	50	59	0.04	0.02	0.05
Landfill 2	77	74	80	0.08	N.A.	N.A.
Landfill 3-Phase 1	70	64	76	0.04	0.01	0.05
Landfill 3-Phase 2				0.10	0.01	0.11
Landfill 4	63	57	68	0.13	0.04	0.25
Landfill 5	61	58	64	0.13	0.06	0.13

N.A.: Not Available

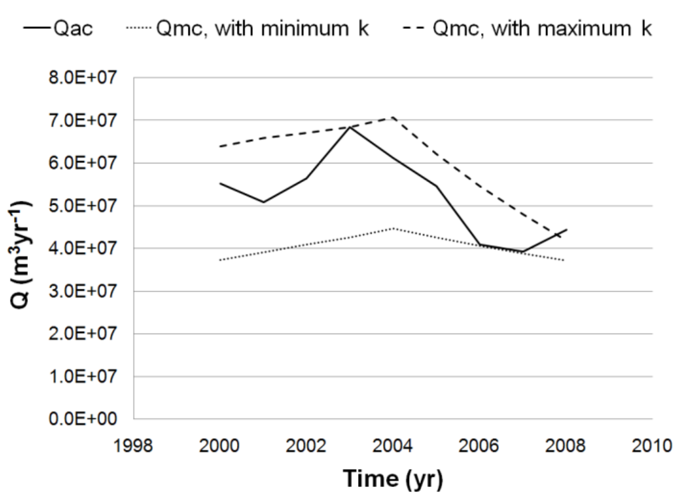

Figure 5. Landfill 1 Q_{ac} and Q_{mc} (calculated with minimum and maximum k values)

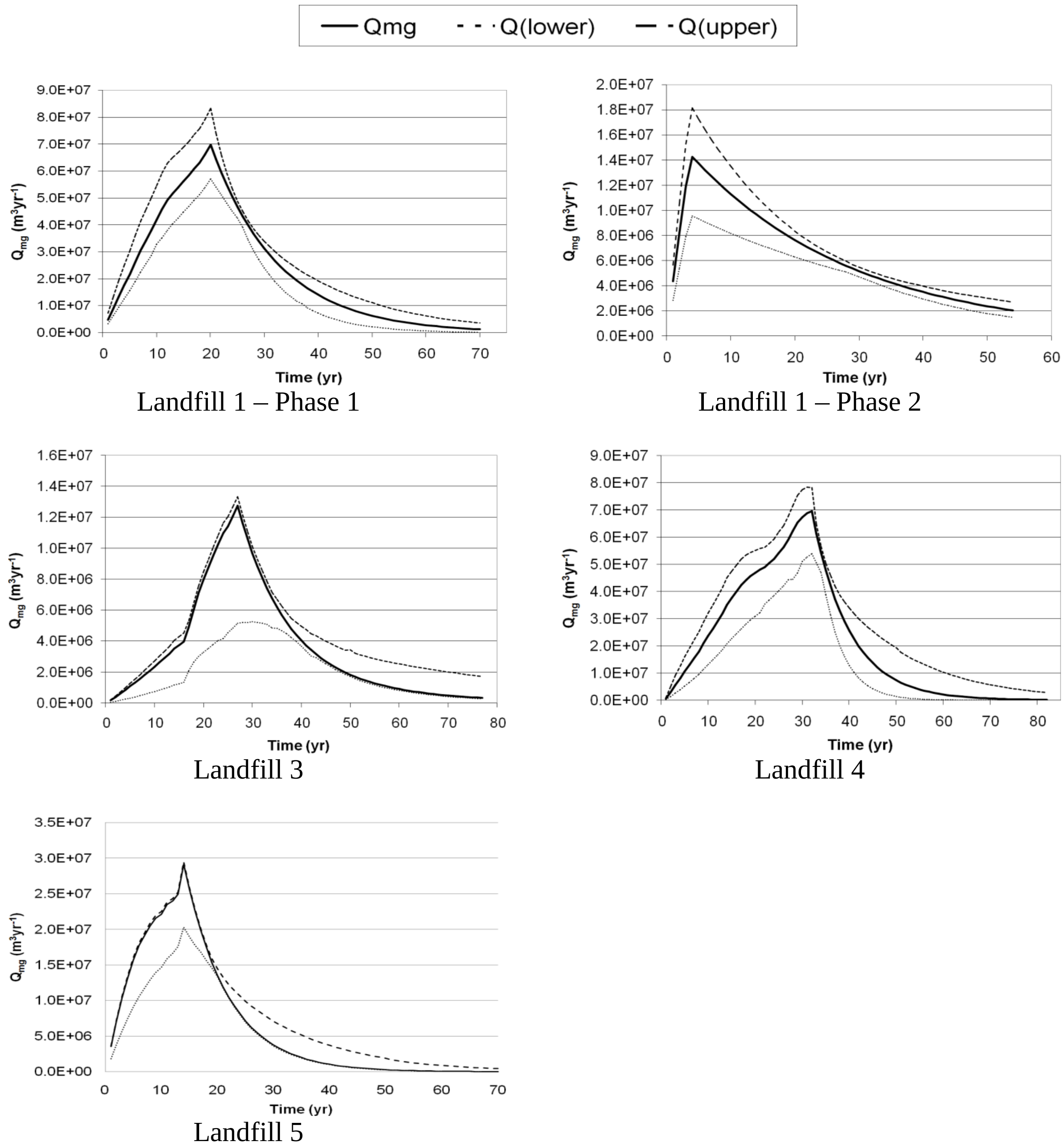

Figure 6. Q_{mg} results showing 95% confidence bands, Q_{lower} and Q_{upper}

Table 16. Coefficient of Variation of Q_{mg}

Landfill	Coefficient of Variation, %						
	5 years before	At closure	10 years after	20 years after	30 years after	40 years after	50 years after
Landfill 1-Phase 1	11	9	9	24	40	56	72
Landfill 1-Phase 2	17	16	10	5	5	10	16
Landfill 3	18	18	6	13	24	33	41
Landfill 4	11	10	34	74	116	159	203
Landfill 5	11	9	9	28	48	70	91

3.3.4. Life-to-Date LFG Collection

The life-to-date LFG collection (estimated by dividing the cumulative actual LFG collected by the estimated LFG generation since initial waste placement) for the case-studies varied from 19 to 65% (Table 17). Low LFG collection could be attributed to the delay in installation of collection systems practiced by landfill operators. For instance, calculations show that for k=0.08 yr^{-1}, approximately 30% of methane generation occurs within five years of waste placement (Barlaz et al., 2009). The short-term use of horizontal trenches (at Landfills 1 and 4) did not appear to impact life-to-date LFG collection significantly. The life-to-date LFG collection is expected to increase over time as the landfill cells are closed and more efficiently collect LFG.

Table 17. Life-to-date LFG collection

Landfill	Life-to-date collection, % of LFG generated to date (with lower and upper limits)
Landfill 1-Phase 1	45 (37-56)
Landfill 1-Phase 2	65 (51-97)
Landfill 2	27 (limits not determined)
Landfill 3	33 (31-70)
Landfill 4	19 (16-28)
Landfill 5	46 (45-63)

CHAPTER FOUR – REGIONAL PREDICTION OF LANDFILL GAS TO ENERGY POTENTIAL

4.1. Background

Being relatively inexpensive and easy-to-acquire, fossil fuels have become the main global energy supply, consumed at a rate of over 85 million barrels of oil each day (US DOE, 2010a). However, the limited global petroleum resources, as well as the social and environmental effects of fossil fuel consumption, have encouraged nations to invest in other energy strategies. In recent decades, renewable energy resources, including wind, hydro, solar, geothermal, and tidal, have gained attention due to their sustainable nature.

Quantifying LFG to energy (LFGTE) potential is a challenge due to the uncertainties involved in modeling LFG generation, especially on a large geographical scale. Accurately estimating potential energy production from resources is necessary when setting energy production portfolio standards. Furthermore, the ability to predict potential energy production under various operating practices is necessary for project developers. Knowledge of the uncertainty incorporated in such predictions could assist policy makers and investors in making informed decisions. In this chapter a methodology is presented to estimate LFGTE potential on a regional scale over a 25-year timeframe with quantifications of modeling uncertainties. The methodology was demonstrated for the US state of Florida.

The state of Florida is more populous than most US states and European countries, and was ranked the third highest energy consuming US state in 2009 (US DOE, 2010b). State-wide

LFGTE production potential was estimated by analyzing LFG generation, collection, and utilization potential for each of 67 Florida counties. Furthermore, the effect of changes in MSW and LFGTE management and operation policies was evaluated, including separate collection and treatment of food waste, increased waste recycling ratios, and enhanced LFG collection and energy production procedures. It should be noted that the focus of this study was on energy estimation, and not on fugitive emissions or the economics of LFGTE projects.

Florida has an estimated population of 19 million, ranking as the fourth most populated state in the US in 2010. High residential and tourist populations in Florida translate into large quantities of MSW generation; therefore, managing MSW in an environmentally safe manner is a high priority. With 225 billion kWh of electricity consumption in 2005 and an annual energy consumption growth rate of 0.8% (US DOE, 2010c), Florida's electricity demand over the 2010-2035 timeframe is estimated to be about 6.8 trillion kWh. Having limited energy resources, it is essential to consider all possible fuel sources, including LFG.

In 2007, 60% of Florida's generated MSW (mass based) was disposed in 64 active Florida Class I landfills (disposing only MSW), with 29% and 11% recycled and treated at waste-to-energy (WTE) facilities, respectively (FDEP, 2010a). Approximately 40% of the landfilled MSW was disposed in the 16 landfills which operated/supported LFGTE facilities, with an estimated LFG to energy flow of 0.24 billion m^3yr^{-1} (US EPA LMOP, 2011).

Although the number of US with horizontal trenches installed for earlier LFG collection has increased in recent years, installation of vertical wells in temporarily or finally closed areas remains the more common practice to date. However, installation of horizontal trenches is particularly relevant for bioreactor landfills (operated to optimize moisture content), due to LFG collection regulations. Current US regulations require LFG collection within five years of initial waste placement or two years after closure for traditional landfills (defined as sanitary landfills operating per US EPA Subtitle D and CAA regulation, with no liquid or air injection) emitting more than 50 Mg per year of non-methane organic gaseous compounds (US EPA, 1996). For bioreactor landfills a gas collection system must be in place prior to initiation of liquids addition, and gas collection must begin 180 days after commencement of liquids addition or when the waste reaches 40% moisture content by weight, whichever is later (US EPA, 2004).

4.2. Methodology

4.2.1. Energy Estimation

To estimate the Florida LFGTE potential, an assumption was made that landfilled MSW from all Florida counties would contribute to energy production. Annual LFG generation rates for each county were modeled using a modified model, generally based on the standard LandGEM equation, with modifications to make it apply to energy production. Methane generation rate constants were previously determined for traditional landfilling from Florida case studies. However, the case-study k values were based on field LFG collection data, representing moderately and slowly degrading MSW and excluding rapidly degrading MSW components, such as food waste. To more accurately model LFG generation over the entire gas-generating period, k values were applied to two waste streams, (1) moderately and slowly degrading material, and (2) food waste, using Equation 7.

$$Q_g = \sum_{i=1}^{n}\sum_{j=0.1}^{1}\beta k_1 \left(\frac{M_{i_1}}{10}\right) L_{0_1} e^{-k_1 t_{zj}} + \sum_{i=1}^{n}\sum_{j=0.1}^{1}\beta k_2 \left(\frac{M_{i_2}}{10}\right) L_{0_2} e^{-k_2 t_{zj}} \qquad (7)$$

where:

Q_g	=	Annual generated LFG, m^3yr^{-1}
k_1 and k_2	=	Methane generation rate constant for waste streams 1 and 2, yr^{-1}
M_{i_1} and M_{i_2}	=	Tonnage of waste disposed in year i for waste streams 1 and 2, Mg
$L_{0_{i_1}}$ and $L_{0_{i_2}}$	=	Methane generation potential of waste disposed in year i for waste streams 1 and 2, m^3Mg^{-1}
i	=	Time period of waste disposal, yr
j	=	1/10 time increments, yr
n	=	Summation period of waste disposal, yr
z	=	Time period of LFG generation from waste disposed in year i, yr
β	=	Inverse ratio of fraction of methane content
t_{zj}	=	Age of j^{th} section of waste M_i in year z, yr

The rate constant of the first waste stream was calculated to be 0.08 yr^{-1} for traditional operation of Florida landfills in Chapter Three and was set at 0.11 yr^{-1} (Tolaymat et al., 2008) for bioreactor landfilling, as there was only one bioreactor landfill in the Florida case-studies in Chapter Three. A methane generation rate constant of k_2=0.35 yr^{-1} was assumed based on a two-year half-life for rapidly degrading MSW under Florida's climate conditions (Machado et al., 2009); which is also comparable to the recommendations of the Intergovernmental Panel on Climate Change (IPCC) guidelines (IPCC, 2006). Due to natural high moisture content, the methane generation rate constant for the food waste stream would not be impacted by increased moisture content under bioreactor landfilling, therefore, $k_2=0.35\ yr^{-1}$ was used for both traditional and bioreactor operating conditions. Methane generation potential, L_0, was calculated for every county based on waste composition, using waste component specific methane yields derived from laboratory measurements (Staley and Barlaz, 2009). Calculated L_0 values for the Florida counties varied from 20 to 78 m^3Mg^{-1} for Stream 1 and were 300 m^3Mg^{-1} for Stream 2 (Staley and Barlaz, 2009).

The uncertainty associated with the first-order LFG generation model was quantified using the Monte Carlo computational method as presented in Chapter Three. Coefficients of Variations (CV) were calculated for annual LFG generation rates values for the five case-study landfills, representing the uncertainty in Equation 7. Calculated CV upper and lower bounds were applied to each Florida county, to incorporate model uncertainty. CV values are presented in Table 18 to show the trend of the model uncertainty over time.

Table 18. First-order LFG generation model coefficient of variation (example years)

Time	CV, %	Time	CV, %
Year of disposal	±18	25 years after disposal	±95
5 years after disposal	±27	30 years after disposal	±116
10 years after disposal	±34	40 years after disposal	±159
15 years after disposal	±58	50 years after disposal	±203
20 years after disposal	±74		

Annual electrical energy production values were calculated by applying gas collection efficiency, LFG utilization ratio, and electrical efficiency values to LFG generation estimates, using

Equations 8 and 9. LFG collection efficiency depends on the type and installation time of the gas collection system and intermediate and final covers (SCS Engineers, 2008; SWANA, 2007; Spokas et al., 2006). For instance, to improve LFG collection efficiency, horizontal gas extraction pipes, trenches, or blankets could be installed as waste is being placed. Complete utilization of collected LFG is difficult to achieve because of equipment limitations and maintenance downtimes, captured as the capacity factor and defined as the ratio of actual energy output to output of energy if operated at 100% capacity. The LFGTE potential is further reduced due to inefficiencies in energy production systems. With current technologies the electrical efficiency of internal combustion (IC) engines, steam turbines, and gas turbines are in the range of 0.31-0.39, 0.10-0.37, and 0.22-0.37, respectively (US EPA, 2002). In this study LFG collection efficiency, capacity factor, and electrical efficiency were varied to evaluate the effect of changes in operating procedures and future improved technologies on LFGTE production estimates.

$$Q_c = \sum_{i=1}^{n} \sum_{j=0.1}^{1} \eta_{iz} \beta k_1 \left(\frac{M_{i_1}}{10}\right) L_{0_1} e^{-k_1 t_{zj}} + \sum_{i=1}^{n} \sum_{j=0.1}^{1} \eta_{iz} \beta k_2 \left(\frac{M_{i_2}}{10}\right) L_{0_2} e^{-k_2 t_{zj}} \quad (8)$$

$$E_p = \varepsilon \varphi_1 \varphi_2 Q_c \quad (9)$$

where:

Q_c = Annual collected LFG, m^3yr^{-1}

E_p = Annual energy production, $kWhyr^{-1}$

η_{iz} = Collection efficiency in year z from waste disposed in year i, fraction ε = LFG energy potential, estimated 5.2 $kWhm^{-3}$, based on CH_4 combustion heat value (Theodore and Reynolds, 1987) and average 50% CH_4 content

φ_1 = LFGTE capacity factor, fraction

φ_2 = Electrical efficiency, fraction

A base-case scenario (Scenario 1) was defined to estimate the LFGTE potential from MSW generated in Florida. Assumptions for the base-case scenario included:

- All MSW not recycled or disposed in WTE facilities at current capacity would be disposed in landfills within Florida,
- MSW compositions and recycle ratios would remain constant at 2007 values; also, the capacity of WTE facilities would remain constant at 2007 levels (3.4 million tonnes per year),
- All landfills would be operated as traditional landfills,
- LFG collection would start five years after disposal at 75% collection efficiency, the US EPA default value (US EPA AP-42, 1997; US EPA 2008a),
- Collected LFG would be utilized at an average ratio of 0.83, the estimated capacity factor of LFGTE projects (NREL, 2010), and
- Electricity would be generated using IC engines, the most commonly applied technology in the US, with an average efficiency of 0.35.

MSW generation compositions, component recycle ratios, and tonnage data of generated, landfilled, combusted, and recycled MSW for every Florida county from 1991-2007 were obtained from the Florida Department of Environmental Protection (FDEP) database (FDEP, 2010a). MSW tonnage disposed for each county was calculated for three time periods, as follows (additional information provided in Appendix E, Tables E1 and E2):

- 1991-2007: Using FDEP data (FDEP, 2010a),
- 2008-2009: Using 2007 per capita waste disposal data reduced by 5% per year as the effect of the economic recession on the waste disposal rate, and population was adjusted by 2.1% for annual growth of served population (average for 2000-2009; BEBR, 2009),
- 2010-2012: Tonnage was determined based on the 2009 values and (1) per capita generation was increased to 2007 rate assuming economic recovery, and (2) increased by 2.1% for annual growth of served population, and
- 2013-2035: Based on estimated 2012 per capita waste disposal rate and served population, considering an annual population growth rate of +2.1%.

Various scenarios were defined to analyze the effect of model parameters on the estimated LFGTE potential, as summarized in Table 19.

Table 19. Summary of assumptions for each scenario

Scenario	Overall recovery ratio in 2020[a]	First order model k_1 and k_2, yr^{-1}	Initiate LFG collection, years after closure	LFG collection efficiency, η			Capacity factor, φ_1	Electrical efficiency, φ_2
				Years 1-2	Years 3-5	Years 6-25		
Scenario 1. Base case	0.53	0.08[b], 0.35[c]	5	NA[e]	NA[e]	0.75[f]	0.83[h]	0.35[i]
Scenario 2. Food waste diversion	0.73	0.08, not applicable	5	NA[e]	NA[e]	0.75	0.83	0.35
Scenario 3. 65% waste diversion	0.84	0.08, 0.35	5	NA[e]	NA[e]	0.75	0.83	0.35
Scenario 4. 75% waste diversion	0.89	0.08, 0.35	5	NA[e]	NA[e]	0.75	0.83	0.35
Scenario 5. Accelerated gas collection	0.53	0.08, 0.35	2	NA[e]	0.75	0.75	0.83	0.35
Scenario 6. Bioreactor landfill operation	0.53	0.11[d], 0.35	2	NA[e]	0.75	0.95[g]	0.83	0.35
Scenario 7. Enhanced energy production	0.53	0.11, 0.35	2	NA[e]	0.75	0.95	1.00	0.45

[a] Recycling and energy recovery ratios; details presented in Section 4.2.2 and Table 20.
[b] Averaged for Florida case-study landfills, Table 11, Chapter Three.
[c] Calculated based on two year half-life of rapidly degrading waste in tropical climate (Machado et al., 2009).
[d] Tolaymat et al., 2008.
[e] Not applicable; no LFG collection.
[f,g] From Table 9, Chapter Three.
[h] Capacity factor of LFGTE (NREL, 2010).
[i] Electrical efficiency of internal combustion engines (US EPA, 2002).

4.2.2. Change in Waste Diversion Policies

Waste diversion from landfills, calculated using Equation 10, has become of increasing interest to policy makers and environmental activists in recent years, with the goal of reducing environmental impacts and energy consumption. Selecting MSW treatment approaches could be governed by economic incentives and/or regulations. For instance, according to the Florida Energy, Climate Change, and Economic Security Act of 2008 (House Bill 7135, also known as the Florida Energy Act), the statewide diversion ratio should reach 0.75 of generated MSW (weight based) by 2020 (FDEP, 2010b). However, the ability to use waste as a renewable resource can be assessed more accurately by including the contribution of LFGTE production to the recovery ratio. In this study, the overall recovery ratio was calculated using Equations 11 and 12, where LFGTE contributions were equal to the fraction of degradable MSW disposed in landfills with LFGTE to the overall generated MSW.

$$R_1 = R_{Recycle} + R_{WTE} \tag{10}$$

$$R_2 = R_1 + R_{LFGTE} \tag{11}$$

$$R_{LFGTE} = R_{LF} R_{EPLF} R_{DG} \tag{12}$$

where:

R_1	=	MSW diversion ratio (mass based)
R_2	=	Recovery ratio (mass based)
$R_{Recycle}$	=	Fraction of generated MSW that is recycled
R_{WTE}	=	Fraction of MSW treated in WTE facilities
R_{LFGTE}	=	Fraction of landfilled MSW contributing to the recovery ratio

R_{LF} = Fraction of generated MSW that is landfilled

R_{EPLF} = Fraction of landfilled MSW disposed in energy-producing landfills

R_{DG} = Fraction of MSW disposed in energy producing landfills that is degradable

One possible approach to reaching a higher diversion goal is to divert selected degradable components from landfills. Yard waste is already banned from disposal in Florida landfills (usually subsequently ground to produce mulch or compost). However, food waste has the highest L_0 and k of MSW components (Staley and Barlaz, 2009; De la Cruz and Barlaz, 2010), and likely decomposes before LFG collection is initiated. Therefore, diverting food waste from landfills could result in significant reductions in fugitive LFG emissions (Levis et al., 2010). Energy could also be recovered from the diverted food waste through anaerobic digestion. However, detailed economic analyses are required, incorporating costs for collection, transportation, and treatment, to evaluate project feasibility. The effect of diverting food waste on the statewide LFGTE potential was evaluated under Scenario 2.

Another approach to reaching a higher diversion goal is to increase recycling of all components. Two future diversion goals, 0.65 and 0.75, were studied under Scenarios 3 and 4. Each county would increase the overall recycle ratio from the current values to the goal value by 2020, assuming a linear increase; other conditions were the same as the base case. In Scenario 3 the diversion goal was set at 0.65, calculated using Equation 10. In this scenario, the average recycle ratios of degradable and non-degradable material were assumed to increase to 0.31 and 0.26, respectively, by 2020 (assuming a linear increase). To meet the 0.75 goal, average recycle ratios must reach 0.37 and 0.30 of degradable and non-degradable material, respectively, by 2020 as shown in Scenario 4. Note that in Scenarios 3 and 4 the values of L_0 and M_i are adjusted annually accounting for changes in MSW composition and reduced landfilling. Diversion and recovery ratios for each scenario are presented in Table 20.

Table 20. Florida waste diversion ratio in 2007 and proposed for 2020, fraction of generated MSW (mass based)

Scenario	Overall recovery ratio, including LFGTE	Overall diversion ratio, excluding LFGTE	Diversion ratio from recycling	Energy recovery	
				WTE	LFGTE
Scenario 1	0.53	0.40	0.29	0.11	0.13
Scenario 2	0.73	0.49	0.38[a]	0.11	0.24
Scenario 3	0.84	0.65	0.57	0.08	0.19
Scenario 4	0.89	0.75	0.67	0.08	0.14
Scenario 5	0.53	0.40	0.29	0.11	0.13
Scenario 6	0.53	0.40	0.29	0.11	0.13
Scenario 7	0.53	0.40	0.29	0.11	0.13

[a] Includes recycling of food waste.

4.2.3. Enhanced Operation Strategies

In Scenario 5 all conditions were the same as the base case, except that LFG collection was assumed to start two years after waste disposal. Earlier collection would require installation of horizontal collection trenches and could be enhanced by partial closure of slopes with impermeable liners. Because much of the LFG is generated in the early years after waste disposal, this strategy could significantly increase the overall LFG collection efficiency.

Several studies have shown that the US EPA default collection efficiency value of 75% is a conservative value, particularly after landfill closure, and recommend 90-99% collection efficiency for landfills with geomembrane cap layers (Table 9). Because US landfills are regulated to use geomembranes in the final cover, a more realistic post-closure LFG collection efficiency was assumed in Scenarios 6 and 7. In Scenario 6 it was assumed that all landfills are operated as bioreactor landfills, with accelerated LFG generation (Reinhart and Al-Yousfi, 1996). Therefore, LFG collection under Scenario 6 was assumed to start two years after placement with an efficiency of 75% for years 3-5 and 98% after closure.

With application of innovative and improved technologies in the operation systems, higher capacity factors and electrical efficiencies are anticipated within the model timeframe, which could include recovery of waste thermal energy from the IC engine (Cohen, 2010) or use of improved turbines (Batten, 2010). Scenario 7 quantified Florida LFGTE production rates for bioreactor operation with capacity factor and average electricity efficiency of 1.00 and 0.45, respectively.

4.3. Results and Discussion

4.3.1. Energy Production Potential

Figure 7 provides the predicted range for Florida annual LFG collection and potential LFGTE production rates under the base-case scenario (details provided in Appendix E, Table E3). If all Florida landfill operators collected LFG and operated LFGTE projects, 2010 statewide LFGTE potential would be in the range of 0.4-1.0 billion $kWh \cdot yr^{-1}$, approximately twice the current

Florida LFGTE facilities design capacity. Florida LFGTE production potential rate is projected to be between 0.8-2.6 billion $kWh \cdot yr^{-1}$ in 2035.

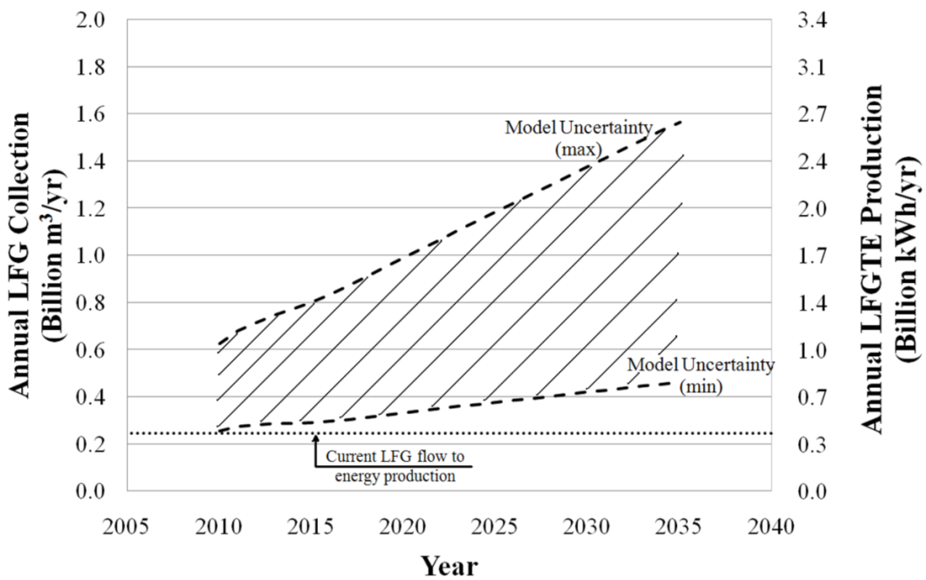

Figure 7. Florida annual LFG collection and LFGTE production potential, base-case scenario

Table 21 provides cumulative LFG collection and LFGTE potential under each scenario, also including model uncertainty ranges. Under the base-case conditions, the state of Florida could potentially produce 31 billion kWh from LFGTE projects over the 2010-2035 timeframe. This estimate is equivalent to an average annual energy production of 136 MW over the study timeframe, which is significant when compared to production levels from other renewable resources. For instance, about 3 MW of electricity were produced from photovoltaic (PV) energy projects in Florida in 2009 (Spear, 2010).

Table 21. Florida statewide LFG generation and collection, and LFGTE production for each scenario, 2010-2035

Scenario	Cumulative LFG generation, Billion m^3 (uncertainty range)	Overall LFG collection, % of generated (uncertainty range)	Cumulative LFGTE production, Billion kWh (uncertainty range)
Scenario 1. Base case	50 (32-68)	38 (29-42)	31 (15-47)
Scenario 2. Food waste diversion	41 (25-57)	43 (34-47)	30 (14-45)
Scenario 3. 65% waste diversion	39 (25-52)	37 (34-38)	24 (14-33)
Scenario 4. 75% waste diversion	31 (19-42)	41 (37-43)	21 (12-30)
Scenario 5. Accelerated gas collection	50 (32-68)	56 (51-58)	46 (27-65)
Scenario 6. Bioreactor landfill operation	54 (36-71)	65 (59-67)	57 (35-79)
Scenario 7. Enhanced energy production	54 (36-71)	65 (59-67)	82 (50-113)

The estimated LFGTE potentials are based on energy production from disposed MSW in all counties. However, significant renewable energy production potential exists even if LFGTE facilities are operated only at large landfills. As presented in Figure 8, 80% of the cumulative LFGTE potential could be provided from MSW generated in 19 of the most populated Florida counties; currently only nine of those counties have active LFGTE projects. Furthermore, over 95% of Florida LFGTE potential could be produced from MSW generated in 34 counties, all having populations over 100,000.

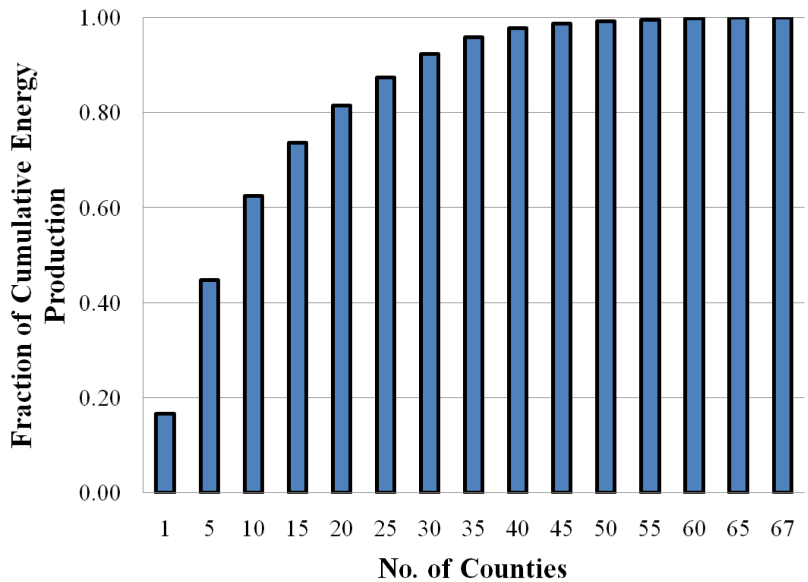

Figure 8. Fraction of cumulative LFGTE production by number of Florida counties, base-case

Power density, defined as the rate of flow of energy produced per unit horizontal land area (Smil, 2010), could be used to compare the energy potential of different resources based on equivalent land consumption. For instance, power densities of hydroelectric power plants and PV cells are similar, but hydroelectric power plants consume much greater land area (by factors of 10^6 to 10^8). The average power density for Florida LFGTE production under base-case conditions was estimated to be about 4.1 Wm^{-2} (based on average 17 tonnes MSW per m^2 land usage). LFGTE production under the base-case conditions has a higher power density than other renewable energy resources, including wind and ocean heat (Smil, 2010). Enhancing landfill operation and energy production practices (Scenario 7) could significantly increase the power density to as high as 10 Wm^{-2}, making LFGTE comparable to technologies such as geothermal, tidal, and hydro (Figure 9). The power density could be further increased by using the closed landfill site for other means of renewable energy production. For example, flexible membranes with PV cells have been installed as a pilot test at the Tessman Road Landfill, San Antonio, Texas, US, on 2.3

hectares of land to produce 182 MWh of solar electricity (Sampson, 2009), equivalent to an approximate power density of 1 Wm^{-2}.

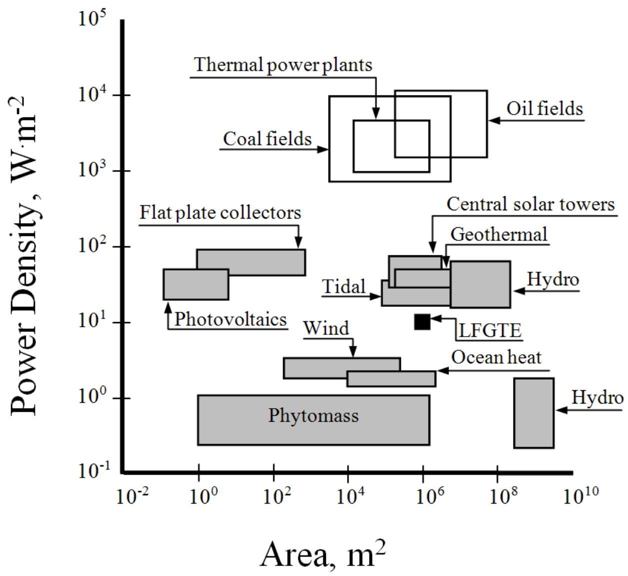

Figure 9. Power density of LFGTE compared to other energy resources (adapted from Smil, 2010)

4.3.2. Waste Diversion

Approaches to increase landfilling diversion ratios have been compared with the base-case practice in Figure 10. The relatively unchanged LFGTE potential under Scenario 2, compared to the base case, demonstrates that diverting food waste from landfills has minimal effect on the LFGTE potential, while reducing LFG generation by as much as 17%. Separate collection and beneficial treatment of the food waste, e.g. anaerobic digestion, could both divert waste from landfills and provide a source of renewable energy.

Reaching an increased diversion goal of 75% (Scenario 4) would be equivalent to an overall recovery ratio of 89% when LFGTE is included. Although the statewide LFGTE production would be reduced by 32% under Scenario 4, compared to the base case, the high waste diversion ratio and reduction in LFG generation could be a major motivation, for policy makers.

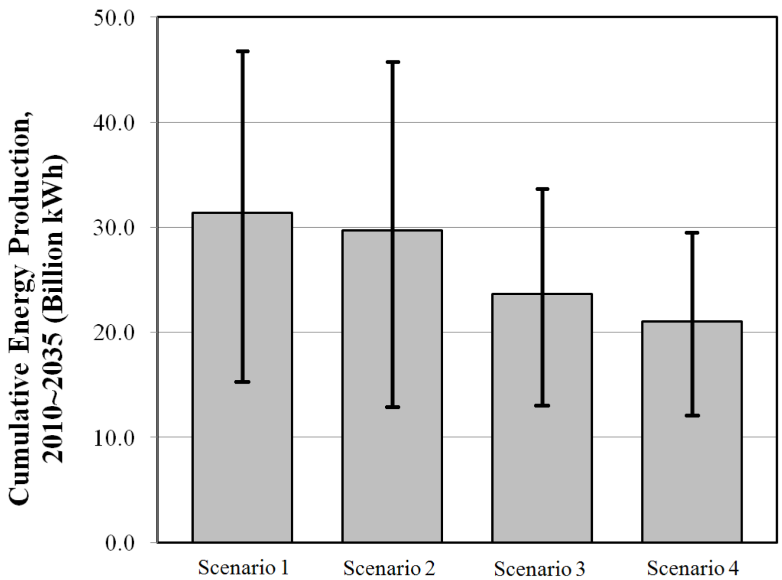

Figure 10. Waste diversion policies, with uncertainty range bar for each scenario (Scenario 1: Base case, Scenario 2: Food waste diversion, Scenario 3: 65% waste diversion, Scenario 4: 75% waste diversion)

4.3.3. Operation Enhancement

Earlier startup of LFG collection, as in Scenario 5, increased cumulative LFGTE potential by 48% compared to the base case (Figure 11), suggesting a significant amount of uncollected LFG exists soon after waste disposal. Operating Florida landfills as bioreactor landfills (Scenario 6) would increase cumulative energy production by 83% compared to the base case (Figure 11), due to accelerated LFG generation, as well as earlier and more efficient collection of LFG.

Applying enhanced operation strategies (Scenario 7) could increase the LFGTE production potential by a factor of 2.6 compared to the base case. With enhanced operation, LFGTE projects could provide approximately 1.2% of the statewide electricity demand over the 2010-2035 period.

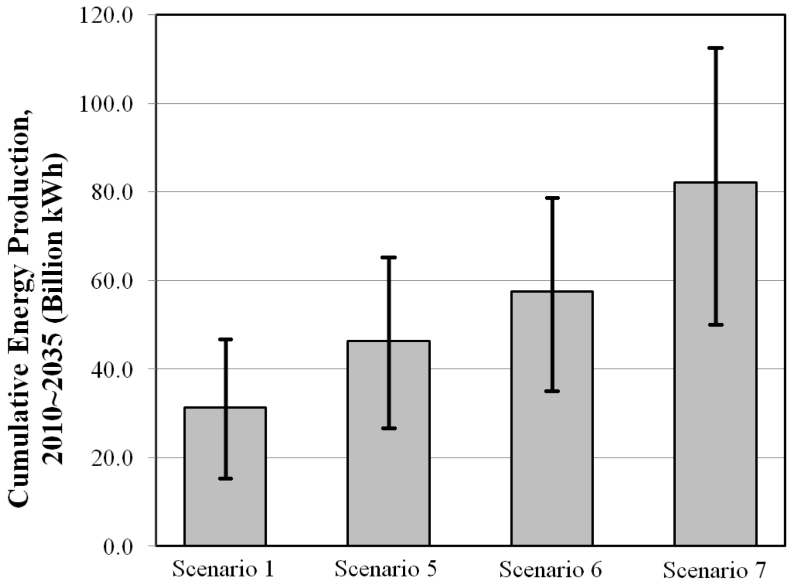

Figure 11. Operation strategies, with uncertainty range bar for each scenario (Scenario 1: Base case, Scenario 5: Accelerated gas collection, Scenario 6: Bioreactor landfill operation, Scenario 7: Enhanced energy production)

CHAPTER FIVE – FUGITIVE LANDFILL GAS EMISSIONS IN THE US: OBLIGATORY PREVENTION OR VOLUNTARY COLLECTION?

5.1. Background

MSW management strategies in the US typically include a combination of three approaches, recycling, combustion, and landfill disposal. Becoming a "zero-waste" community in future decades may be possible, but until then MSW will continue to be generated and a significant fraction will be landfilled. More than 54% of the US generated MSW was landfilled in 2008 (US EPA, 2009a), mainly because of its simplicity and cost-effectiveness. However, landfills are major contributors to climate change due to the methane content of LFG generated from anaerobic decomposition of biodegradable waste. Therefore, most US landfills are required to collect LFG.

The construction, operation, and maintenance costs of the LFG management system (approximately 5% of the total landfill costs; Berge et al., 2009) must be offset by revenues, such as selling energy from a LFG to energy (LFGTE) facility, carbon credit trading, and renewable energy production tax credits. According to the US National Renewable Energy Laboratory, LFGTE projects have lower capital cost compared to other renewable energy resources; however, operation and maintenance costs of LFGTE projects were found to be higher than most renewable resources (NREL, 2010). Few studies have evaluated costs and benefits of LFGTE projects with consideration of landfill operating practices and policies. The objectives of this chapter are to (1) investigate costs and benefits of emitting vs. collecting LFG emissions with regard to operation strategies and regulations, (2) analyze the sensitivity of LFG collection and

LFGTE production to changes in cost and revenue sources, and (3) facilitate decision making for landfill owners and policy makers.

The main potential negative impacts of landfilling on the environment are leachate and fugitive gas emissions. Most of the leachate emission problems have been resolved in sanitary landfills in recent years through improved liner design and leachate management practices. However, problems still remain with respect to fugitive LFG emissions, especially during the active disposal period when a major fraction of the LFG potential is generated. The point in time that landfills are required to start LFG collection depends on the type of operation and quantity of emissions.

Landfills are generally long-term projects, with typically 5-10 years of active disposal and 30 years of monitoring and maintenance after closure in the US. Changes in regulations, as well as improved operating practices, are likely to occur during the lifetime and affect the economics of a landfill project. Economic debates regarding GHG emission control have mainly focused on two strategies, carbon tax and carbon trading. Carbon tax penalizes all GHG emitting sources based on the quantity of emissions. In a carbon trading (or cap-and-trade) program a cap is set on fugitive emissions for all GHG emitting facilities and the cap is reduced over time. Owners of regulated facilities must obtain permits and limit their fugitive emissions to the permitted cap. In an ideal market, carbon tax and carbon trade should eventually result in similar costs/benefits. Under carbon tax legislation, the tax rate is established and collected by the government and later invested in infrastructure to reduce GHG emissions. In a carbon trade program, however, the value of a tradable carbon credit is defined in response to supply and demand, and the landfill owner can directly benefit economically and invest in the facility. A carbon credit is the quantity of prevented GHG emissions equivalent to one tonne of carbon dioxide (CO_2eq), based on the 100-year global warming potential (a measure of how much a specific compound contributes to climate change).

Although conceptually simple to understand, policy makers and communities are less likely to consider a carbon tax, particularly in light of the recent economic recession. Alternatively, the US carbon trading market may follow one of two paths; first, a federal carbon trading scheme is set that considers carbon credits as a commodity, to be regulated under the Commodity Exchange Act by the Commodity Futures and Trading Commission. In this market, carbon credits can only be traded under a contract authorized by the Commission. Alternatively, the carbon trading market can be over-the-counter and project based, and carbon credits can be authorized under non-federal standards and traded between businesses and individuals based on negotiated prices.

Under a carbon trading program, owners of facilities with fugitive emissions higher than the regulated cap must buy carbon credits from facilities that have excess or banked credits. A successful example of this policy is the US sulfur dioxide cap-and-trade program, established in 1990. As a result of that program, US sulfur dioxide emissions declined by 43% between 1990 and 2007 (US EPA, 2009b). Increased costs due to a carbon trading program can force many businesses, including landfill owners, to limit their emissions to the permitted cap. Alternatively, facilities can benefit from employing improved technologies and trading excess credits in the carbon market. LFGTE projects can provide other economic incentives, including renewable energy credits and renewable energy production tax credits. For instance, US LFGTE facilities can benefit from electricity sales at a nationwide price range of USD 0.025 to 0.070 per kWh and renewable energy production tax credits at USD 0.010 per kWh (US EPA, 2010; ARRA, 2009).

The value of the European carbon trading market (the EU Emission Trading Scheme, established by the European Union and in operation since 2005) was about USD 95 billion in 2008. Conversely, the US voluntary over-the-counter market value was over USD 700 million in the same year (compared to USD 300 and 100 million in 2007 and 2006, respectively; Hamilton et al., 2009). The value of the carbon market declined globally since late 2008, due to the recession. While some markets, including the EU Emission Trading Scheme, recently showed some recovery from the recession, lack of legislative action in the past and uncertainty of action in the future has kept the US carbon market from recovering. The value of carbon credits in the EU Emission Trading Scheme was about USD 21.00 per credit in late 2010 (Carbon Positive, 2010a), while prices were around USD 2.00 per credit in the US market in the same timeframe (Carbon Positive, 2010b).

5.2. Methodology

The potential economic benefits of LFG collection and LFGTE production were studied through case-study modeling. Evaluated parameters included tonnes CO_2eq fugitive LFG emissions avoided, net cost or net benefit of the project, budget neutrality (the break-even point where net costs and net benefits are equal), and marginal abatement cost (or marginal abatement benefit; defined as the change in total cost or total benefit due to incremental change in LFG collection efficiency). These parameters were calculated assuming different carbon policies to compare the cost of LFG collection to the economic implications of fugitive emissions.

As the base case, an average-sized single-cell traditional landfill was modeled operating under US EPA Resource Conservation and Recovery Act (RCRA) Subtitle D and Clean Air Act (CCA) regulations in the state of Florida, US. Annual LFG generation rates were estimated using Equation 3.

Parameter k was assumed to be 0.08 yr^{-1}, determined from statistical analyses of LFG generation for the five Florida landfills (Chapter Three). An average L_0 of 55 $m^{3} \cdot Mg^{-1}$ was used, calculated from 2007 statewide MSW composition data and using waste component specific methane yield derived from laboratory measurements (Staley and Barlaz, 2009; Chapter Four). The modeled landfill received MSW for five years (2010-2014), and was then closed. MSW disposal tonnage, based on Florida statewide average waste generation data in 2007 and assuming an annual average 2% increase due to population growth, was estimated to be 1.3 million tonnes over the five-year active lifetime. The dimensions of the landfill cell were assumed to be 380 m x 380 m footprint, height of 43 m, and 3.5:1 (H:V) side slopes. Soil would be used as daily cover at a volume ratio of 4:1 (MSW:soil) and leachate would be treated at off-site municipal facilities.

As shown in Equation 2, generated LFG would be collected, oxidized, or emitted to the atmosphere. Annual collected LFG was estimated using Equation 4, applying year-by-year collection efficiencies to the waste, as a function of the cover material, gas collection system type, and time of installation. LFG collection was assumed to start after closure for the base case, with an efficiency of 0.75 (US EPA AP-42, 1997; US EPA 2008a) and no LFG collection for years 1-5. Oxidation is defined as the uncollected methane emission fraction oxidized to carbon dioxide in the soil covers by methanotrophic bacteria. The US EPA and the Intergovernmental Panel on Climate Change (IPCC) recommend an oxidation fraction of 0.10 (IPCC, 2006; US EPA, 2004), which was utilized in this study for the base case according to Equation 13. The collected LFG was assumed to be flared under the base-case scenario, with no energy production and no benefits from carbon credits.

$$Q_{ox} = \sigma_{ox} \frac{(Q_g - Q_c)}{\beta} \quad (13)$$

where:

σ_{ox} = Methane oxidation fraction

A US federal renewable portfolio standard, if established, would most likely include LFGTE as a renewable energy resource. To examine the LFGTE potential under various scenarios, a model was created to estimate annual energy production in the form of electrical energy using Equation 9. Capacity factor is defined as the fraction of energy output under typical operating times to energy output if the system is operated full-time, taking into account downtimes such as system failure and periodic maintenance. The capacity factor for LFGTE was assumed to be, on average, 0.83 (NREL, 2010). Electrical efficiency represents the fraction of electricity produced to the energy consumed by the device. Electricity would be produced using an internal combustion engine with average electrical efficiency of 0.35 (range of 0.31-0.39; US EPA, 2002), because it is the most common practice for US LFGTE facilities.

Net benefit (or net cost) for the landfill was calculated using Equation 14. Total cost, shown in Equation 15, included explicit costs (direct payments for land, construction, equipment purchases, and carbon tax) and implicit costs (expenses of owning the facility, such as operation and maintenance). Total benefits for landfills and LFGTE facilities include tipping fee, energy sales, carbon credit trading, and tax credits. Marginal abatement cost (or benefit) was calculated using Equation 16 or 17.

$$NB\ (or\ NC) = TB - TC \tag{14}$$

$$TC = EC + IC \tag{15}$$

$$MAC = \frac{TC_y - TC_{(y-1)}}{\eta_y - \eta_{(y-1)}} \tag{16}$$

$$MAB = \frac{TB_y - TB_{(y-1)}}{\eta_y - \eta_{(y-1)}} \tag{17}$$

where:

NB	=	Net benefit, USD (US Dollar)
NC	=	Net cost, USD
TB	=	Total benefit, USD
TC	=	Total cost, USD
EC	=	Explicit costs, USD
IC	=	Implicit costs, USD
MAC	=	Marginal abatement cost, USD per unit collection efficiency
MAB	=	Marginal abatement benefit, USD per unit collection efficiency
y	=	Modeled practice (refer to Table 22)

Costs and benefits in Equations 14 and 15 were calculated using a modified version of the Bioreactor Landfill Economic Model (BLEM) created by Berge et al. (2009). The BLEM model is a spreadsheet-based model incorporating economic factors related to landfill design, construction, operation, and maintenance to evaluate the influence of construction modes and operational practices on landfill economics. Construction and equipment costs were based on 2006 unit prices and adjusted to present worth using an annual inflation rate of 3%,. Unit costs were confirmed by experts in the field (personal communication, 2010; details provided in Appendix F, Table F1). Future costs and revenues were calculated and applied at time of occurrence based on interest rate of 5% and inflation rate of 3%, and later adjusted to present worth to make outcomes comparable, with the base year to be 2010.

Because current regulations allow a delay in LFG collection, a major fraction of generated LFG over the lifetime of a landfill remains uncollected. New regulations are likely in the future, forcing landfills to limit fugitive LFG emissions more effectively. Under such regulations, landfill owners must enhance landfilling and LFG collection strategies, which would result in increased cost. For instance, installing horizontal trenches during disposal years and vertical wells immediately after reaching final elevation allows earlier LFG collection, although at increased cost compared to delaying LFG collection system installation to after closure.

Several operating practices that resulted in increased lifetime LFG collection efficiencies, compared to the base case, were modeled (summarized in Table 22). In Practices 2-7, LFG collection was assumed to start after one, two, or three years of MSW disposal using a network of active horizontal and vertical LFG collection trenches and wells. LFG collected from MSW mass disposed in year *i* was determined as a function of the collection system and cover material applied to that mass in year *z* (see Equation 4). For years with no LFG collection, the collection efficiency, η_{iz}, was assumed to be zero. A collection efficiency of 0.35 was assumed for active landfilling years with active LFG collection and only daily cover. During active LFG collection and partial closure η_{iz} of 0.90 was assumed. For active LFG collection after closure with low permeable soil and geomembrane final cover η_{iz} was assumed to be 0.95.

Table 22. LFG collection efficiencies (fraction of generated) assumed for modeled practices

	Years since waste placement						Resulting lifetime LFG collection efficiency	
	1	2	3	4	5	6-35	Traditional	Bioreactor
Practice 1: Base case	0.0	0.0	0.0	0.0	0.0	0.75	0.50	NA
Practice 2	0.0	0.0	0.0	0.35	0.35	0.95	0.73	0.66
Practice 3	0.0	0.0	0.0	0.90	0.90	0.95	0.74	0.68
Practice 4	0.0	0.0	0.35	0.35	0.90	0.95	0.78	0.73
Practice 5	0.0	0.0	0.90	0.90	0.90	0.95	0.81	0.76
Practice 6	0.0	0.35	0.35	0.90	0.90	0.95	0.85	0.81
Practice 7	0.0	0.90	0.90	0.90	0.90	0.95	0.87	0.84

High performance of LFG collection systems would require confirmation through whole-site emissions monitoring. In such scenarios, monitoring cost using the US EPA recommended OTM-10 method (US EPA, 2007) was assumed. The equipment and personnel unit costs were added based on values reported by Babilotte et al. (2010), with the assumption that equipment would require replacement at 10-year intervals.

Cost and revenue sources affecting landfill economics from either carbon tax or carbon trade strategies were added to the original BLEM model. The carbon tax rate and carbon credit values were varied for each collection efficiency practice. Landfill owners would gain carbon credits for the avoided fugitive GHG emissions beyond the regulated limit. For example, US EPA estimates LFG collection and emissions in landfills with an active LFG collection system based on a default 0.75 collection efficiency and traditional landfills are required to start LFG five years after waste disposal. Therefore, if gas collection starts in year six with efficiency of 0.75, the regulated amount is collected and carbon credits from LFG collection could not be claimed. However, LFG oxidized in the soil cover layer (prior to final closure with geomembrane material) could be claimed for carbon credits.

LFG generation, collection, and emission rates, as well as costs and benefits for bioreactor landfilling (liquid injection in order to optimize moisture content and enhance gas generation) were also modeled under Practices 2-7. In this practice a methane generation rate constant of $k=0.11\ yr^{-1}$ (Tolaymat et al., 2010) was used to estimate LFG generation. Enhanced decomposition of degradable MSW in bioreactor landfills results in earlier settlement of disposed waste. This earlier settlement makes available landfill volume during the active lifetime, defined as air space recovery. Air space recovery was included in this study as additional cell-volume for waste disposal and tipping fee revenue. Post-closure care under bioreactor landfilling was reduced to 20 years, assuming landfill settlement, leachate, and LFG emissions are below the regulated thresholds at that time, and most of the LFG generation potential would be exhausted.

5.3. Results and Discussion

5.3.1. Avoided Fugitive Emissions

The avoided fugitive LFG emission under each operation practice is presented in Figure 12. Under the base-case assumptions, for instance, the landfill could avoid approximately 162,000 tonnes of carbon equivalent GHG emissions, comparable to planting some 130,000 acres of forests or removing emissions of 110,000 vehicles, using EPA conversion factors (US EPA, 2008b). Bioreactor operation resulted in higher avoided fugitive emissions (by approximately 80,000 tonnes CO_2eq), because a higher quantity of LFG was generated over the collection period, thus more gas was available for collection.

The main source of economic benefits for landfill owners is a tipping fee, defined as the amount charged by landfill owners to permit disposal of a unit weight of MSW in the landfill. In this study, tipping fee was varied for the base case to find the budget neutralizing value for 2010, and was then adjusted annually, accounting for inflation. For the base-case landfill, the 2010 budget neutralizing tipping fee was USD 42 per tonne MSW, which was comparable to the Florida statewide average of USD 40 per tonne MSW in 2007 (FDEP, 2010c). Cost and benefit estimations for all other practices were based on the same tipping fee.

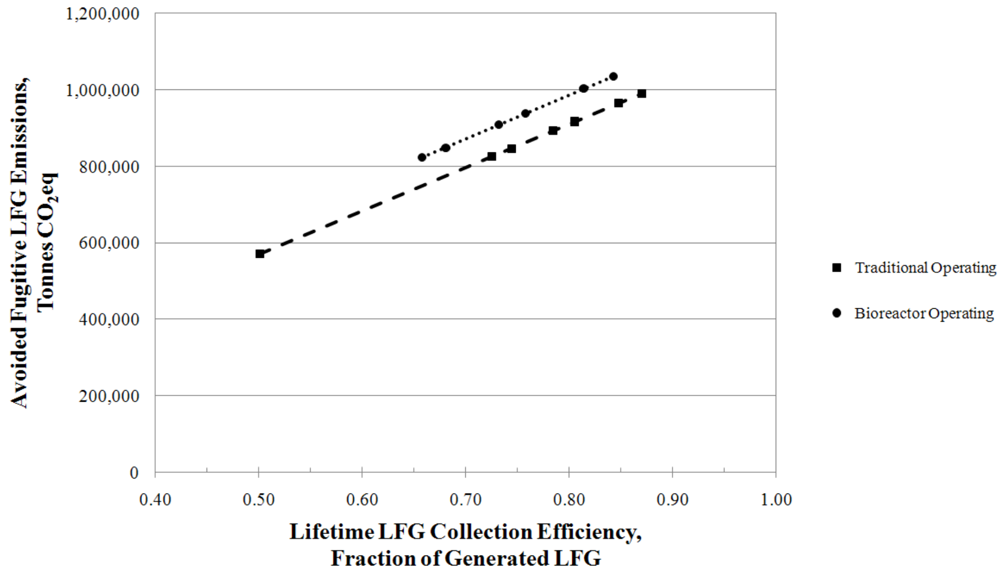

Figure 12. Avoided fugitive LFG emissions under various lifetime LFG collection efficiencies

5.3.2. Carbon Tax

With the base case at budget neutrality, any carbon tax imposed would result in a net cost for the landfill, regardless of the collection efficiency. Bioreactor operation, however, provided net benefit under lifetime LFG collection efficiencies up to 0.73 with carbon tax up to USD 5.50 per tonne CO_2eq (details not shown). Handley (2010) reported a carbon price/value of USD 21 per tonne CO_2eq in 2010 would take into account the effect of climate change on agricultural productivity, human health, flooding, and ecosystem services. As shown in Figure 13, carbon tax of USD 21 per tonne CO_2eq increased the net cost significantly for both traditional and bioreactor landfilling. The slopes of the "with carbon tax" and "without carbon tax" trendlines are much steeper and merge at collection efficiencies above 0.80 and 0.75 for traditional and bioreactor landfilling, respectively, due to the significant costs of accomplishing high collection efficiencies

The cost of the carbon tax on the traditional landfill operating at collection efficiency less than 0.80 could be offset by increasing the tipping fee, converting LFG to energy, or converting the landfill to bioreactor operation. At collection efficiency higher than 0.80, however, the cost of collecting LFG exceeds the potential revenue at current prices. For example, at 0.87 collection efficiency at the traditional landfill the owners must increase tipping fee by 60% or sell electricity at 0.40 USD/kWh to neutralize the cost of a USD 21 per tonne CO_2eq carbon tax.

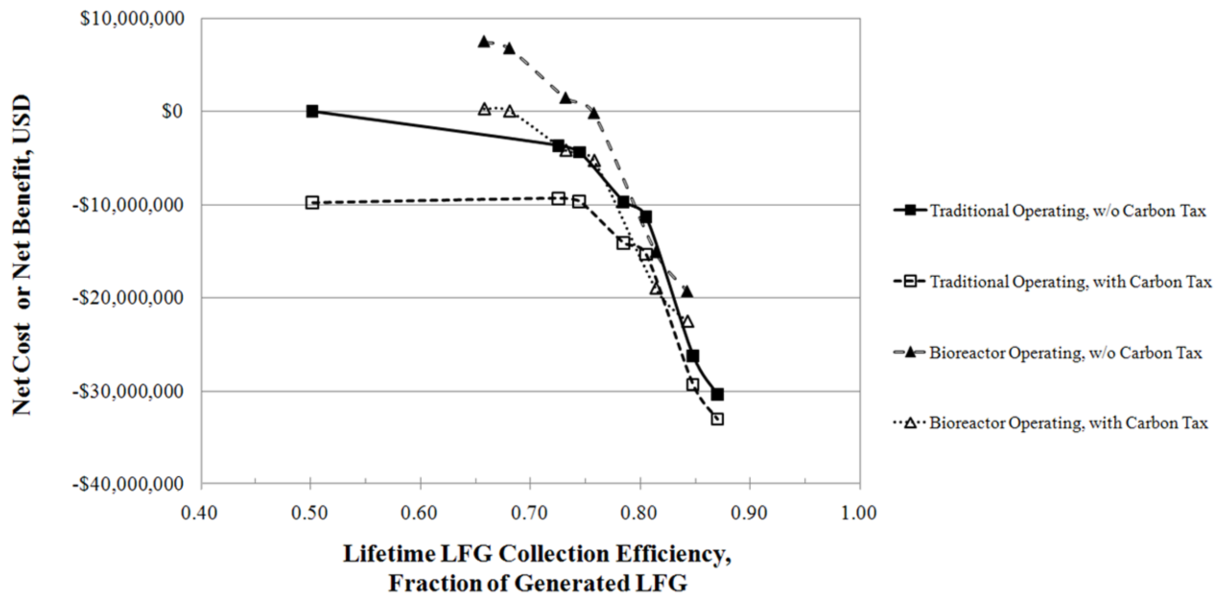

Figure 13. Net cost or benefit with carbon tax at USD 21 per tonne CO_2eq under various lifetime LFG collection efficiencies

5.3.3. Carbon Trading

In the carbon trading scenarios, the required carbon value to neutralize total cost (TC) is presented in Table 23, where the carbon credits compensate for the cost of the attained lifetime collection efficiency. The resulting cost neutralizing values were an order of magnitude greater than the current US market credit of USD 2.00 (Carbon Positive, 2010b); but was comparable to the EU Emission Trading Scheme price of USD 21.00 at 0.73 lifetime collection efficiency.

Table 23. Total cost neutralizing carbon credit value under various lifetime LFG collection efficiencies, traditional operating landfill

Lifetime LFG collection efficiency, fraction of generated	Total cost neutralizing carbon credit value, USD per tonne CO_2eq
0.73	22.80
0.74	24.10
0.78	40.70
0.81	43.40
0.85	82.40
0.87	89.40

In Figure 14, budget neutrality under carbon trading with revenue from electricity sales is presented for various collection efficiency practices. The carbon emission value/price estimated by Handley (2010) and the typical revenue rate for LFGTE facilities (electricity sale plus tax credit) are also shown in Figure 14 (US EPA, 2010; ARRA, 2009). Without revenue from carbon trading and only benefiting from electricity sales at the present US average rate, the traditional landfill was budget neutral for lifetime collection efficiency up to 0.70 (details not shown). If regulations require higher collection efficiencies, landfill owners would need to produce revenue from trading carbon credits at prices higher than those typical in the current US market to offset costs. For example, at the present US average electricity sales price and operating at 0.74 lifetime collection efficiency, the landfill must trade carbon credits at approximately USD 6 per tonne CO_2eq to be budget neutral. At 0.81 lifetime collection efficiency, however, the landfill must trade carbon credits at approximately USD 27 per tonne CO_2eq to offset costs.

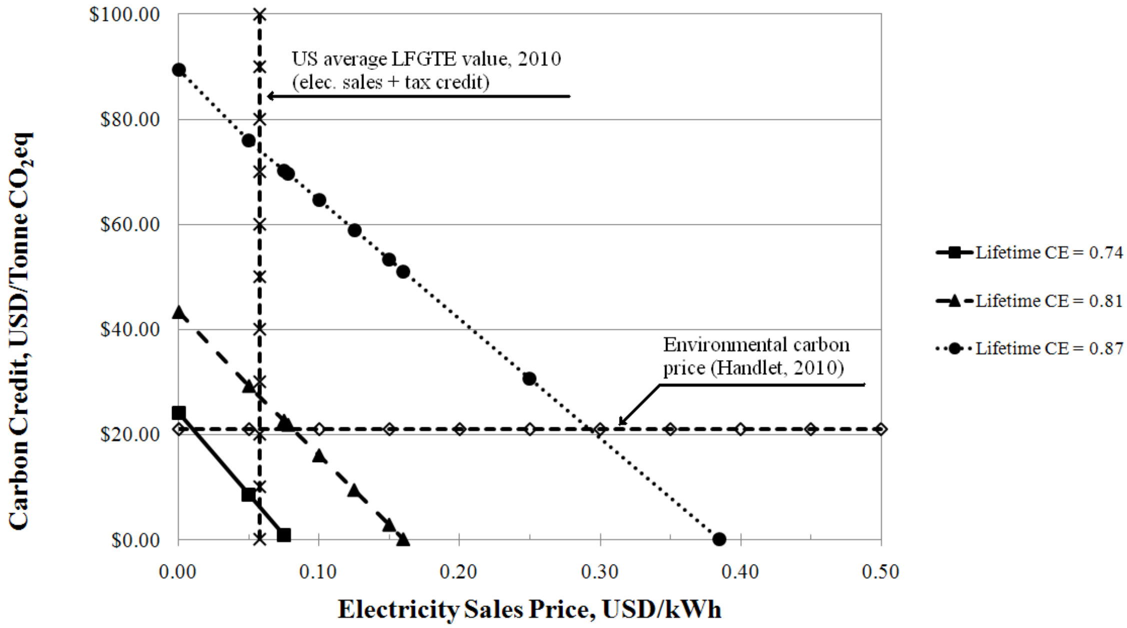

Figure 14. Budget neutrality with carbon trading and electricity sales under various lifetime LFG collection efficiencies

5.3.4. Cost of Avoiding Fugitive Emissions

The MAC for each modeled scenario was determined as a function of lifetime LFG collection efficiency. In Figure 15, MAC per tonne of disposed MSW is plotted against the lifetime LFG collection efficiency (η_y) for each modeled practice *y*, as numbered in Table 22 and using Equation 16. Figure 15 depicts the trend of this relationship and extends the model using two limiting assumptions (1) MAC is zero when not collecting LFG or avoiding fugitive emissions, and (2) approaching lifetime LFG collection efficiency of 1.0 (collecting 100% of generated LFG), MAC would asymptotically approach infinity due to operating and technological limitations.

The MAC was near zero for lifetime collection efficiencies up to 0.50 because of the low incremental cost of improving the collection efficiency, but increased beyond that point. For example, MAC doubled for a 14% increase in lifetime collection efficiency from 0.70 to 0.80, and tripled for an increased lifetime collection efficiency from 0.80 to 0.90. This behavior was attributed to extreme measures required for LFG emission avoidance and the cost of monitoring necessary to document attainment, particularly during the active landfilling phase to achieve high lifetime collection efficiencies.

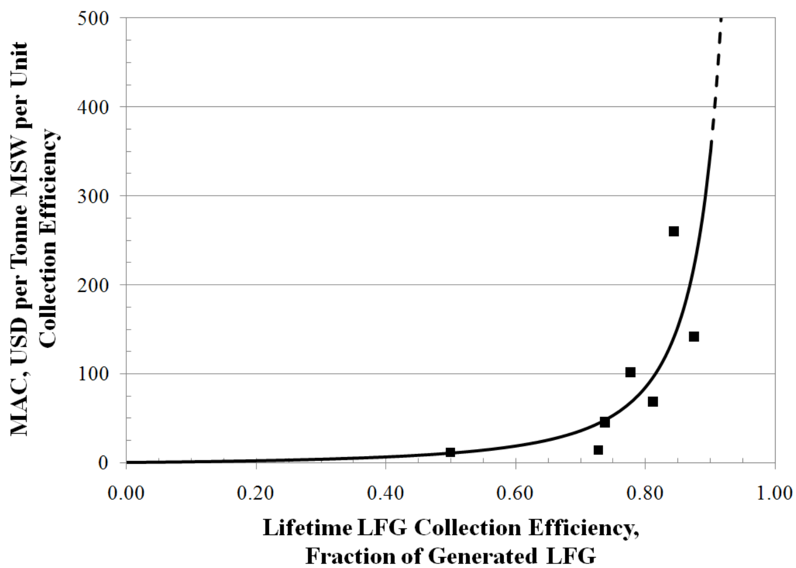

Figure 15. Functional behavior of lifetime collection efficiency vs. marginal abatement cost

CHAPTER SIX – CONCLUSIONS AND RECOMMENDATIONS

With 54% of the generated MSW landfilled in 2008, landfilling remains the dominant solution to MSW management in the near future in the US. As a major source of anthropogenic methane emissions, it is necessary to estimate LFG generation rates. Accurate estimates of LFG generation could help in better estimating the LFG collection efficiency and the uncollected LFG, which is either oxidized in the landfill cover or emitted to the atmosphere. However, limited data on landfilling operations and the nature of using empirical models for site-specific conditions, result in uncertainties in the estimates.

Modeling LFG generation and collection potential is necessary for regulators, policymakers, and landfill owners, not only for the GHG emission issue, but also for the energy value of LFG. Considering LFG as a source of renewable energy in most state-established renewable portfolio standards has resulted in a significant increase in the number of LFGTE projects in the US in recent years. While energy potential estimates could facilitate decision making for investors in LFGTE projects on a small-scale, large-scale long-term LFGTE potential estimates are necessary for regulators and policymakers, especially with the current debates on federal renewable energy policies.

For the first time, various approaches of quantifying first-order LFG generation model parameters were evaluated and uncertainty ranges were quantified for model outcome. Knowledge on these uncertainty ranges could reduce the risk in LFG collection and LFGTE production facilities design and evaluation. A unique methodology was presented to calculate long-term energy production potential from LFG for large regions. The model was demonstrated for the state of Florida, the fourth most populous state in the US. This unique methodology was designed to incorporate model uncertainties, as well as changes in landfilling and energy production. Also, no published literature was found to specifically study the impact of strict GHG emission reduction regulations on landfills. In this research a distinctive economic evaluation was performed on landfill gas emission control policies under various operating practices. Finding from each section of the research are summarized in the following sections.

6.1. Determination of Landfill Gas Model Parameters and Uncertainties

The first-order empirical model appeared to be insensitive to the approach taken in quantifying k and L_0, suggesting that the model may be inadequate to accurately describe LFG generation and collection. Further studies are recommended to improve the sensitivity of the model, which may require inclusion of additional parameters or using a higher kinetic-order model. However, these changes could jeopardize the main advantage of the model, i.e. simplicity. The recommended method to estimate LFG model parameters is to determine methane generation potential using disposed MSW composition and laboratory component-specific methane potential values. The methane generation rate constant can be selected by model fitting and regression using the first-order model if LFG collection data are available. When such data are not available, k can be selected from technical literature, based on site conditions related to climate and landfilling operations.

Life-to-date LFG collected was calculated based on reported LFG collected and modeled LFG generated, and was found to vary from 19% to 65% of LFG generated. It is important to note that the uncollected methane is not necessarily emitted to the atmosphere, but may also be oxidized within soil covers.

The uncertainty values for the model were, in general, at their lowest within five years after waste placement ended. Because of the exponential nature, the uncertainty increased as LFG generation declined to low values decades after the end of waste placement. The effect of the uncertainty in LFG generation rates should be considered when designing and operating landfills based on model estimates.

6.2. **Regional Prediction of Landfill Gas to Energy Potential**

Setting long-term policies and investment plans for renewable energy resources requires credible estimation of energy potential of different resources. Estimating LFGTE potential is a challenge due to the uncertainties involved in modeling LFG generation potential, especially on a large scale. In this paper a methodology was presented to estimate LFGTE potential for an area with population exceeding 18 million over a 25-year timeframe, i.e. 2010-2035, with consideration of modeling uncertainties.

Florida could increase the annual LFGTE production by more than threefold by 2035, compared to current practice, through use of LFGTE facilities at all landfills. The statewide LFGTE production could be significantly increased to about three billion kWh per year in 2035, with application of bioreactor operation and enhanced energy production strategies. Over 95% of the statewide potential could come from LFG generated by MSW from the 34 most populated counties. The average power density for Florida LFGTE production under base-case conditions was estimated to be about 4.1 Wm^{-2}. The power density could be further increased with enhanced landfill operation and energy production practices, making LFGTE comparable to technologies such as central solar towers, geothermal, tidal, and hydro.

Diverting food waste from landfills could significantly reduce LFG generation, while it would have minimal effect on the LFGTE potential. Although achieving high diversion goals through increased recycling could result in loss of energy production potential, it would also reduce LFG generation rates.

Florida landfills operators could avoid approximately 320 $MTCO_2e$ of uncollected GHGs and potentially generate over 80 billion kWh of electricity from LFG during the 2010-2035 timeframe. Using US EPA conversion factors (US EPA, 2001), this energy production would be equivalent to removing some 70 million vehicles from Florida highways or eliminating the need to import over 800 million barrels of foreign oil. With approximately half of the Florida landfill energy potential used at present, there is great untapped capacity for LFGTE. The environmental benefits from increased lifetime LFG collection efficiencies, as well as potential economic benefits from energy production, the carbon market, and tax credits, could magnify the value of LFGTE projects.

6.3. Fugitive landfill gas emissions in the US: Obligatory prevention or voluntary collection?

In this study, economic parameters were evaluated under various operation practices to assess the sensitivity of costs and benefits to various levels of LFG emission avoidance. For lifetime LFG collection efficiency less than 0.80, the extra revenue from air space recovery, reduced leachate volume, and reduced post-closure care period in bioreactor landfilling could neutralize the costs of improving the collection efficiency. At high lifetime collection efficiencies (greater than 0.80), however, it would be challenging for landfill owners (traditional or bioreactor) to achieve budget neutrality, even with revenue from electricity sales and carbon trading at current values. Considering the significant marginal abatement cost for lifetime collection efficiency greater than 0.90, costs of achieving those efficiencies are unlikely to be covered with revenues from tipping fee, electricity sales, tax credits, or carbon credit trading. Under scenarios of highly regulated LFG emissions, sustainable landfilling will require development and application of technologies to reduce the marginal abatement cost, including:

- Reducing fugitive emissions through usage of daily and intermediate cover materials with low permeability and high methane oxidation potential,
- Increasing the lifetime LFG collection efficiency by initiating gas collection earlier and applying improved techniques such as phased partial closure, and
- Increasing LFG energy value – for instance by increasing the capacity factor and electrical efficiency of the LFGTE production system.

6.4. Policy Change Recommendation

As presented in this research, diverting food waste could significantly reduce LFG generation, and thus emission, while having minimal effect on the energy potential. However, considering the high cost of separate collection of food waste and alternative treatment methods, such as anaerobic digestion, waste management professionals are not likely to voluntarily divert the food waste. Until regulations are set to enforce the diversion, research is required to find solutions to reduce the cost and increase the efficiency of alternative collection and treatment methods.

The applied assumptions in this research were typical of the current practice in most US landfills and showed that only half of the generated LFG is collected over the lifetime. Therefore, more aggressive operations must be considered to avoid fugitive LFG emissions, which could significantly affect the economic viability of landfills.

With little economic motivation for US landfill owners to voluntarily reduce fugitive emissions, regulations are necessary to increase the cost of emitting GHGs. A carbon tax will generate a significant immediate cost to landfill owners and the serviced community with no short-term return revenue. In light of the recent economic recession, it is not likely that a carbon tax will be established; while a carbon trading program will enforce emission caps and provide a tool to offset some costs and improve emission-reduction systems. The US is not interested in establishing a government-controlled program; yet, delaying effective action in establishing an active market has resulted in businesses losing interest in investing in the carbon market in recent years (Sills, 2011). Immediate action establishing a US carbon trading market with carbon credit pricing and trading supervised by the federal government may be the solution. Such a program will not be supply-and-demand driven and will aim to reduce GHG emissions rather than increase economic benefits, similar to the EU Emission Trading Scheme.

6.5. Future Research Recommendations

The ultimate goal of sustainable landfilling is to minimize negative environmental impacts, including fugitive LFG emissions. A comprehensive study is required to generalize the state of LFG collection efficiency and quantify uncertainties under various practices. The uncertainty in model estimated LFG generation was quantified in this research. However, major uncertainties remain regarding LFG oxidation and fugitive emissions. Research studies have shown the oxidation fraction in various types of landfills covers (excluding geomembranes) is greater than the US EPA recommended value of 0.10 (Chanton et al., 2008). Fugitive LFG emission fluxes measured at different landfills also vary significantly, depending on various parameters including the measurement technique, quantity of generated LFG, and landfilling and LFG collection operation practice. To estimate the uncertainty in LFG collection efficiency values, further research is required to quantify the uncertainties in LFG oxidation and emissions and evaluate their simultaneous impact with LFG generation and collection terms.

The size of the landfill is a major driver of the costs and benefits of landfilling. Costs and benefits were studied for an average sized landfill in this study. Future research should consider the sensitivity of economics to the size of the landfill. Furthermore, the economic feasibility could be studied for landfilling under various climatic conditions, reflected as various methane generation rate constants and oxidation fractions. Economic sensitivity analysis could also be done on the application of practices to reduce fugitive emissions, for example using daily and intermediate covers with high methane oxidation potential, in future researches.

Further research is required on increasing the energy value of LFG. One area of research is to biologically alter the LFG generation pathway to produce high-methane gas to increase the energy value of LFG. Improving electrical efficiency of energy producing devices and methods to combine energy recovery systems and reduce exhaust energy are also recommended subjects for future research. Increased energy value of LFG can beneficially affect the economics of LFGTE production.

APPENDIX A: EXAMPLE CALCULATION OF LFG GENERATION AND COLLECTION

Example Q_g calculation is shown for LFG generation in the year 2000 from waste disposed in 1986 in Landfill 1 – Phase 1.

$$Q_g = \sum_{i=1}^{n} \sum_{j=0.1}^{1} \beta k (\frac{M_i}{10}) L_{0_i} \, e^{-kt_{zj}}$$

where:

$\beta = 1.85$ (54% average methane content)

$M_{1985} = 523{,}993 \; Mg$

$k = 0.08 \; yr^{-1}$

$L_{0_{2000}} = 65 \; m^3 Mg^{-1}$

thus:

$$Q_{g_{2000}} = \left\{1.85 \times 0.08 \times (\frac{523993}{10}) \times 65 \times e^{-[0.08\times(2000-1986-1.0)]}\right\}$$

$$+ \left\{1.85 \times 0.08 \times (\frac{523993}{10}) \times 65 \times e^{-[0.08\times(2000-1986-0.9)]}\right\}$$

$$+ \left\{1.85 \times 0.08 \times (\frac{523993}{10}) \times 65 \times e^{-[0.08\times(2000-1986-0.8)]}\right\}$$

$$+ \left\{1.85 \times 0.08 \times (\frac{523993}{10}) \times 65 \times e^{-[0.08\times(2000-1986-0.7)]}\right\}$$

$$+ \left\{1.85 \times 0.08 \times (\frac{523993}{10}) \times 65 \times e^{-[0.08\times(2000-1986-0.6)]}\right\}$$

$$+ \left\{1.85 \times 0.08 \times (\frac{523993}{10}) \times 65 \times e^{-[0.08\times(2000-1986-0.5)]}\right\}$$

$$+ \left\{1.85 \times 0.08 \times (\frac{523993}{10}) \times 65 \times e^{-[0.08\times(2000-1986-0.4)]}\right\}$$

$$+ \left\{1.85 \times 0.08 \times (\frac{523993}{10}) \times 65 \times e^{-[0.08\times(2000-1986-0.3)]}\right\}$$

$$+ \left\{1.85 \times 0.08 \times (\frac{523993}{10}) \times 65 \times e^{-[0.08\times(2000-1986-0.2)]}\right\}$$

$$+ \left\{1.85 \times 0.08 \times (\frac{523993}{10}) \times 65 \times e^{-[0.08\times(2000-1986-0.1)]}\right\}$$

$$= 157{,}465 + 156{,}210 + 154{,}966 + 153{,}731 + 152{,}506 + 151{,}291 + 150{,}085$$

$$+ 148{,}889 + 147{,}703 + 146{,}526 = 1{,}519{,}373 \text{ m}^3\text{yr}^{-1}$$

LFG collection was calculated for each year based on the model estimated LFG generation and the gas collection and cover system applied to each mass of disposed waste over the lifetime. For instance, based on information from Landfill 1 officials, the MSW landfilled in 1986 had a geomembrane final cover and a gas collection system in the year 2000 (assumed collection efficiency of 0.90), therefore:

$$Q_{c_{(in\ 2000\ from\ 1986\ mSW)}} = 0.90 \times 1{,}519{,}373 = 1{,}367{,}436\ m^3 yr^{-1}$$

To calculate all LFG collected in 2000, Q_g is modeled for MSW disposed in each year (1985-2000) and collection efficiencies are applied to each year and summarized.

$$Q_{c_{2000}} = 51{,}750{,}660\ m^3 yr^{-1}$$

APPENDIX B: EXAMPLE L_0 CALCULATION FROM WASTE COMPOSITION

The example is demonstrated for Landfill 2 in year 2000:

- Step 1: Extract waste composition with consideration to assumptions (based on composition study provided by case-study landfill officials):
    - "Other paper" was assumed 60% office paper and 40% mixed paper
    - "Metals" was assumed 60% aluminum and 40% steel
    - "Miscellaneous" was assumed 50% organic and 50% non-organic

Preliminary		Adjusted	
Waste Type	Composition, %	Waste Type	Composition, %
Newspaper	0	Newspapers	0
Other paper	40	Office Paper	23
		Mixed Paper	17
Glass	4	Glass	4
Metals	12	Steel (ferrous)	5
		Aluminum (non-ferrous)	7
Plastics	7	Plastic	7
Tires	0	Tires	0
Textiles	6	Textiles	6
Food Waste	18	Food Waste	18
Yard Trimmings	5	Yard Trimmings	5
Miscellaneous	5	Miscellaneous organics	2
		Miscellaneous non-organics	2
C&D	4	C&D	4
Summary	100	Summary	100

- Step 2: Calculate average moisture content based on assumed 1000 Mg tonnage, waste composition, and typical moisture content.

Waste Type	Typical Moisture Content, % (weight)	Wet Weight, Mg	Dry Weight, Mg
Newspapers	6	3	3
Office Paper	6	230	217
Mixed Paper	6	167	157
Glass	2	38	38
Steel (ferrous)	3	47	45
Aluminum (non-ferrous)	3	70	68
Plastic	2	73	72
Tires	2	0	0
Textiles	10	59	53
Food Waste	70	177	53
Yard Trimmings	60	48	19
Miscellaneous organics	50	24	12
Miscellaneous non-organics	5	24	23
C&D	6	40	38
Summary		1000	796

where:

$$Wet\ Weight\ (Mg) = 1000(Mg) \times Composition\ (\%)$$

$$Dry\ Weight\ (Mg) = Wet\ Weight\ (Mg) \times [1 - Typical\ Moisture\ Content(\%)]$$

thus:

$$Average\ Moisture\ Content\ (\%) = 100 - \left[\frac{Dry\ Weight\ (Mg)}{Wet\ Weight\ (Mg)} \times 100\right]$$

$$Average\ Moisture\ Content = 100 - \left[\frac{796}{1000} \times 100\right] = 20\%$$

- Step 3: Calculate L_0 (dry based) for each component based on composition and typical methane yield.

Waste Type	Dry Weight, Mg	Typical Methane Yield, m^3Mg^{-1}	Dry Component Methane Yield, m^3
Newspapers	3	74	206
Office Paper	217	217	47,060
Mixed Paper	157	146	22,867
Glass	38	0	0
Steel (ferrous)	45	0	0
Aluminum (non-ferrous)	68	0	0
Plastic	72	0	0
Tires	0	0	0
Textiles	53	15	784
Food Waste	53	301	15,926
Yard Trimmings	19	72	1,373
Miscellaneous organics	12	145	1,772
Miscellaneous non-organics	23	0	0
C&D	38	0	0
Summary	796		89,989

where:

$$Dry\ Methane\ Yield\ (m^3) = Dry\ Weight\ (Mg) \times Typical\ Methane\ Yield\ (m^3Mg^{-1})$$

- Step 4: Calculate dry-based methane yield (L_0) from summarized dry methane yield and dry weight.

$$L_{0_{dry}} = \frac{\sum Dry\ Methane\ Yield\ (m^3)}{\sum Dry\ Weight\ (Mg)} = \frac{89989}{796} = 113\ m^3Mg^{-1}$$

- Step 5: Calculate wet-based methane yield (L_0) from average moisture content.

$$L_0\ (m^3Mg^{-1}) = L_{0_{dry}} \times [1 - Average\ Moisture\ Content(\%)]$$

$$L_0\ = 113 \times \left[1 - \frac{20}{100}\right] = 90\ m^3Mg^{-1}$$

APPENDIX C: ADDITIONAL INFORMATION TABLES FOR CHAPTER THREE

Table C1. Annual landfilled waste composition and L_0 for Landfill 1

No.	Waste Type	1996	1997	1998	1999	2000	2001	2002	2004	2005	2006	Average
1	Newspaper	5%	5%	6%	7%	7%	6%	3%	6%	5%	5%	5%
2	Other paper	27%	31%	25%	25%	25%	24%	23%	22%	24%	23%	25%
3	Glass	4%	4%	5%	4%	5%	4%	3%	2%	1%	1%	3%
4	Metals	32%	24%	24%	25%	28%	27%	30%	35%	37%	42%	30%
5	Plastics	3%	3%	4%	3%	4%	3%	2%	4%	5%	4%	4%
6	Tires	0%	0%	0%	0%	0%	0%	0%	2%	1%	1%	0%
7	Textiles	3%	3%	4%	4%	4%	3%	4%	4%	3%	3%	3%
8	Food waste	5%	8%	9%	9%	9%	8%	9%	8%	7%	8%	8%
9	Yard trash	5%	5%	6%	5%	5%	9%	9%	4%	3%	3%	5%
10	Misc	6%	7%	8%	8%	6%	7%	8%	7%	9%	6%	7%
11	C&D	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%
12	Biosolids	5%	5%	5%	5%	5%	5%	5%	0%	0%	0%	4%
L_0, m^3Mg^{-1}		65	75	66	67	65	64	62	56	57	55	62

Table C2. Annual landfilled waste composition and L_0 for Landfill 2

No.	Waste Type	1996	1997	1998	1999	2000	2001	2002	2004	2005	2006	Average
1	Newspaper	1%	1%	0%	3%	0%	3%	15%	7%	5%	5%	4%
2	Other paper	36%	37%	34%	32%	40%	40%	29%	29%	26%	27%	33%
3	Glass	4%	5%	4%	4%	4%	3%	2%	3%	3%	3%	3%
4	Metals	16%	13%	12%	20%	12%	18%	8%	16%	19%	33%	17%
5	Plastics	11%	7%	7%	8%	7%	6%	11%	5%	5%	4%	7%
6	Tires	0%	0%	0%	1%	0%	0%	0%	0%	0%	0%	0%
7	Textiles	5%	6%	6%	3%	6%	1%	5%	1%	0%	0%	3%
8	Food waste	16%	15%	16%	8%	18%	21%	18%	19%	13%	13%	16%
9	Yard trash	0%	1%	12%	6%	5%	3%	1%	15%	25%	11%	8%
10	Misc	8%	10%	5%	10%	5%	1%	7%	1%	1%	1%	5%
11	C&D	4%	4%	4%	4%	4%	4%	4%	4%	4%	4%	4%
L_0, m^3Mg^{-1}		82	85	80	71	90	92	81	71	62	60	77

Table C3. Annual landfilled waste composition and L_0 for Landfill 3

No.	Waste Type	1996	1997	1998	1999	2000	2001	2002	2004	2005	2006	Average
1	Newspaper	5%	5%	5%	5%	7%	5%	3%	5%	4%	6%	5%
2	Other paper	26%	34%	35%	36%	31%	31%	40%	38%	38%	32%	34%
3	Glass	7%	2%	1%	0%	1%	1%	2%	2%	2%	2%	2%
4	Metals	22%	18%	18%	20%	16%	16%	19%	18%	18%	17%	18%
5	Plastics	4%	13%	14%	13%	13%	11%	13%	14%	14%	14%	12%
6	Tires	0%	1%	1%	1%	1%	3%	1%	3%	3%	1%	2%
7	Textiles	9%	3%	3%	3%	3%	3%	3%	3%	3%	3%	4%
8	Food waste	7%	5%	5%	5%	5%	5%	8%	9%	9%	9%	7%
9	Yard trash	9%	6%	5%	3%	10%	14%	5%	2%	2%	10%	7%
10	Misc	5%	8%	8%	8%	7%	5%	1%	1%	2%	1%	5%
11	C&D	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%
L_0, m^3Mg^{-1}		62	74	74	75	70	69	82	68	68	64	70

Table C4. Annual landfilled waste composition and L_0 for Landfill 4

No.	Waste Type	1996	1997	1998	1999	2000	2001	2002	2004	2005	2006	Average
1	Newspaper	6%	6%	6%	5%	5%	6%	9%	2%	4%	1%	5%
2	Other paper	34%	37%	37%	34%	32%	27%	24%	14%	16%	19%	27%
3	Glass	4%	5%	4%	4%	4%	4%	4%	1%	1%	5%	4%
4	Metals	20%	20%	19%	19%	17%	15%	14%	10%	13%	6%	15%
5	Plastics	11%	12%	11%	12%	10%	9%	10%	5%	6%	12%	10%
6	Tires	0%	1%	1%	1%	0%	0%	0%	0%	0%	0%	0%
7	Textiles	3%	3%	3%	3%	3%	3%	10%	1%	1%	3%	3%
8	Food waste	9%	9%	8%	9%	8%	6%	10%	5%	4%	4%	7%
9	Yard trash	8%	3%	0%	1%	1%	3%	4%	6%	5%	17%	5%
10	Misc	4%	4%	1%	0%	1%	1%	1%	38%	35%	1%	9%
11	C&D	1%	1%	10%	14%	19%	26%	12%	17%	15%	33%	15%
L_0, m^3Mg^{-1}		77	80	77	90	68	64	61	43	44	36	63

Table C5. Annual landfilled waste composition and L_0 for Landfill 5

No.	Waste Type	1996	1997	1998	1999	2000	2001	2002	2004	2005	2006	Average
1	Newspaper	1%	1%	3%	3%	2%	2%	5%	6%	6%	6%	4%
2	Other paper	35%	36%	37%	34%	31%	25%	27%	17%	16%	15%	27%
3	Glass	1%	2%	4%	3%	4%	3%	6%	2%	1%	1%	3%
4	Metals	18%	18%	19%	24%	24%	23%	24%	23%	24%	35%	23%
5	Plastics	2%	1%	3%	4%	4%	3%	12%	12%	12%	12%	6%
6	Tires	0%	0%	1%	1%	1%	1%	1%	2%	2%	2%	1%
7	Textiles	7%	6%	4%	4%	6%	6%	5%	9%	10%	9%	7%
8	Food waste	3%	3%	7%	8%	8%	6%	9%	9%	10%	9%	7%
9	Yard trash	1%	13%	11%	9%	7%	18%	4%	6%	8%	4%	8%
10	Misc	28%	15%	5%	6%	7%	7%	3%	8%	7%	1%	9%
11	C&D	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%
L_0, m^3Mg^{-1}		77	76	79	74	69	60	62	44	43	38	61

Table C6. Waste disposal and LFG collection history in case-study landfills

Year	Landfill 1 – Phase 1		Landfill 1 – Phase 2		Landfill 2		Landfill 3		Landfill 4		Landfill 5	
	Disposed waste, Mg	Collected LFG, x10^3 m^3	Disposed waste, Mg	Collected LFG, x10^3 m^3	Disposed waste, Mg	Collected LFG, x10^3 m^3	Disposed waste, Mg	Collected LFG, x10^3 m^3	Disposed waste, Mg	Collected LFG, x10^3 m^3	Disposed waste, Mg	Collected LFG, x10^3 m^3
1972	---	---	---	---	---	---	32,155	---	---	---	---	---
1973	---	---	---	---	---	---	39,459	---	---	---	---	---
1974	---	---	---	---	---	---	42,495	---	---	---	---	---
1975	---	---	---	---	---	---	45,530	---	---	---	---	---
1976	---	---	---	---	---	---	48,565	---	---	---	---	---
1977	---	---	---	---	---	---	51,601	---	36,078	---	---	---
1978	---	---	---	---	123,521	---	54,636	---	171,804	---	---	---
1979	---	---	---	---	131,605	---	57,671	---	207,146	---	---	---
1980	---	---	---	---	139,688	---	60,707	---	203,063	---	---	---
1981	---	---	---	---	147,772	---	63,742	---	233,140	---	---	---
1982	---	---	---	---	155,855	---	66,777	---	248,543	---	---	---
1983	---	---	---	---	163,938	---	69,813	---	274,050	---	---	---
1984	---	---	---	---	172,022	---	72,848	---	289,173	---	---	---
1985	544,961	---	---	---	180,105	---	83,445	---	337,524	---	---	---
1986	523,993	---	---	---	188,189	---	67,673	---	356,171	---	234,998	---
1987	568,757	---	---	---	196,272	---	67,673	---	368,620	---	258,598	---
1988	582,616	---	---	---	204,355	---	87,247	---	397,134	---	277,597	---
1989	619,398	---	---	---	212,439	---	110,654	---	425,373	---	270,797	---
1990	689,911	---	---	---	220,522	---	109,827	---	466,996	---	272,997	---
1991	724,828	---	---	---	228,606	---	109,613	---	447,170	---	259,997	---
1992	675,247	---	---	---	236,689	---	108,864	---	458,726	---	238,998	---
1993	722,714	---	---	---	214,190	---	110,311	---	475,458	---	236,997	---
1994	766,245	---	---	---	232,837	---	117,752	---	459,861	---	235,998	---
1995	813,627	---	---	---	238,727	---	120,931	---	451,523	3,398	210,998	---
1996	780,122	---	---	---	225,851	---	119,844	---	448,018	3,314	212,084	---
1997	709,237	---	---	---	235,479	---	122,241	---	451,324	5,409	177,746	16,180
1998	695,216	---	---	---	235,144	---	124,686	---	441,303	13,877	195,020	17,375
1999	725,290	---	---	---	243,278	---	---	---	490,627	13,254	398,490	16,263
2000	732,978	55,245	---	---	241,996	---	---	17,156	505,495	13,877	---	14,440
2001	785,046	50,845	---	---	241,220	20,273	---	13,245	560,837	13,424	---	14,430
2002	779,793	56,409	---	---	276,349	20,708	---	10,280	571,178	12,659	---	15,939
2003	886,216	68,373	---	---	275,784	20,614	---	8,034	640,756	7,890	---	16,756
2004	980,936	61,170	---	---	291,662	26,085	---	6,102	677,595	27,315	---	16,234
2005	---	54,517	1,129,257	---	317,122	26,571	---	5,108	706,144	32,996	---	17,166
2006	---	44,598	1,045,445	3,630	317,907	18,617	---	5,164	657,410	31,750	---	17,877
2007	---	46,683	1,042,342	7,392	317,679	19,161	---	3,464	631,197	33,396	---	15,504
2008	---	58,378	721,996	14,072	309,713	18,530	---	2,229	595,326	---	---	---

APPENDIX D: L_0 CALCULATION FOR CASE-STUDY LANDFILL 3

- Step 1: Assuming LFG generation was at peak in 1999 (the year after final MSW disposal) and extrapolating from 2000-2008 data to 1999 (details presented in Table C1 below):

$$Q_{g_{1999}} = 20 \times 10^6 \ m^3 yr^{-1}$$

- Step 2: Extrapolating from 2000-2008 data it is calculated that LFG generation will be approximately zero in year 38.

- Step 3: The area under the triangle with height of $19.5\text{x}10^6$ and base of 38 would be the overall LFG generation:

$$Q_{g_{total}} = 370 \times 10^6 \ m^3$$

- Step 4: L_0 can be calculated by dividing $Q_{g_{total}}$ by the average methane content (54%) and summary of disposed MSW ($2.2\text{x}10^6$ Mg)

$$L_0 = \frac{370 \times 10^6}{0.54 \times 2.2 \times 10^6} = 93 \ m^3 Mg^{-1}$$

Table D1. Waste disposal and LFG collection and generation history for case-study Landfill 3

Calendar Year	Year No.	MSW Disposal Tonnage, Mg	Annual LFG collected, m^3	Annual LFG generated, m^3 (assumed LFG collection efficiency of 0.90)
1972	1	32,155	---	---
1973	2	39,459	---	---
1974	3	42,495	---	---
1975	4	45,530	---	---
1976	5	48,565	---	---
1977	6	51,601	---	---
1978	7	54,636	---	---
1979	8	57,671	---	---
1980	9	60,707	---	---
1981	10	63,742	---	---
1982	11	66,777	---	---
1983	12	69,813	---	---
1984	13	72,848	---	---
1985	14	83,445	---	---
1986	15	67,673	---	---
1987	16	67,673	---	---
1988	17	87,247	---	---
1989	18	110,654	---	---
1990	19	109,827	---	---
1991	20	109,613	---	---
1992	21	108,864	---	---
1993	22	110,311	---	---
1994	23	117,752	---	---
1995	24	120,931	---	---
1996	25	119,844	---	---
1997	26	122,241	---	---
1998	27	124,686	---	---
1999	28	---	---	---
2000	29	---	17,155,971	19,948,803
2001	30	---	13,244,657	15,400,764
2002	31	---	10,280,261	11,953,792
2003	32	---	8,033,537	9,341,322
2004	33	---	6,102,210	7,095,593
2005	34	---	5,108,154	5,939,714
2006	35	---	5,164,177	6,004,857
2007	36	---	3,463,662	4,027,513
2008	37	---	2,228,569	2,591,359
Summary		2,166,760	70,781,196	82,303,716

APPENDIX E: ADDITIONAL INFORMATION TABLES FOR CHAPTER FOUR

Table E1. Florida population, past data and future predictions

Year	Population	Annual Percent Change				Type	Reference
2060	35,814,574	1.13%	during a period of	20	years	Prediction	BEBR (2009)
2040	29,203,842	1.38%	during a period of	20	years	Prediction	BEBR (2009)
2020	22,894,295	2.13%	during a period of	10	years	Prediction	BEBR (2009)
2010	18,881,445	0.20%	during a period of	2	years	Prediction	Office of Economic & Demographic Research, The Florida Legislature (2009)
2008	18,807,219	0.68%	during a period of	1	year	Estimate	Office of Economic & Demographic Research, The Florida Legislature (2009)
2007	18,680,367	1.81%	during a period of	1	year	Estimate	Office of Economic & Demographic Research, The Florida Legislature (2009)
2006	18,349,132	2.40%	during a period of	1	year	Estimate	Office of Economic & Demographic Research, The Florida Legislature (2009)
2005	17,918,227	2.29%	during a period of	1	year	Estimate	Office of Economic & Demographic Research, The Florida Legislature (2009)
2004	17,516,732	2.92%	during a period of	1	year	Estimate	Office of Economic & Demographic Research, The Florida Legislature (2009)
2003	17,019,068	1.83%	during a period of	1	year	Estimate	Florida Quick Facts (2009)
2002	16,713,149	1.93%	during a period of	1	year	Estimate	Florida Quick Facts (2009)
2001	16,396,515	2.59%	during a period of	1	year	Estimate	Florida Quick Facts (2009)
2000	15,982,824	2.35%	during a period of	10	years	Census Data	Florida Quick Facts (2009)
1990	12,937,926	3.27%	during a period of	10	years	Census Data	Florida Quick Facts (2009)
1980	9,746,961	4.35%	during a period of	10	years	Census Data	Florida Quick Facts (2009)
1970	6,791,418	3.72%	during a period of	10	years	Census Data	Florida Quick Facts (2009)
1960	4,951,560	7.87%	during a period of	10	years		BEBR (2009)
1950	2,771,305	4.61%	during a period of	10	years		BEBR (2009)
1940	1,897,414	2.92%	during a period of	10	years		BEBR (2009)
1930	1,468,211						BEBR (2009)

Table E2. Landfilled MSW composition in each Florida County and calculated L_0 for 2007

No.	Waste Type	Newspaper	Other paper	Glass	Metals	Plastics	Tires	Textiles	Food waste	Yard trash	C&D	Misc	L_0, m^3Mg^{-1}
1	Alachua	5%	32%	2%	16%	12%	2%	4%	7%	9%	5%	7%	72
2	Baker	2%	11%	2%	10%	6%	1%	2%	5%	8%	5%	48%	45
3	Bay	4%	23%	4%	23%	9%	2%	2%	9%	14%	5%	7%	58
4	Bradford	2%	17%	4%	22%	9%	1%	3%	8%	9%	5%	20%	49
5	Brevard	2%	29%	7%	11%	18%	0%	4%	5%	18%	5%	2%	64
6	Broward	4%	25%	4%	19%	8%	0%	2%	5%	19%	5%	9%	60
7	Calhoun	5%	25%	5%	30%	9%	4%	3%	6%	5%	5%	4%	56
8	Charlotte	10%	28%	7%	13%	10%	1%	2%	5%	13%	5%	5%	67
9	Citrus	3%	31%	3%	18%	13%	0%	5%	11%	3%	5%	9%	71
10	Clay	3%	22%	6%	17%	11%	0%	5%	21%	0%	5%	10%	64
11	Collier	1%	13%	2%	34%	8%	0%	0%	28%	7%	5%	2%	52
12	Columbia	8%	28%	6%	20%	11%	1%	3%	9%	3%	5%	6%	66
13	Desoto	11%	16%	10%	20%	17%	0%	3%	16%	1%	5%	0%	51
14	Dixie	6%	16%	3%	29%	10%	3%	3%	10%	8%	5%	8%	47
15	Duval	1%	23%	1%	36%	9%	2%	3%	5%	16%	5%	0%	50
16	Escambia	6%	28%	1%	34%	8%	1%	1%	3%	11%	5%	2%	60
17	Flagler	4%	9%	1%	13%	3%	0%	0%	24%	3%	5%	38%	55
18	Franklin	3%	22%	2%	19%	9%	2%	2%	9%	25%	5%	3%	57
19	Gadsden	2%	9%	2%	39%	5%	1%	1%	5%	8%	5%	22%	33
20	Gilchrist	3%	22%	5%	19%	14%	3%	4%	13%	10%	5%	1%	57
21	Glades	6%	19%	11%	24%	15%	7%	4%	5%	1%	5%	2%	44
22	Gulf	3%	18%	3%	12%	5%	1%	1%	5%	44%	5%	2%	52
23	Hamilton	14%	10%	3%	36%	1%	1%	0%	0%	30%	5%	0%	36
24	Hardee	1%	21%	6%	48%	10%	0%	4%	5%	1%	5%	0%	43
25	Hendry	2%	15%	1%	38%	5%	0%	1%	4%	2%	5%	27%	42
26	Hernando	7%	24%	2%	29%	8%	1%	2%	6%	6%	5%	10%	58
27	Highlands	15%	31%	3%	19%	7%	0%	3%	6%	8%	5%	3%	74
28	Hillsborough	3%	28%	1%	28%	6%	4%	8%	8%	7%	5%	3%	62
29	Holmes	3%	14%	4%	18%	8%	4%	3%	7%	7%	5%	26%	46
30	Indian River	10%	13%	1%	15%	4%	1%	13%	4%	7%	5%	25%	47
31	Jackson	1%	22%	4%	7%	10%	2%	2%	9%	10%	5%	27%	61
32	Jefferson	2%	13%	2%	15%	8%	3%	2%	6%	4%	5%	39%	45
33	Lafayette	4%	25%	4%	21%	10%	2%	4%	10%	10%	5%	4%	61
34	Lake	5%	16%	2%	14%	1%	0%	0%	18%	9%	5%	29%	62
35	Lee	2%	13%	6%	20%	3%	2%	16%	16%	10%	5%	7%	47
36	Leon	5%	27%	5%	21%	11%	2%	4%	13%	3%	5%	3%	66
37	Levy	3%	19%	5%	13%	12%	2%	3%	10%	2%	5%	25%	55
38	Liberty	2%	10%	2%	40%	7%	2%	2%	7%	6%	5%	16%	34
39	Madison	1%	15%	2%	44%	7%	1%	2%	6%	7%	5%	11%	38
40	Manatee	0%	24%	2%	8%	11%	1%	3%	10%	14%	5%	21%	64

Table E2. Landfilled MSW composition in each Florida County and calculated L_0 for 2007 (continued)

No.	Waste Type	Newspaper	Other paper	Glass	Metals	Plastics	Tires	Textiles	Food waste	Yard trash	C&D	Misc	L_0, m^3Mg^{-1}
41	Marion	1%	9%	0%	62%	3%	6%	2%	2%	9%	5%	1%	21
42	Martin	20%	35%	8%	8%	8%	0%	2%	6%	5%	5%	2%	84
43	Miami-Dade	4%	26%	3%	16%	7%	1%	5%	5%	14%	5%	14%	64
44	Monroe	2%	31%	6%	7%	9%	0%	2%	0%	20%	5%	17%	68
45	Nassau	1%	23%	4%	17%	11%	0%	2%	8%	8%	5%	21%	59
46	Okaloosa	4%	39%	2%	9%	12%	0%	3%	12%	4%	5%	10%	87
47	Okeechobee	0%	6%	0%	41%	0%	2%	2%	3%	22%	5%	20%	28
48	Orange	7%	26%	2%	26%	5%	1%	5%	10%	3%	5%	9%	65
49	Osceola	4%	18%	2%	9%	2%	0%	1%	12%	9%	5%	36%	62
50	Palm Beach	3%	20%	3%	25%	9%	1%	3%	7%	9%	5%	16%	52
51	Pasco	6%	23%	3%	14%	9%	7%	9%	9%	7%	5%	8%	60
52	Pinellas	6%	26%	4%	11%	9%	1%	3%	8%	6%	5%	22%	67
53	Polk	7%	17%	1%	25%	13%	2%	9%	9%	3%	5%	8%	47
54	Putnam	3%	17%	4%	35%	7%	1%	2%	10%	14%	5%	2%	47
55	Santa Rosa	3%	21%	2%	37%	4%	0%	1%	9%	13%	5%	4%	53
56	Sarasota	3%	31%	4%	15%	14%	0%	5%	16%	1%	5%	7%	74
57	Seminole	6%	33%	3%	19%	4%	0%	1%	16%	12%	5%	1%	80
58	St. Johns	14%	19%	4%	15%	10%	0%	1%	8%	18%	5%	5%	58
59	St. Lucie	4%	21%	4%	30%	7%	0%	4%	7%	2%	5%	16%	54
60	Sumter	2%	21%	4%	28%	11%	1%	4%	9%	15%	5%	1%	50
61	Suwannee	7%	12%	1%	37%	5%	2%	2%	5%	12%	5%	11%	38
62	Taylor	1%	10%	1%	30%	4%	0%	1%	4%	12%	5%	33%	37
63	Union	1%	10%	2%	20%	7%	1%	2%	6%	2%	5%	43%	40
64	Volusia	3%	26%	4%	19%	9%	0%	4%	9%	15%	5%	6%	63
65	Washington	1%	7%	2%	4%	6%	1%	1%	6%	11%	5%	56%	43
66	Wakulla	7%	31%	3%	48%	6%	0%	0%	0%	0%	5%	0%	59
67	Walton	0%	9%	4%	11%	11%	0%	4%	25%	4%	5%	28%	50
Average		4%	21%	3%	23%	8%	1%	3%	9%	9%	5%	13%	55

Table E3. LFG generation and collection, and LFGTE production potential for each Florida County under base case, 2010-2035

No.	County	LFG Generation, $x10^6$ m^3	LFG Collection, $x10^6$ m^3	LFGTE Production, $x10^6$ kWh
1	Alachua	862	328	541
2	Baker	37	13	22
3	Bay	783	272	448
4	Bradford	42	16	26
5	Brevard	2,171	881	1,452
6	Broward	4,357	1,726	2,846
7	Calhoun	15	6	9
8	Charlotte	486	203	335
9	Citrus	514	193	317
10	Clay	431	127	209
11	Collier	875	210	345
12	Columbia	185	71	118
13	Desoto	79	24	40
14	Dixie	20	7	12
15	Duval	2,874	1,155	1,905
16	Escambia	1,169	512	844
17	Flagler	188	46	76
18	Franklin	40	15	25
19	Gadsden	64	22	37
20	Gilchrist	15	5	9
21	Glades	24	9	15
22	Gulf	39	15	25
23	Hamilton	9	4	7
24	Hardee	40	16	27
25	Hendry	64	25	41
26	Hernando	426	164	270
27	Highlands	408	162	267
28	Hillsborough	2,319	898	1,480
29	Holmes	31	11	17
30	Indian River	520	202	333
31	Jackson	99	38	63
32	Jefferson	19	7	11
33	Lafayette	11	4	7
34	Lake	382	106	174
35	Lee	968	293	484
36	Leon	844	310	511
37	Levy	57	21	34
38	Liberty	6	2	3
39	Madison	20	8	13
40	Manatee	893	342	564

Table E3. LFG generation and collection, and LFGTE production potential for each Florida County under base case, 2010-2035 (continued)

No.	County	LFG Generation, $x10^6$ m^3	LFG Collection, $x10^6$ m^3	LFGTE Production, $x10^6$ kWh
41	Marion	256	104	171
42	Martin	660	275	453
43	Miami-Dade	7,882	3,150	5,193
44	Monroe	408	179	296
45	Nassau	243	92	152
46	Okaloosa	1,056	401	661
47	Okeechobee	55	21	35
48	Orange	4,287	1,613	2,660
49	Osceola	704	245	403
50	Palm Beach	1,800	687	1,132
51	Pasco	655	231	381
52	Pinellas	1,633	648	1,068
53	Polk	1,485	522	861
54	Putnam	146	52	85
55	Santa Rosa	381	156	258
56	Sarasota	997	364	601
57	Seminole	1,422	509	838
58	St. Johns	500	197	325
59	St. Lucie	679	256	422
60	Sumter	117	42	70
61	Suwannee	280	105	173
62	Taylor	24	9	16
63	Union	15	5	9
64	Volusia	1,553	605	998
65	Washington	54	17	29
66	Wakulla	29	13	21
67	Walton	273	61	101
Summary		49,981	19,030	31,375

APPENDIX F: UNIT PRICES FOR ECONOMIC ANALYSIS

Table F1. Unit prices for economic analysis, Chapter Five

		2006 Unit Price	2010 Unit Price
GENERAL			
Inflation rate		3%	3%
Sinking fund rate		4%	4%
Interest rate		5%	5%
CONSTRUCTION			
Initial work	Survey	$16,000/hectare	$18,000/hectare
	Clearing site	$5,000/hectare	$5,500/hectare
Bottom liner	Excavation	$500,000/hectare	$550,000/hectare
	Berm	$32,000/hectare	$36,000/hectare
	Clay layer	$240,000/hectare	$270,000/hectare
	Composite liner	$320,000/hectare	$360,000/hectare
	QA/QC	$220,000/hectare	$240,000/hectare
Leachate collection system	Pipes	$25,000/ hectare	$28,000/ hectare
	Sumps		
	Storage tank/pond		
Gas flare		$1,100/hectare	$1,300/hectare
Leachate recirculation system	Piping and valves	$7,000/hectare	$8,000/hectare
	Pumps	$8,000/hectare	$9,000/hectare
	Ponds	$52,000/hectare	$58,000/hectare
	Well drilling	$4,000/hectare	$4,500/hectare
	Installation	$10,000/hectare	$11,000/hectare
Support facilities	Offices, fencing, etc.	$1,500,000	$1,700,000
Engineering costs	Based on total construction costs	1%	1%
OPERATION & MAINTENANCE			
Operations	Equipment, staff, facilities, etc.	$1,000,000	$1,130,000
Environmental sampling		$30,000	$34,000
Engineering services		$60,000	$68,000
LEACHATE TREATMENT			
Off-site treatment		$0.06/liter	$0.07/liter

Table F1. Unit prices for economic analysis, Chapter Five (continued)

		2006 Unit Price	2010 Unit Price
TEMPORARY CLOSURE			
Final grades survey		$12,000/hectare	$14000/hectare
Cover and vegetative soil		$50,000/hectare	$56,000/hectare
Seed, mulch, and fertilizer		$5,000/hectare	$5,600/hectare
Run-off water control		$15,000/hectare	$17,000/hectare
Gas collection system		$68,000/hectare	$76,000/hectare
FINAL CLOSURE			
Final grades survey		$12,000/hectare	$14,000/hectare
Compacted clay cap		$99,000/hectare	$110,000/hectare
Geomembrane cap		$50,000/hectare	$56,000/hectare
Cover and vegetative soil		$50,000/hectare	$56,000/hectare
Seed, mulch, and fertilizer		$5,000/hectare	$5,600/hectare
Run-off water control		$15,000/hectare	$17,000/hectare
QA/QC		$210,000/hectare	$240,000/hectare
POST-CLOSURE CARE			
Security and fencing		$10/hectare/yr	$12/hectare/yr
Final cap and cover		$1,100/hectare/yr	$1,200/hectare/yr
Landfill gas mechanics		$1,200/hectare/yr	$1,400/hectare/yr
Wells/probes		$60/hectare/yr	$70/hectare/yr
Environmental monitoring		$1,300/hectare/yr	$1,500/hectare/yr
Gas collection system maintenance	Based on annual capital costs	5%	5%

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