ECONOMIC FEASIBILITY OF CONVERTING LANDFILL GAS TO NATURAL GAS FOR USE AS A TRANSPORTATION FUEL IN REFUSE TRUCKS

A Thesis

by

STEPHEN M. SPRAGUE

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

December 2009

Major Subject: Civil Engineering

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Approved by:

Chair of Committee,	Mark Burris
Committee Members,	David Ellis
	Josias Zietsman
Head of Department,	John Niedzwecki

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ABSTRACT

Economic Feasibility of Converting Landfill Gas to Natural Gas for Use as a
Transportation Fuel in Refuse Trucks. (December 2009)
Stephen M. Sprague, B.S., University of South Carolina at Columbia
Chair of Advisory Committee: Dr. Mark Burris

Approximately 136,000 refuse trucks were in operation in the United States in 2007. These trucks burn approximately 1.2 billion gallons of diesel fuel a year, releasing almost 27 billion pounds of greenhouse gases. In addition to contributing to global climate change, diesel-fueled refuse trucks are one of the most concentrated sources of health-threatening air pollution in most cities. The landfills that they ultimately place their waste in are the second largest source of human-related methane emissions in the United States, accounting for approximately 23 percent of these emissions in 2007. At the same time, methane emissions from landfills represent a lost opportunity to capture and use a significant energy resource.

Many landfill-gas-to-energy (LFGTE) projects are underway in an attempt to curb emissions and make better use of this energy. The methane that is extracted from these landfills can be converted into a transportation fuel, sold as a pipeline-quality natural gas, operate turbines for electricity, or be flared. The unique relationship that occurs between refuse trucks' constant visits to the landfill and the ability of the landfill itself to produce a transportation fuel creates an ability to accomplish emissions reduction in two sectors with the implementation of using landfill gas to fuel refuse trucks.

Landfill owners and operators are very reluctant to invest in large capital LFGTE projects without knowing their long-term feasibility. The costs and benefits associated with each LFGTE project have been presented in such a way that owners/operators can make informed decisions based on economics while also implementing clean energy

technology. Owners/operators benefit from larger economic returns, and the citizens of the surrounding cities benefit from better air quality.

This research focused on six scenarios:

- converting landfill gas (LFG) to liquefied natural gas (LNG) for use as a transportation fuel,
- converting LFG to compressed natural gas (CNG) for use as a transportation fuel,
- converting LFG to pipeline-quality natural gas,
- converting LFG to electricity,
- flaring LFG, and
- doing nothing.

For the test case of a 280-acre landfill, the option of converting LFG to CNG for use as a transportation fuel provided the best benefit-cost ratio at 5.63. Other significant benefit-cost findings involved the LFG-to-LNG option, providing a 5.51 benefit-cost ratio. Currently, the most commonly used LFGTE option of converting LFG to electricity provides only a 1.35 benefit-cost ratio while flaring which is the most common mitigation strategy provides a 1.21, further providing evidence that converting LFG to LNG/CNG for use as a transportation fuel provides greater economic benefits than the most common LFGTE option or mitigation strategy.

ACKNOWLEDGEMENTS

I would like to thank my committee chair, Dr. Mark Burris, and my other committee members, Dr. David Ellis and Dr. Josias Zietsman, for their support and guidance during the course of this thesis. I would specially like to thank Dr. Josias Zietsman for allowing me to work under his direction at the Center for Air Quality Studies at the Texas Transportation Institute (TTI). Previous projects along with work conducted at the center during my tenure provided the foundation for this thesis.

Mary Jo-Rowan, project manager at the Texas State Energy Conservation Office (SECO), was pivotal in awarding research grants for landfill gas and refuse truck emissions studies in both India and San Antonio, which provided the basis for this research. Dr. Rakesh Kumar of the National Engineering Research Institute (NEERI) in Nagpur, India, and Dr. Bruce Smackey of Mack Trucks both provided essential information that was used in this thesis. Employees with the City of San Antonio were especially helpful, particularly those we worked with at the Solid Waste Management Department's Northeast Service Center, specifically Catarino DeLuna, Fidel Valdovinos, and Florencio Pena. Miguel Parra of the City of El Paso provided data about the Clint landfill. The emissions results from that study are a result of the work of those at TTI, including Dr. Doh-Won Lee and Dr. Mohamadreza Farzaneh, both of the Center for Air Quality Studies.

I would like to thank my friends, colleagues, and other faculty members in the Department of Civil Engineering at Texas A&M University for making my coursework an enjoyable as well as enlightening educational experience. I would also like to thank the Texas Transportation Institute and Texas A&M University for providing me with the necessary facilities, funding, and resources for my research.

Finally, I would like to thank my family for their continued support and encouragement.

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CHAPTER I

INTRODUCTION

The first chapter of this thesis is an introduction to landfill gas to energy (LFGTE) projects. Numerous landfill-gas-to-energy (LFGTE) projects are appearing across the nation, but the most common types of projects being implemented may not be accomplishing their main purposes, which are profitability and energy conservation. This chapter outlines the overall economics and reasoning behind various LFGTE projects.

Volatile energy prices, growing concern over America's energy security, and global climate change have caused numerous municipalities to look for alternative solutions to solve their energy demands while appeasing citizens' requests for "greener" lifestyles. Landfills, once thought to be the problem, now play a role in the solution. LFGTE projects have been popping up across the nation due to new engineering designs that allow the once-harmful methane gas emitted from landfills to become a source of energy. A majority of the LFGTE projects focus on converting methane, a byproduct of waste decomposition, into electricity (U.S. EPA 2009a). Other methods focus on converting the methane into pipeline-grade natural gas or flaring it, yet very little research has explored the use of landfill gas as a transportation fuel.

Landfill gas is a major source of air pollution throughout the United States, including in the state of Texas, which is home to 246 landfills (Table 1) (TCEQ 2007). With international political pressure to lower global greenhouse-gas emissions in an aim to curb the effects of global warming; engineers, scientists, entrepreneurs, and businessmen alike are all looking for feasible, innovative solutions that can not only solve the problem but provide a return that is worthy of their investment.

This thesis follows the journal style of the American Society of Civil Engineers (ASCE): *Journal of Transportation Engineering*.

Table 1: Texas Landfill Activity Status in 2007 (TCEQ 2007)

Activity Status	**Open or Closed**	**Count**
Active	Open	188
Inactive—yet to receive waste	Open	11
Inactive—previously received waste	Open	16
Post-closure care	Closed	31
Total		**246**

Financial feasibility is the largest deterrent for most politicians and corporations to invoking stricter air-quality emissions standards in their respective jurisdictions or companies. Politicians feel that their constituents will be hindered through these stricter standards, with companies looking to cut costs in the form of job losses and company relocation in order to mitigate costly pollutant issues. Others argue that global warming is not an issue at all and that it has not been proven beyond a reasonable doubt in order to pass legislation that will require cleaner emissions from both municipalities and corporations. The globalization of all industries and services has created another deterrent in the fight against global warming. Many feel that there is no need to hinder their economic advancement with stricter regulations and emissions standards when global warming is a global issue. If it costs a private company more money to produce their product due to these regulations, there will always be another city, state, or country with more relaxed regulations that will produce the same product cheaper. Supporters in this camp feel a global initiative is the only true mitigation strategy.

People appear to be most interested in LFGTE projects when the costs of traditional fossil fuels reach a "tipping point." A survey by the Automotive Aftermarket Industry Association sets a tipping point at $4 per gallon for gasoline, the point where 65 percent of American drivers said they would change their driving behavior. Some analysts believe that $4 prices at the pump must be sustained for a long period in order to yield significant changes (HybridCARS 2008). For many alternative-energy projects this tipping point is directly correlated with the feasibility of numerous alternative-energy projects.

The most popular alternative fuels are biodiesel and ethanol. Biodiesel is produced from "feedstock," which is comprised of various vegetable oils, such as soybean, canola, and palm. Ethanol is primarily comprised of corn or sugar cane. When the starches are refined, they produce ethyl alcohol, or "grain alcohol." Both the biodiesel and ethanol are then refined and sold as fuels. It is important to look at the overall or total energy balance when looking at various energy solutions. For each unit of gasoline that is produced (gallon, liter, etc.), 1.22 units of energy are needed to produce that unit of gasoline (Table 2).

Table 2: Energy Balance

Fuel	Units Needed to Produce 1 Unit of Fuel
Gasoline	1.22
Diesel	0.83
Ethanol	0.76
Biodiesel	2.5-4.5

Based on energy balance, ethanol appears to be the most efficient fuel source, needing only 0.76 units of energy to produce 1 unit of fuel. Numerous economic factors make ethanol and biodiesel unable to currently compete with gasoline and diesel, which are derived from crude oil. Ethanol can be competitive with oil-based fuels if oil is greater than $30 per barrel (bbl) with current government subsidies or $50 without subsidies (EFC 2007). Biodiesel needs to have oil at the $43/bbl mark to make it a competitive option (Timmerman 2007). This value can vary greatly depending on the feedstock components that produce it. A tax credit of $0.051/gallon is provided to ethanol suppliers. Whether ethanol is comprised of either corn or sugar cane is dependent upon those crops. If there is a bad crop, then the price of those commodities will naturally rise; thus the cost of oil would to need to be higher in order for ethanol to be cost-effective. One caveat for ethanol is that it is processed or refined by heating it with natural gas. Natural gas prices vary, and thus so does the price of ethanol vary accordingly (EFC 2007). For the purposes of using natural gas as a fuel, very little additional processing or refining is needed to clean the methane gas from landfills into precipitate-free, dry natural gas.

Infrastructure and accessibility to alternative fuels via fueling stations as well as changing human behavior are all unknowns when attempting to quantify the feasibility of various projects. If LFGTE projects were 100 percent economical at all landfills, they would already be implemented. LFGTE projects can be feasible, yet the public as well as owners and operators know very little about them. With so much propaganda, literature, and biased press releases, how can owners/operators figure out which LFGTE project is best for them? This thesis answers some of those questions.

One of the most promising reduction technologies for greenhouse gases (GHGs) appears to come from landfills. Since the passage of the Resource Conservation and Recovery Act (RCRA) of 1976, the U.S. Environmental Protection Agency (EPA) has placed strict regulations on the design and construction of landfills within the United States. Because of this, a new era of landfill gas collection is possible. Landfills must now be designed with various geotextile, geomembrane, and liner systems in order to prevent leachate from percolating into the surrounding soil(s) or groundwater and contaminating valuable potable water supplies (see Figure 1) (Qian et al. 2002). Leachate includes liquid that builds in landfills from rainwater and excess fluids in municipal solid waste (MSW), such as soft drinks, detergents, household cleaners, etc.

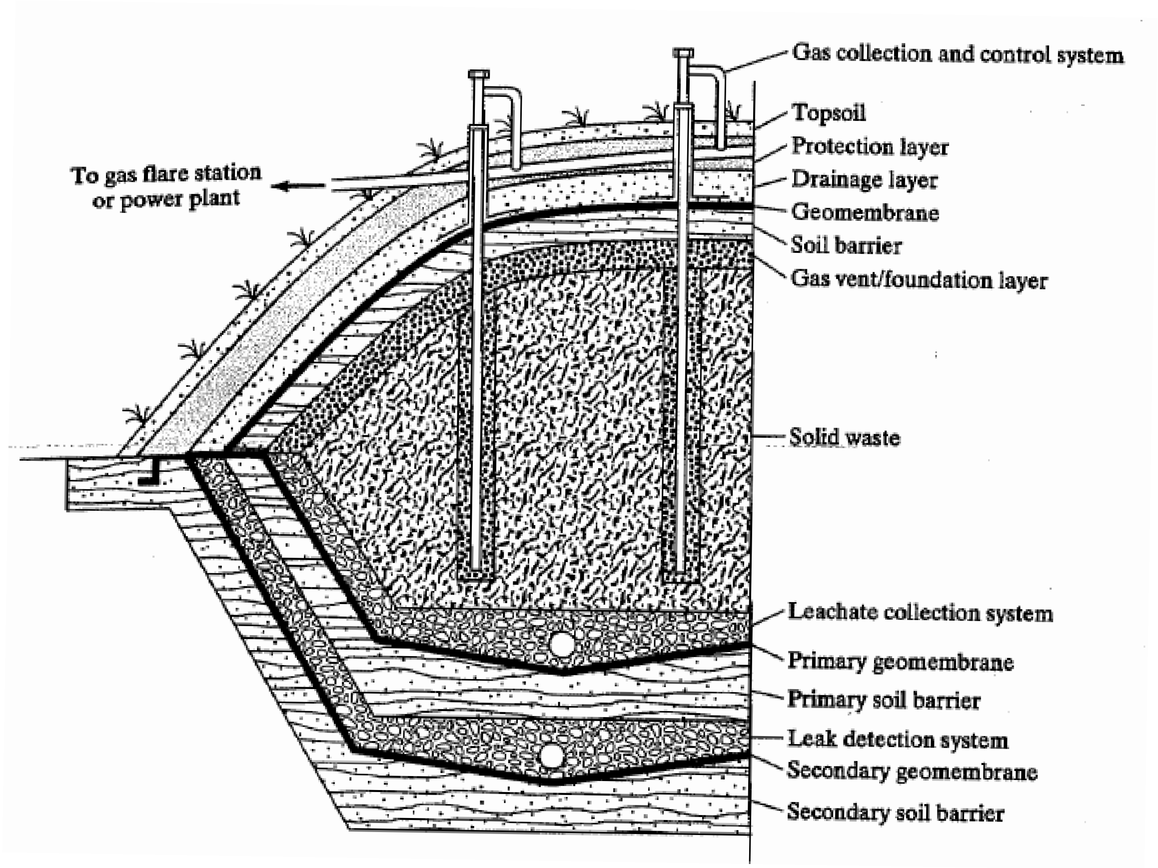


Figure 1: Basic Engineered Landfill Schematic (Qian et al. 2002)

The liners at the base of the landfill create an impermeable layer to stop leachate from flowing downward, ultimately acting as a giant trash bag to contain all waste and pollutants. More than 150 different gases, mostly in the parts per million (ppm) range, have been identified in landfill gas. The most common emissions come in the form of carbon dioxide (CO_2) and methane (CH_4), and trace amounts come from other gases, including hydrogen sulfide (H_2S) and non-methane organic content (NMOC), which all escape from a landfill and are released into the atmosphere (Table 3).

Table 3: Typical Constituents of MSW Landfill Gas (Qian et al. 2002)

Component	**Percent**
Methane (CH_4)	45-58
Carbon dioxide (CO_2)	35-45
Nitrogen (N_2)	<1-20
Oxygen (O_2)	<1-5
Hydrogen (H_2)	<1-5
Water vapor (H_2O)	<1-5
Trace constituents*	<1-3

*NMOCs are among the trace constituents.

The hydrogen sulfide is typically what is associated with the distinctive odor of landfill gas (Qian et al. 2002). In cases where these emissions cannot escape into the atmosphere, they act in the same manner as any other fluid, moving in the path of least resistance. Before the days of engineered or sanitary MSW landfills, this would include not only atmospheric pollution but also contamination of the soil(s) and groundwater. Since the liner systems created in today's engineered landfills prevent downward leakage of all fluid (gas and liquid) pollutants, gaseous emissions are forced to travel upwards, which creates an opportunity to harvest these emissions when a landfill is capped.

A landfill is traditionally capped once it is closed or has ceased accepting waste. Landfills are capped in an attempt to dramatically reduce air pollution (primarily smell) and provide a "green" area typically in the form of parks and recreation space from a once-intrusive, unwelcome trash heap. Caps consist of similar liner systems that are used to trap MSW and its leachate from contaminating soil(s) and groundwater. The top layer is traditionally grass since its root system will not negatively impact the integrity of the liners below it, causing the system as a whole to fail. Typical layers of a landfill cap can be seen in Figure 2.

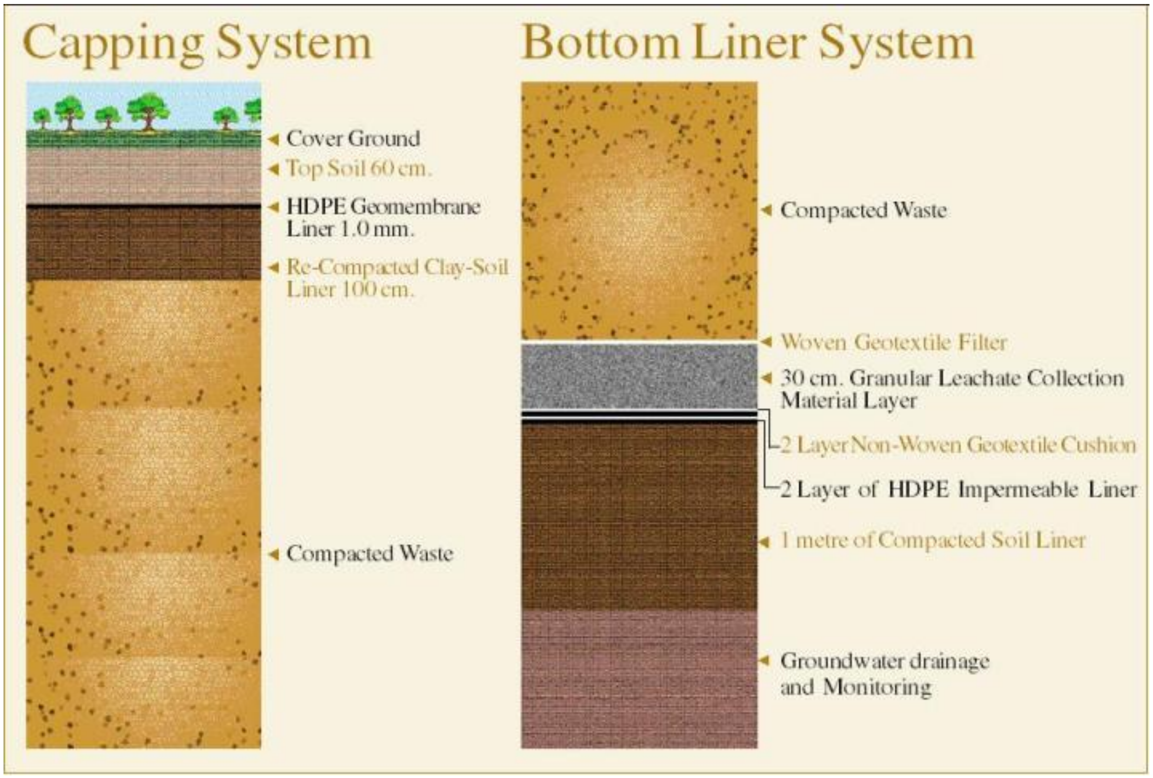
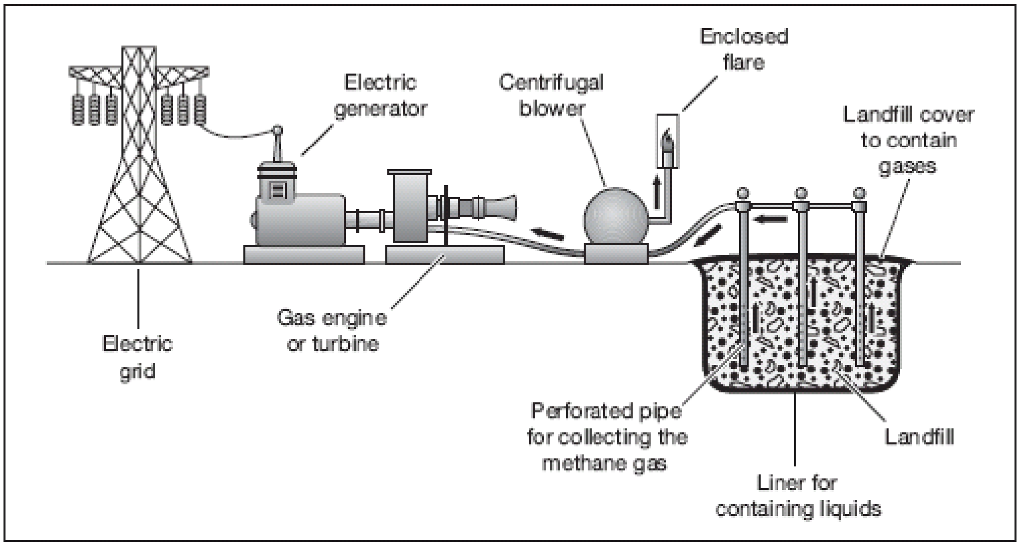


Figure 2: Layers of a Landfill (Waste Management Siam 2006)

Recently, many municipalities have chosen to recapture the methane from their nearby or local landfills through landfill-gas-to-electricity projects. This process uses widely available technology to produce electricity from the extracted methane gas (Figure 3). Although this method has been the most frequently used LFGTE process, recent research has shown that converting landfill methane gas to liquefied natural gas (LNG) or compressed natural gas (CNG) for use as a transportation fuel in refuse trucks is the most beneficial way to maximize emissions benefits and financial returns (Zietsman et al. 2008).



SCHEMATIC DIAGRAM OF LFG-TO-ELECTRICITY PLANT *Major components include the collection system, engine and generator.*

Figure 3: LFG-to-Electricity Plant (TCEQ 2007)

With the recent creation of carbon credit trading platforms in the United States, Europe, India, and China, carbon credits have provided a new financial benefit for LFGTE projects. These carbon credits, currently valued anywhere from $1 in the United States to $25 (U.S. dollars [USD]) in Europe, will give landfill owners and operators another reason to extract LFG from their landfills—financial profit (CCX 2009). Landfill operators can now profit from each ton of emissions that is captured and either create another form of energy (i.e., fuel) or flare (i.e., burn off) the harmful emissions.

Study Objectives

The purpose of this thesis is to develop a methodology that can be used to evaluate the economic feasibility of using landfill gas as a natural gas fuel source (CNG/LNG) for refuse trucks. The methodology considers the various characteristics that comprise the creation of LFG and the quantity that is available for capture based on a landfill's size, waste composition, age, and climate. The methodology differs from other research in that it incorporates landfill-gas generation rates with monetary dollar amounts for the emissions that result (assuming 50 percent of both CO_2 and CH_4) by incorporating carbon credit prices with these emissions. Interested parties, such as landfill owners/operators, municipalities, refuse truck vendors, environmental agencies, and researchers, can all consider this methodology in order to make informed decisions as to which LFGTE project may be best for them depending on the characteristics of the landfill they are studying. A feasibility tool (spreadsheet) included with the thesis aims to make this process even easier by allowing the user to input values stated in the methodology/analysis section into the spreadsheet to receive an output that explicitly states the feasibility of the six scenarios studied, providing a benefit-cost ratio. This tool allows users to view the pre-feasibility of implementing LFGTE projects at their landfill. Based on the results, users can decide to look into the various options that are deemed profitable or desirable in greater detail. The specific objectives of this thesis include:

- prepare a review of relevant literature;
- prepare a methodology to provide the feasibility of various LFGTE projects based on critical factors, such as:
    - carbon credit pricing (based on current and future potential market conditions);
    - cost of diesel, natural gas, LNG, and electricity;
    - cost of each LFGTE option;
    - modeling of LFG emissions; and
    - tax benefits;
- evaluate the difference in emissions from CNG versus diesel refuse trucks; and
- apply the methodology to a Texas landfill to obtain benefit-cost ratios for various LFGTE scenarios.

Thesis Organization

This thesis is divided into six chapters. Chapter I provides an introduction to the research presented in this thesis and the overall goals of the research. Chapter II provides a review of the literature on various topics related to landfill gas creation, LFGTE projects, and carbon credit trading. Chapter III takes the reader through a step-by-step process describing the methodology used in this analysis along with any assumptions used. Chapter IV goes into greater detail about the analysis and provides an estimate of the benefits derived from each of the six scenarios examined using the Clint landfill in El

Paso as a case study. Chapter V describes the costs that would be incurred from each of the various options as well as the findings from the analysis of the benefits and costs. All conclusions and recommendations are reported in Chapter VI. Appendix A contains additional information on the CO_2 WASH^{TM} process. Appendix B is a spreadsheet that enables the user to input information and receive a pre-feasibility output based on the calculations stated in the methodology section of this thesis. Appendix C provides the output tables of the spreadsheet in Appendix B.

CHAPTER II
LITERATURE REVIEW

This chapter provides a review of published literature on topics related to MSW generation, landfill-gas creation, landfill design, methods of landfilling, and landfills that have the potential to become energy producers in Texas. The definition of natural gas is explained, as well as how LFG collection systems are created and how the gas is processed. Background information on existing LFGTE projects as well as the growing market for carbon credit trading provides detailed information on LFGTE projects.

Solid Waste Management

According to the U.S. EPA, the amount of MSW generated by residents, businesses, and institutions in the United States in 2007 was 254 million tons, or 4.62 pounds per person per day. Our trash is made up of the things we commonly use and then throw away. These materials range from packaging, food scraps, and grass clippings to old sofas, computers, tires, and refrigerators. These are the materials generally disposed of in landfills along with some other materials not classified as MSW such as construction debris, municipal waste treatment sludge, and non-hazardous industrial waste although construction and demolition debris (C&D) typically has its own landfill. The solid waste materials are classified under Subtitle D of the Resource Conservation and Recovery Act. A breakdown of the composition of waste can be seen in Figure 4.

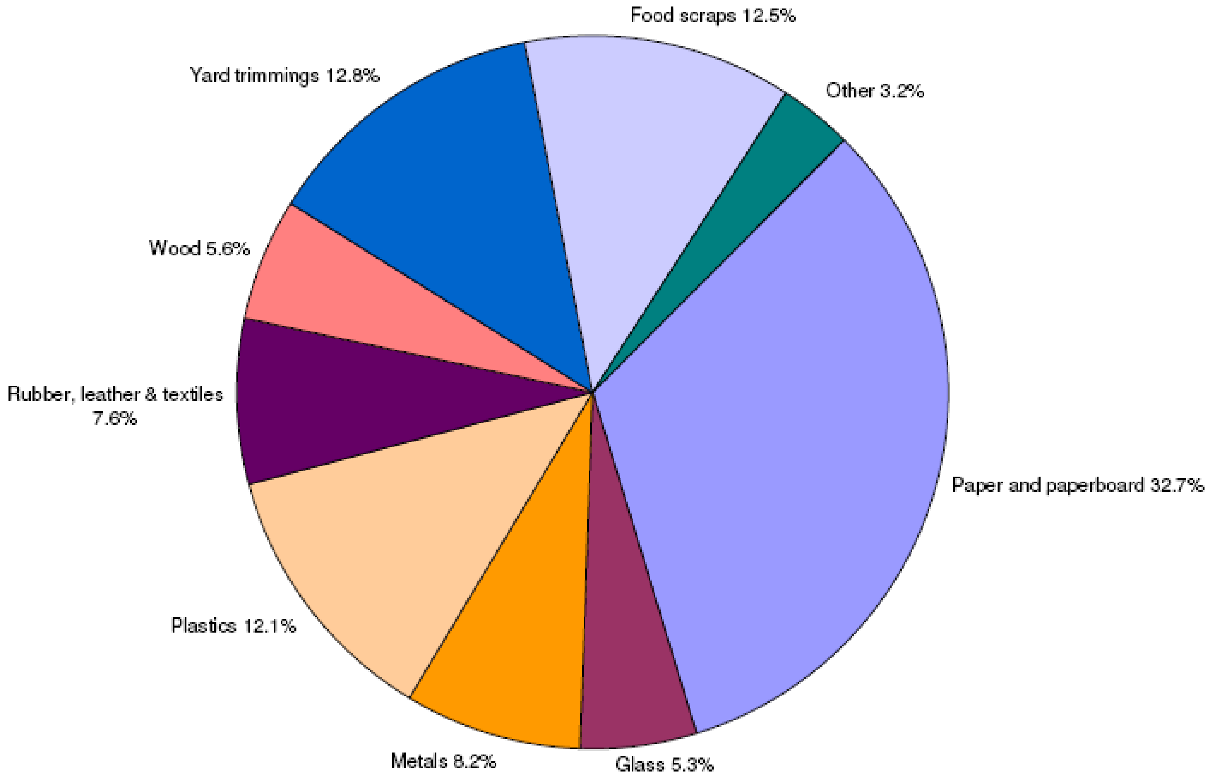


Figure 4: Materials Generated in MSW, 2007 (U.S. EPA 2008a)

There has recently been a decrease in the amount of refuse that Americans produce. Despite this decrease there is still a high level of waste generation and with rising levels of recycling or waste recovery, optimal levels of methane can be generated (Table 4). The “recovery for recycling” row in Table 4 provides evidence that greater quantities of recyclable materials are indeed being recycled. Recyclable items include various items such as plastic bottles, rubber tires, paper, aluminum cans, glass bottles, and scrap metal. The removal of these items will enable organic materials to occupy a greater percentage of the landfill space. These items degrade much more quickly than non-organic materials. Methane is generated in higher concentrations from the decomposition of organic matter than from inorganic items (i.e., car batteries). A greater proportion of a landfill’s volume being taken up by food scraps, compost, and yard clippings will enhance the decomposition rate, creating a higher level of methane output and leading to greater methane recovery volumes and feasibility for LFGTE projects.

Table 4: Generation, Materials Recovery, Composting, Combustion with Energy Recovery, and Discards of MSW, 1960-2007 (in Millions of Tons) (U.S. EPA 2008a)

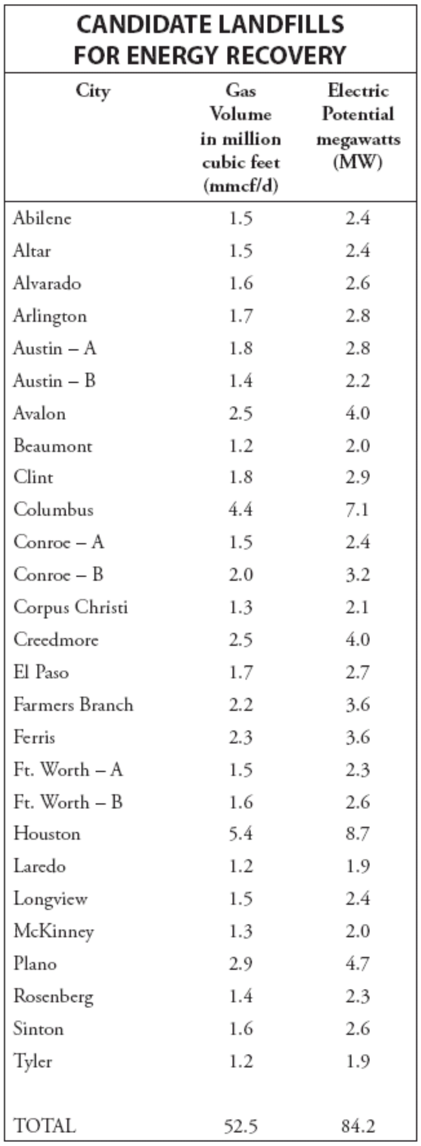
Activity	**1960**	**1970**	**1980**	**1990**	**2000**	**2004**	**2005**	**2006**	**2007**
Generation	88.1	12.1	151.6	205.2	239.1	249.8	250.4	254.2	254.1
Recovery for recycling	5.6	8.0	14.5	29.0	52.9	57.5	58.8	61.4	63.3
Recovery for composting*	Neg.	Neg.	Neg.	4.2	16.5	20.5	20.6	20.8	21.7
Total materials recovery	5.6	8.0	14.5	33.2	69.4	78.0	79.4	82.2	85.6
Combustion with energy recovery**	0.0	0.4	2.7	29.7	33.7	31.5	31.6	31.9	31.9
Discards to landfill, other disposal***	82.5	112.7	134.4	142.3	136.0	140.3	139.4	140.1	137.2

*Includes composting of yard trimmings, food scraps, and other MSW organic material but does not include backyard composting.
**Includes combustion of MSW in mass burn or refuse-derived fuel farm and combustion with energy recovery of source-separated materials in MSW (e.g., wood pallets and tire-derived fuel).
***Includes discards after recovery minus combustion with energy recovery. Discards include combustion without energy recovery.

Texas Potential

About 22 million tons of trash are landfilled in Texas each year. That trash, in turn, creates approximately 70 billion cubic feet of methane. That quantity is equivalent to 1 percent of the natural gas produced in Texas each year and 7 percent of the gas used by Texas' electric utility companies. If the 70 largest landfills in Texas were fully developed for energy use, approximately 40 billion cubic feet of methane now drifting into the atmosphere or being wasted in flares would be utilized. It is estimated that nearly 200 megawatts (MW) of electricity could be generated from this LFG, meeting the electricity needs of more than 100,000 Texas homes. Nationwide, more than 339 LFG utilization projects are in operation, and perhaps 600 additional projects are feasible. In Texas, 11 LFGTE projects were in service by the end of 2002. At least 55 more LFGTE projects have the potential to be feasible based on their size and waste composition (TCEQ 2007) (Table 5).

Table 5: Candidate Landfills for Energy Recovery in Texas (TCEQ 2007)



CANDIDATE LANDFILLS FOR ENERGY RECOVERY

City	Gas Volume in million cubic feet (mmcf/d)	Electric Potential megawatts (MW)
Abilene	1.5	2.4
Altar	1.5	2.4
Alvarado	1.6	2.6
Arlington	1.7	2.8
Austin – A	1.8	2.8
Austin – B	1.4	2.2
Avalon	2.5	4.0
Beaumont	1.2	2.0
Clint	1.8	2.9
Columbus	4.4	7.1
Conroe – A	1.5	2.4
Conroe – B	2.0	3.2
Corpus Christi	1.3	2.1
Creedmore	2.5	4.0
El Paso	1.7	2.7
Farmers Branch	2.2	3.6
Ferris	2.3	3.6
Ft. Worth – A	1.5	2.3
Ft. Worth – B	1.6	2.6
Houston	5.4	8.7
Laredo	1.2	1.9
Longview	1.5	2.4
McKinney	1.3	2.0
Plano	2.9	4.7
Rosenberg	1.4	2.3
Sinton	1.6	2.6
Tyler	1.2	1.9
TOTAL	52.5	84.2

Methods of Solid Waste Management

There are different methods of managing MSW. The integrated waste management (IWM) technique developed by the EPA is one such methodology in which different practices are used to safely and effectively handle the solid waste. The EPA's 1989 *Agenda for Action* identifies the hierarchy of the following basic components of IWM as (U.S. EPA 1996a):

- recycling,
- composting,
- waste combustion with energy recovery, and
- landfilling.

Figure 5 is a graphical representation of the IWM process (U.S. EPA 2003). The figure illustrates that there are several sources of waste and several processes to handle the waste. These waste management options can be performed in a specific order, or they can be implemented simultaneously with effective coordination between them. However, the final purpose of the process should be to effectively handle the solid waste and increase the efficiency of energy recovery. Currently, 33.4 percent of the solid waste generated in the United States is recovered, recycled, or composted; 12.6 percent is incinerated; and the remaining 54 percent is disposed of in landfills (U.S. EPA 2008a).

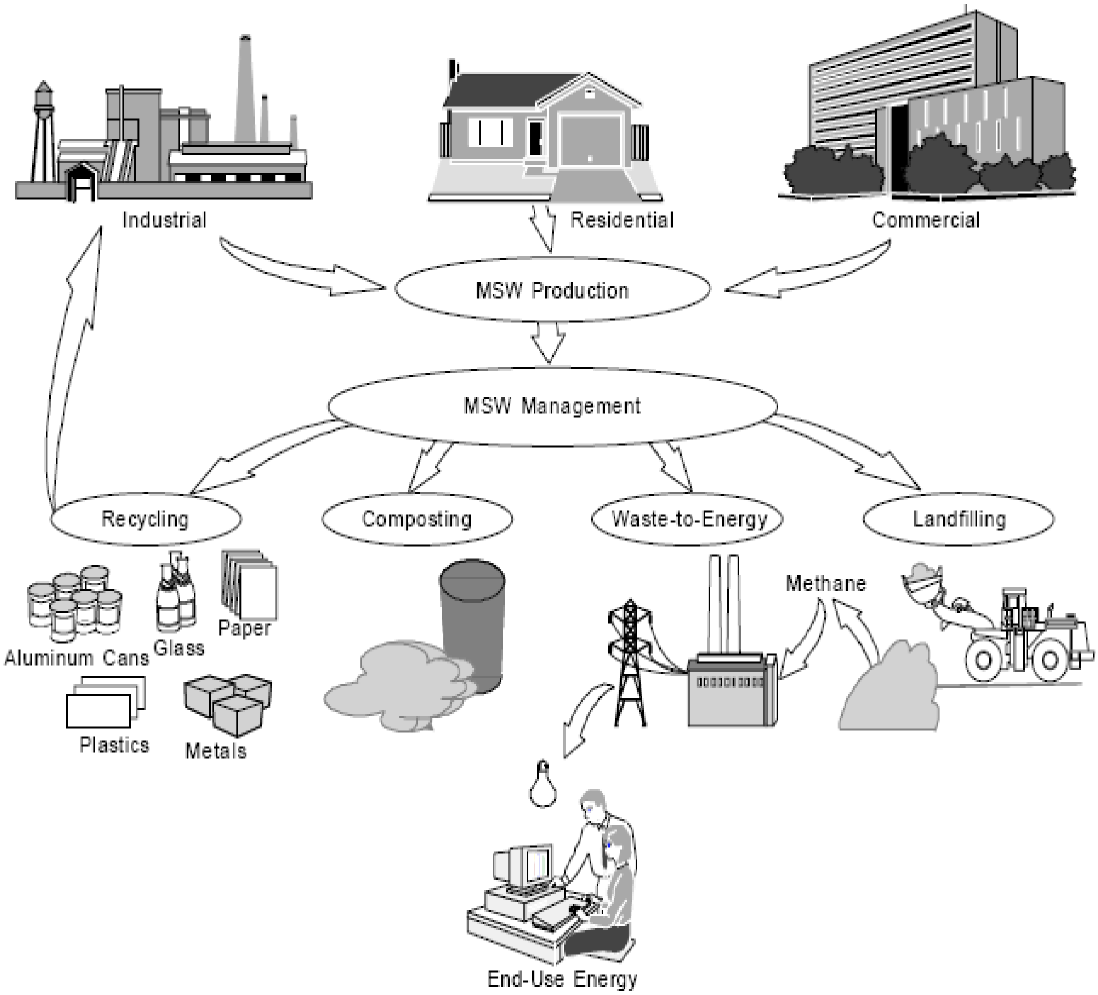


Figure 5: Integrated Waste Management of Municipal Solid Waste (U.S. EPA 2003)

Landfills

Land disposal has always been and continues to be the most common form of handling and disposing of various types of waste and can occur in numerous different forms. The most common is the shallow burial vault in soil, commonly known as a landfill.

Landfill Composition

Landfills are most commonly classified into three different categories based on the type of waste that is placed into them. The classifications include:

1. *MSW or sanitary landfill*: This type of landfill is comprised of MSW classified as RCRA Subtitle D (non-hazardous waste) as well as non-hazardous sludge (sludge from waste-water treatment plants).

2. *Construction and demolition debris landfill*: C&D materials consist of the debris generated during the construction, renovation, and demolition of buildings, roads, and bridges. C&D materials often contain bulky, heavy materials, such as concrete, wood, metals, glass, and salvaged building components.
3. *Hazardous waste landfill*: These landfills are comprised of wastes classified as hazardous in accordance with RCRA Subtitle C (petroleum byproducts, acids, etc.) (U.S. EPA 1999).

For efficient and safe operations, the landfill should adhere to specific regulations and design standards. It should be designed to prevent the migration of LFG and leachate to the surrounding areas, especially groundwater reservoirs, and should have systems that would facilitate the collection of LFG. The following are the general components of a landfill. These components would maintain the sanitary conditions at a landfill and improve its gas collection efficiency (U.S. EPA 1995).

- *Primary and secondary liners*: These layers surround the base of the landfill and are anchored by anchor trenches that hold them in place (simply trenches with soil backfill). This layer is designed to prevent the flow of the leachate from migrating to the surrounding areas and the ground below the landfill. Typically the liner systems have:
    - *Soil drainage layer*: This layer acts as the primary defense against leachate migration and helps to soak up any leachate that builds on the liner system.
    - *Geotextile*: A geotextile liner helps to provide strength and stability to the liner system as a whole. Its main purpose is for reinforcement. The strength of the geotextile keeps the soil above it separated from the geonets and geomembranes below it.
    - *Geonet*: A geonet acts as a drainage liner. Any leachate or liquid that has reached this point needs to be filtered down to the geomembrane below it to be removed and recycled to the leachate collection and removal system (if possible).

  - *Geomembrane*: The geomembrane is the first and one of the last lines of defense against leachate migration. The geomembrane is essentially a large trash bag that has next to zero permeability.
  - *Compacted clay liner (CCL)/geosynthetic clay liner (GCL)*: This is the last defense against leachate migration. Clay has a very low permeability, and manufactured liners with the same mechanical properties act to soak up any remaining leachate or liquid that gets to this point.
  - *Secondary liner system*: The system consists of another round of all these liners.
- *Leachate collection system*: The system consists of a network of pipes or geosynthetic material placed to transmit leachate to various collection points where it can be treated or re-injected into the landfill to enhance biodegradation rates. Depending on the classification of the landfill, additional liners and leachate collection systems may be required.
- *Cover*: A typical landfill has two covers. One is placed after the daily operations—primarily soil or in some instances a large geosynthetic cover. The second is also referred to as a cap and is placed at the end of the landfill’s design capacity. It is comprised of many of the layers listed previously in order to make sure emissions are controlled after the landfill ceases accepting waste and that no additional rainwater or contaminants get into the landfill.
- *Gas collection system*: The system consists of a network of pipes placed to collect LFG and transmit it to a central location.
- *Gas monitoring probe system*: The system consists of a network of probes placed at several points across the landfill to detect the flow of gas throughout the landfill.
- *Groundwater monitoring well system*: The system consists of monitoring wells placed at selected points around the landfill but typically downstream from the landfill to ensure that the byproducts of the landfill do not enter the local ecosystem. This is especially critical if the surrounding geomembrane is ruptured.

Landfill Development

There are several ways to develop a sanitary landfill. The selection of a particular method may be based on the topographic conditions and the ease of operations at a landfill. The following are some of the methods that might be used for developing a landfill.

1. *Trench method:* Solid waste is filled in a series of deep and narrow trenches for this type of landfill. It is generally used only for small waste quantities. This method is still used for hazardous waste landfills in some states. See Figure 6.

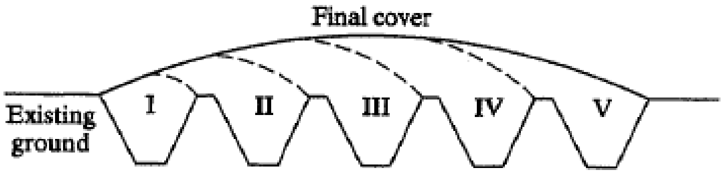


Figure 6: Trench Method of Landfilling (Qian et al. 2002)

2. *Area or ramp method:* The landfill progresses with little or no excavation. Normally this type of landfill is used in areas with high groundwater or where the terrain is unsuitable for excavation. See Figure 7.

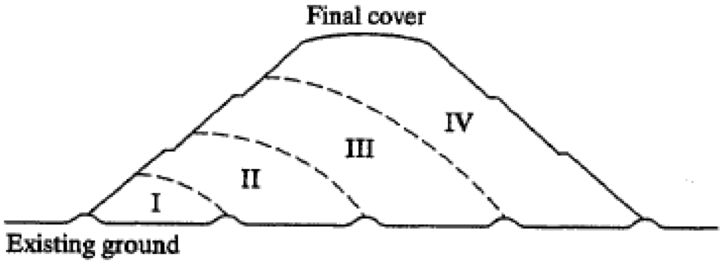


Figure 7: Area or Ramp Method of Landfilling (Qian et al. 2002)

3. *Above- and below-ground fill:* This type of landfill is a combination of the two previously mentioned types, trench fill and area fill. However, the excavation area is much larger than in a trench fill landfill. The depth of excavation normally depends on the depths of the natural clay layer and the groundwater level. See Figure 8.

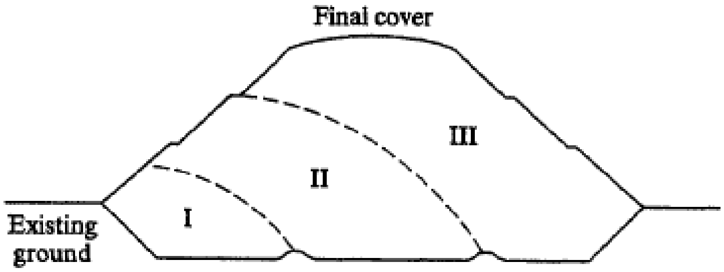


Figure 8: Above- and Below-Ground Fill (Qian et al. 2002)

4. *Canyon, valley, or ravine method:* This method, as its name suggests, is most appropriate in a canyon, valley, or ravine. The solid waste is placed in lifts from the bottom of the ravine to the top. The first lift is normally placed a short length from the head of the ravine across its width. Succeeding lifts are placed by trucking the solid waste on the top of the first lift toward the head of the ravine. This is performed until the final grade is reached, after which the length of the first lift is extended further. See Figure 9.

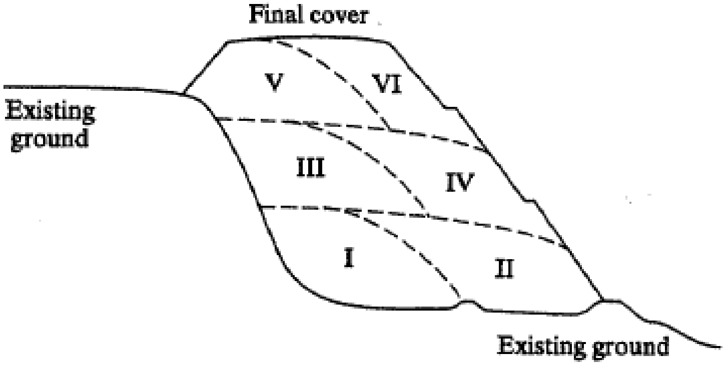


Figure 9: Valley Fill (Qian et al. 2002)

In these methods, the waste is placed in a specific order in the form of cells or units (Figure 10). The densities of these cells or units are important in evaluating the overall economics of the landfill. This is due to the fact that the amount of waste that can be placed in a specific area is dependent on its density and the geotechnical capabilities of the surrounding soils, and the overall economics of a landfill is dependent on the amount of waste the landfill can accommodate. The average density of the waste present in a landfill should be 800 pounds/cubic yard to make it economically competitive with other means of disposal such as composting, recycling, and energy recovery (Salvato et al. 2003).

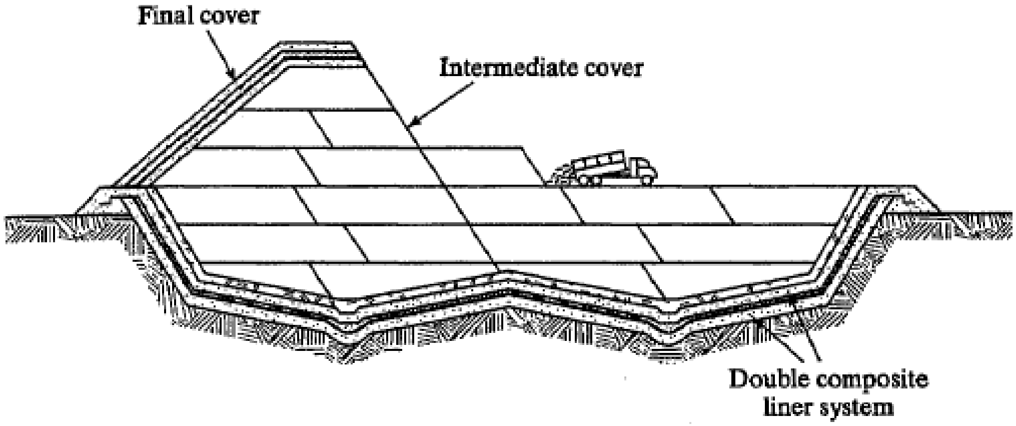


Figure 10: Placement of Waste to Form Cells (Qian et al. 2002)

A solid waste landfill can be conceptualized as a relatively long-term biochemical reactor, with solid waste and water as the major inputs, and with landfill gas and leachate as the principal outputs. MSW can generate tremendous quantities of gas during its decomposition. The decomposition phase can take anywhere from 10 to 80 or more years. The lower number is indicative of bioreactor landfills (today's traditional MSW engineered landfills), and the higher number is indicative of conventional landfill practices (Salvato et al. 2003).

Landfill gas goes through five phases from the point at which it is placed in the landfill until it decomposes. The various phases and their characteristics are listed below.

Phase 1: Aerobic Decomposition Phase

Aerobic decomposition begins soon after the waste is placed in a landfill and continues until all of the entrained oxygen is depleted from the voids in the waste and from within the organic material itself. Aerobic bacteria produce a gaseous product characterized by relatively high temperatures (130 to 160° Fahrenheit [F], or 51 to 71° Celsius [C]), high carbon content, and no methane content. Other byproducts include water, residual organics, and heat. Aerobic decomposition may continue from 6 to as long as 18 months in the case of waste placed in the bottom of the landfill although it may last only 3 to 6 months in the upper lifts if methane-rich landfill gas from below flushes oxygen from voids in the disposed waste (Qian et al. 2002).

Phase 2: Aerobic/Acid Generation

After all entrained oxygen is depleted, decomposition enters a transitional phase in which acid-forming bacteria begin to hydrolyze and ferment the complex organic compounds in the waste.

Phase 3: Transition to Anaerobic

This phase typically occurs within 3 months to 3 years at a landfill and is signified to be ending when methane and carbon dioxide concentrations stabilize and no nitrogen remains in the landfill gas.

Phase 4: Anaerobic (Methane) Generation Phase

Methane-forming bacteria, which thrive in an oxygen-deficient environment, become dominant. Studies have shown that anaerobic gas production is typified by somewhat lower temperatures (100 to 130°F, or 38 to 54°C), significantly higher methane concentrations (45 to 57 percent), and lower CO_2 concentrations (40 to 48 percent). Anaerobic gas production will continue until all of the carbonaceous material is depleted or until oxygen is re-introduced into the waste, which would then return the decomposition process to aerobic conditions. A return to aerobic decomposition does not stop landfill gas production, but it will retard the process until anaerobic conditions resume.

Phase 5: Transition to Stabilization

In this phase the phases of decomposition have run their course and begin to stabilize back to aerobic digestion.

Phases of LFG Generation

Figure 11 illustrates graphically the formation of various gases during each phase of the decomposition process (Qian et al. 2002). The figure shows that generation of CO_2 peaks in the third phase, whereas the generation of CH_4 peaks during phase 4 and remains more or less constant during this phase of decomposition. This phase is also the most important phase for energy recovery. The figure also indicates that the overall composition of the LFG changes from phase to phase. Hence the amount and content of the LFG from a particular landfill depends upon the age of the landfill and the current phase of decomposition.

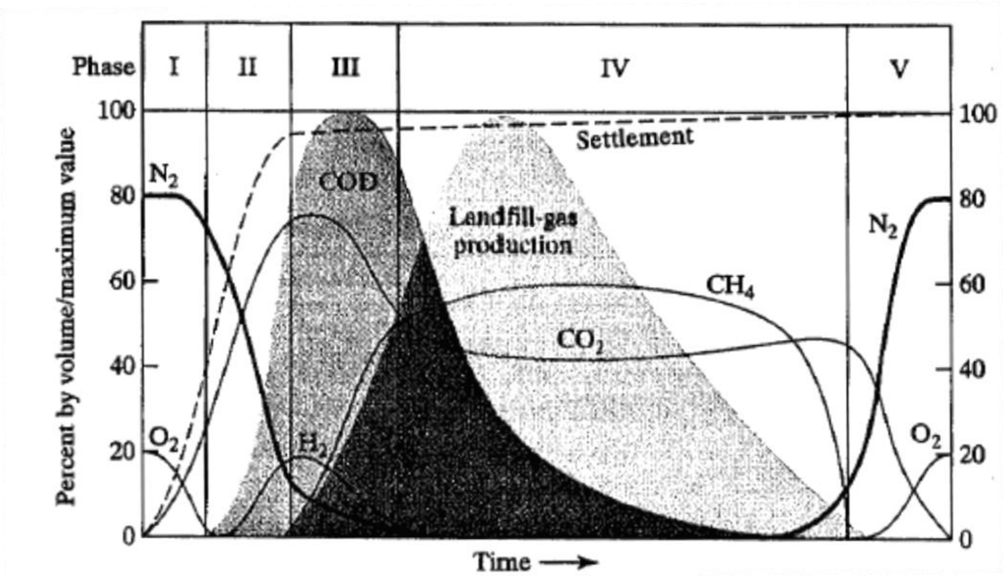


Figure 11: Phases of Landfill Gas Generation (Qian et al. 2002)

Landfill Gas Recovery

Landfill gas recovery may be the ultimate in recycling. It taps one of society's least-desirable items—garbage—and turns it into useful, high-value energy products such as electricity and natural gas. Turning hazardous LFG into marketable energy enhances landfill safety. It also reduces odors and greenhouse gases while generating revenue. Therefore, cities should carefully evaluate their LFG potential because "the dump" could be a cost-effective and reliable energy resource.

Each Texan discards about 2,000 pounds of trash per year. Most trash is biomass, meaning it is derived from plants or animals. Methane, which typically makes up half of all the gases emitted by a landfill, is the main component of natural gas and a valuable energy product. Therefore, LFG is considered a renewable form of natural gas. Although methane is a marketable commodity, methane is also a destructive “greenhouse gas,” and landfill operators are required by federal law to control it.

Methane currently accounts for about 24 percent of America’s total greenhouse-gas emissions. Landfill operators are required to trap the methane and other gases. If the landfill volume is over 1 million tons, the methane produced can be captured, purified, and sold to gas utility suppliers or used to generate electricity on the spot. Since the methane must be captured anyway, turning it into a commercial product can help defray the landfill’s operating costs while reducing pollution (U.S. EPA 2003).

Natural Gas

Natural gas in its pure form is colorless, odorless, and highly combustible. It is clean burning, gives off a great deal of energy, and has lower levels of harmful byproducts than other fossil fuel sources. Natural gas, which occurs in various natural sources, is composed primarily of methane. Its composition varies, and the typical components are listed in Table 6. LFG (when purified and cleaned of toxins) and CO_2 can be sources of natural gas (U.S. EPA 1996b).

Table 6: Composition of Natural Gas (NaturalGas.org 2004)

Component	Chemical Symbol	Composition
Methane	CH_4	70-90%
Ethane	C_2H_6	0-20%
Propane	C_3H_8	
Butane	C_4H_{10}	
Carbon dioxide	CO_2	0-8%
Oxygen	O_2	0-0.2%
Nitrogen	N_2	0-5%
Hydrogen sulfide	H_2S	0-5%
Rare gases	A, He, Ne, Xe	Trace

LFG Collection Systems

The gases generated by the decomposition of solid waste flow throughout the landfill and must be collected efficiently to avoid leaking into the atmosphere or spreading into the surrounding areas. (Figures 12 and 13 show LFG collection wells.) This is very critical since the gases contain CH_4 in large quantities, which when present in concentrations between 5 to 15 percent can be highly explosive (NaturalGas.org 2004). The collection of the gases should be performed in such a way that air intrusion into the landfill is prevented. This normally occurs if gases are extracted from the landfill at a high rate. Air intrusion leads to the development of aerobic pockets, which might be detrimental to the process of CH_4 generation and can affect the viability of the landfill as a long-term CH_4 generator (Qian et al. 2002). Air intrusion can be controlled by maintaining the spacing of the collection wells in a landfill. It is, however, important to understand the design of a collection well before understanding its spacing.

Figure 12: Drilling of LFG Collection Wells in Landfill (New Cure 2007a)

Figure 13: LFG Collection Well Drilling Rig (New Cure 2007b)

A typical collection well is developed by drilling a 12- to 36-inch diameter trench through the waste to the bedrock or water table. Then a 3 to 8 inch pipe, with the top two thirds of its length perforated, is placed vertically inside the trench. This pipe is placed on a thin layer of gravel and is backfilled with gravel around the perforations. The gravel is capped with a thick layer of concrete or bentonite slurry, which prevents any ingress of air into the landfill. Thus the gases developed in the landfill travel through the perforated pipe and can be collected at the top of the pipe. Typically a butterfly valve is used to regulate the flow of gas from the landfill. The gas is then transferred to a network of pipes established to collect gases from several collection wells around the landfill and transfer the gases to a central location. A slight suction pressure may be applied at the central location to facilitate the movement of gases to the central location. Figure 14 shows a typical collection well (Qian et al. 2002).

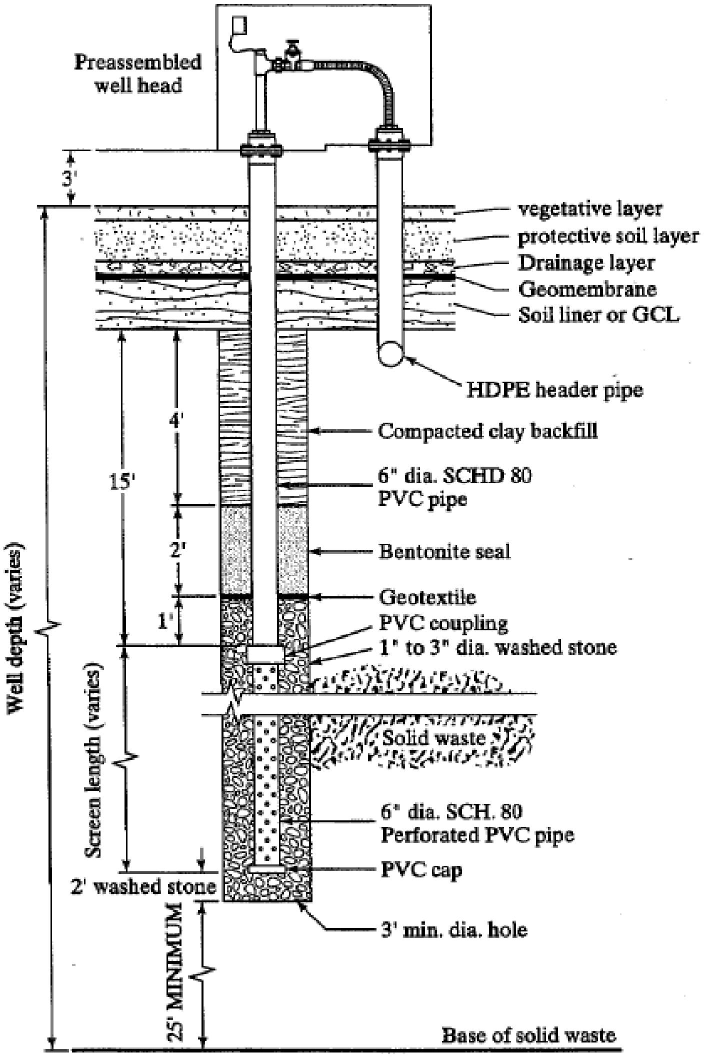


Figure 14: Gas Collection Well at a Landfill (Qian et al. 2002)

As discussed, well spacing is very important and is normally determined by using the "radius of influence" concept. According to this concept the radius of influence of a particular extraction well depends upon the extraction rate (i.e., well flow rate), depth of landfill, in-place refuse density, CH_4 production rate, and fractional CH_4 concentration. This relationship is determined by using Equation 1 (Qian et al. 2002).

$$r = \frac{x}{2 * Cos(30)} \tag{1}$$

Where:

r = specified or desired radius of influence, meters or feet; and

x = distance between triangulated wells, meters or feet.

Thus the well should be placed in such a way that the "radii of influence" of the neighboring wells just overlap each other. This would ensure that gas from the entire landfill is collected. The collection wells should also be placed in a pattern that maximizes the efficiency of gas collection. Figure 15 shows an equilateral triangle pattern that might be an efficient method of collecting the gas, considering uniform conditions throughout the landfill.

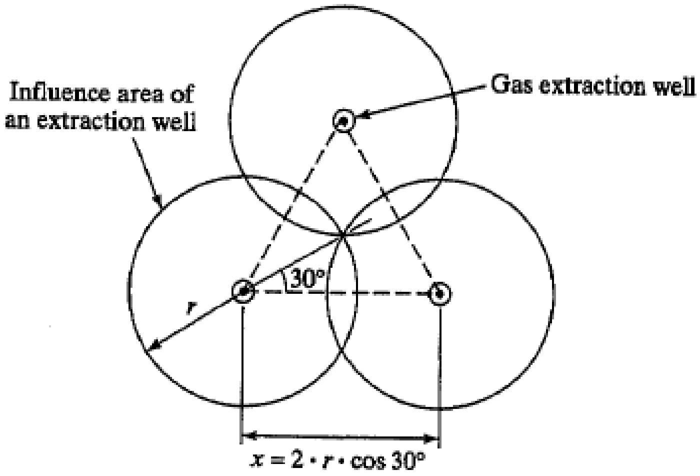


Figure 15: Equilateral Pattern of Gas Collection Wells (Qian et al. 2002)

The pattern shown in Figure 15, however, is not always possible, and hence the patterns must be modified depending upon the local landfill conditions. The spacing of wells is also dependent upon their location in a landfill. If they are located in the central part, the spacing may be large since higher well flow rates are desired. However if the wells are located at the periphery, then lower spacing would be favorable since lower well flow rates are desired. In addition, the location of the wells in a landfill is governed by the purpose of gas collection. If the gas is collected only to prevent it from migrating to neighboring areas, then the wells may be located at the periphery of the landfill. If energy recovery is the purpose of gas collection, then wells may be located at the center of the landfill. The wells may be located both at the center and on the periphery if gas is collected for the dual purpose of migration control and energy recovery (Qian et al. 2002).

Landfill Economics

Economic analysis of landfills is important to minimize the cost of waste disposal and maximize the benefits of energy recovery. It can also assist the owner/operator in selecting the best possible option for waste disposal from the different waste management options.

A typical economic analysis includes the costs and benefits of developing a landfill site. The costs of landfills can be subdivided into the development costs and operating costs. The primary development cost is the cost of land required for the development of a landfill. This cost may vary from region to region but is normally higher in metropolitan areas. Landfills near the metropolitan area tend to result in lesser hauling cost but higher cost of land and health-related costs. Hence, a trade-off must be made on the location of a landfill near a metropolitan area.

The operating costs for the landfills include labor costs, operation and maintenance costs of the equipment, and costs associated with the purchase and hauling of cover material. The labor costs generally account for half of the operating and maintenance costs.

The benefits of developing a landfill site might include societal benefits, such as general hygiene of the local municipality via the removal of harmful waste, improved air quality post-closure, parks and golf courses post-closure, and potential cost savings that could ultimately affect the everyday citizen if corporations are making enough of a profit. Nearly all other benefits come in monetary form. All private landfills are privately run to make money. Earnings from dumping/tipping fees, garbage collection contracts, and various other fees are what sustain the financial feasibility of the landfills themselves.

LFG Cleaning Process

As previously mentioned, LFG is primarily composed of CH_4 and CO_2 along with some quantities of N_2 and O_2. A few trace compounds may also occur in LFG. The composition of the gas depends upon various factors such as the type of waste in a landfill, climatic conditions at the landfill, age of the landfill, etc. The composition of the gas may also vary by location within the landfill, i.e., if it is collected at the center or at the periphery (Qian et al. 2002).

The various applications of the LFG require some of the components of the gas to be removed, which is referred to as cleaning. The degree of cleaning depends on the intended application of the LFG (Qian et al. 2002). Each energy-recovery project, therefore, has a unique requirement for processing the gas. The LFG typically has heating values that range between 450 and 600 British thermal units per thousand cubic feet (Btu/mcf) and is mostly saturated with water (U.S. DOE 2009a). The various medium- to high-Btu applications of the gas demand removal of moisture from the gas, and the cost of such preprocessing is high and could have a significant impact on the overall economic feasibility of the project (ACS 1978).

The gas can be directly utilized, but it may have some detrimental long-term effects such as inefficient operations and deterioration of the equipment. There are several cleaning processes that can remove the contaminants for different applications of LFG. An integral part of all these processes is the removal of condensate, particulates, and hydrogen sulfide, irrespective of the application for which the gas is used. This is due to the fact that these elements can cause heavy corrosion to the equipment.

CO_2 WASH™ Process

As previously mentioned, LFG is saturated with water vapor at atmospheric temperature and pressure, which is typically considered to be 70°F and 1 atmosphere. The water vapor is removed in a knockout chamber by the process of condensation. In this process, the water vapor is condensed after it contacts a surface that is below its saturation temperature (Cook et al. 2005). This gas is passed on to a blower, which increases the pressure of the gas from negative to positive.

The gas then enters a reciprocating three-stage compressor that gradually increases the pressure to 400 pounds-force per square inch gauge (psig). After each stage of compression the gas is cooled down. This helps remove the condensate from the gas at every stage of compression. The gas is further passed into a chamber filled with iron-based solid granular material that specifically absorbs H_2S. This removes the odor from the gas and reduces its corrosive ability. The gas is further allowed to flow into the drying chamber, which is composed of alumina beads. The gas at high pressure is absorbed by the alumina beads in one vessel, and then another vessel regenerates the gas at atmospheric pressure. These vessels operate on a cyclic basis (Cook et al. 2005).

After the H_2S removal and drying of the gas, the gas enters the bottom of the CO_2 WASH™ absorber. The inner surface of this 6-inch diameter vessel is designed in such a way that it promotes better contact between the LFG and liquid CO_2 absorbent. The LFG is refrigerated as it moves upward, causing the CO_2 to liquefy. This chilled liquid CO_2 flows down the chamber, and as it moves down, it further strips the upward-moving LFG of its contaminants, thus purifying it further. There is a valve at the bottom of the absorber that helps maintain the level of liquid CO_2 in the chamber. A tray may also be provided to withdraw the liquid CO_2 from the chamber for commercial purposes (Cook et al. 2005).

The cleaner LFG (70 percent CH_4 and 30 percent CO_2) is electrically heated to 70°F before it is allowed to enter a chamber with two membranes. The pressure of the gas is also lowered to 200 psig. The membranes separate the CO_2 and O_2 from CH_4, providing clean LFG with a high CH_4 content that can be liquefied and used as an LNG fuel (Cook et al. 2005).

Figure 16 shows this process (Cook et al. 2005). The figure shows that pre-treatment of the gas before it enters the CO_2 WASH™ chamber is extremely essential and constitutes a substantial part of the entire process. The figure also shows that the impurities obtained from the CO_2 WASH™ chamber are eliminated through flaring. The output of the process is natural gas that can either be liquefied for use as a vehicle fuel or can be directly introduced into a natural gas pipeline network. Additional information can be seen in Appendix A.

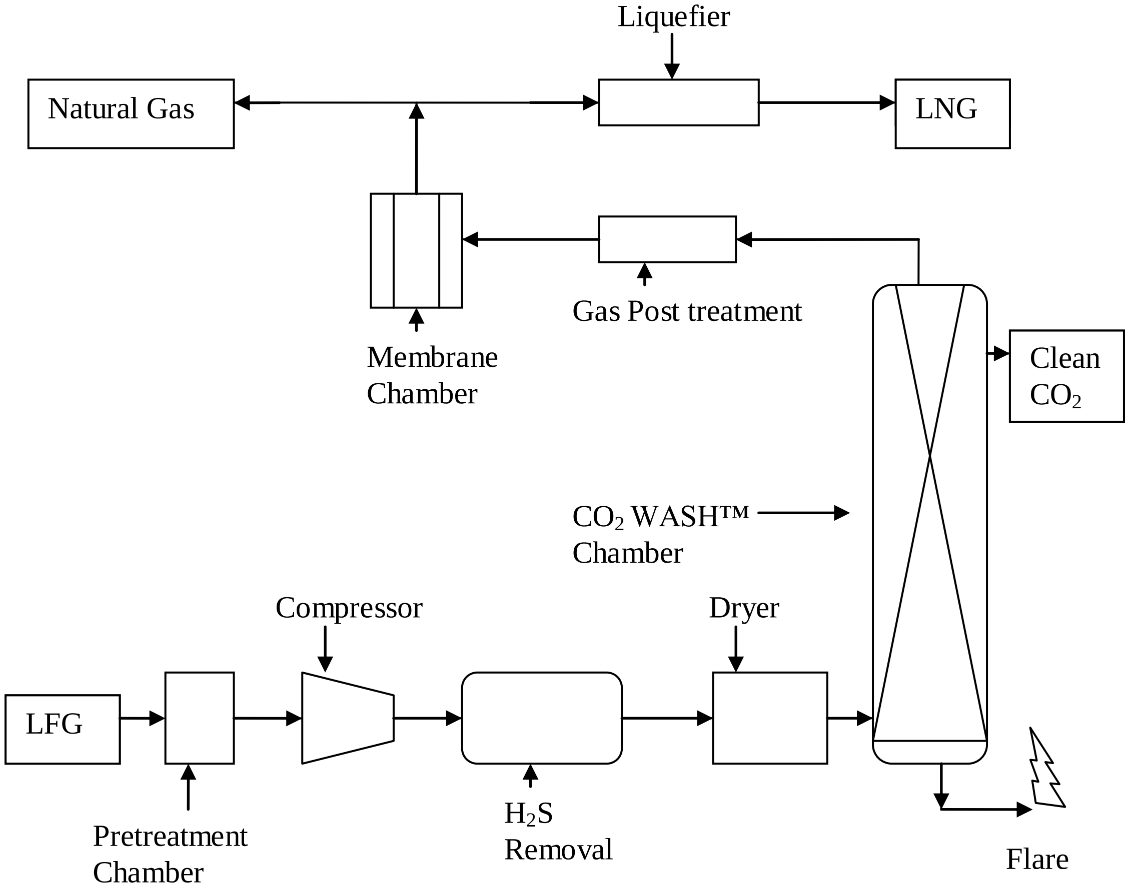


Figure 16: CO_2 WASH™ Process (Cook et al. 2005)

Need for Landfill Gas Collection Mechanisms

In addition to the increasing importance of alternative sources of energy that makes LFG an important potential source of natural gas, there are other reasons for collecting LFG rather than allowing it to escape into the atmosphere. Methane is a greenhouse gas with a global warming potential (GWP) that is 21 times that of CO_2. The formation of methane and other potentially toxic gases at landfills is also tied to increased health risks and the risk of fire due to combustibility.

The broad classification of action steps that can be taken at a landfill in terms of LFG collection are as follows:

- *Do nothing*: Landfill is capped but LFG is allowed to escape into the atmosphere.
- *Flaring*: LFG is collected and burnt off in a controlled combustion process. This converts the methane into CO_2.
- *Conversion to an energy source:* This could include converting the LFG into natural gas, heat, electricity, or vehicle fuel.

Of these, the do-nothing option is generally considered to be the most environmentally harmful, due to the risks discussed previously and the release of greenhouse gases with a high GWP. The true do-nothing scenario in which a landfill owner/operator does not place a cap on the landfill post-closure is legal in the United States for landfills that receive less than 20 tons of waste per year, yet other monitoring procedures must be in place at these sites to earn an exemption status from the EPA under the Land Disposal Program Flexibility Act of 1996 (LDPFA) (U.S. EPA 1996a). The landfills that would consider the option of methane or energy recovery would not meet this requirement.

All landfills that do not meet this exception are regulated by the U.S. EPA in accordance with their state governing agency. For Texas, the Texas Commission on Environmental Quality (TCEQ) is the governing body that decides what landfill design standards and emission standards are required for each individual landfill based on the landfill's impact on the surrounding community and ecosystem. The TCEQ and EPA work together to meet both federal and state goals that are constantly changing. The do-nothing scenario is provided strictly as a baseline for emissions generation. Creating a methodology to use at all landfills is extremely difficult since each landfill has very different characteristics. Most landfills are required to regulate their emissions based on the air quality needs of the surrounding regions; therefore, it must be noted that for the purposes of this analysis the cost placed on the do-nothing scenario may be higher if air quality mitigation strategies are currently in place at a given landfill. The do-nothing option for this thesis is assumed to be equal to the total costs of capping the landfill, operation and maintenance costs, and the purchasing of diesel refuse trucks that would have been purchased.

Flaring is a better option because it converts the methane into CO_2, which is less harmful than methane. However, the collection and conversion of LFG into a source of energy is the most preferred option from an environmental standpoint. While this study is specifically concerned with the feasibility of converting LFG into LNG for fueling refuse trucks or buses, the range of possible options for dealing with LFG are all presented in further detail in this report.

The simplest method of collecting and disposing of LFG is through the use of a flare. This technique was common 50 years ago for disposing of the explosive casing head gas that came along with the oil from oil wells. But the oil industry eventually developed markets and infrastructure to sell the valuable natural gas rather than wasting it. In a similar fashion, landfill operators are developing markets for LFG, which can be used for many applications (Spaulding 1997).

A Call to Action

Energy consumption across the transportation sector is expected to grow by 10 percent from now (2009) until 2030 (U.S. DOE 2009a). With increasing political pressure to reduce greenhouse-gas emissions to curb the potential effects of global warming, the federal government, as well as many other governing agencies, is considering ways to reduce its carbon footprint via new laws or policy changes.

The Energy Policy Act (EPAct) of 1992 requires certain federal agency fleets to acquire a percentage of alternatively fueled vehicles (AFVs) each year. The EPAct of 2005 requires federal fleets to use alternative fuels in dual-fuel vehicles the majority of the time if alternative fuel is available within 5 miles or 15 minutes of the garaged location of the vehicles unless an exemption has been given. Federal agency fleets must also comply with Executive Order (E.O.) 13423, signed by then-President George W. Bush in January 2007. E.O. 13423 requires agencies to decrease petroleum consumption by 2 percent per year (relative to their fiscal year 2005 baseline) through fiscal year 2015. In addition, the mandate requires agencies to increase alternative fuel use by 10 percent, compounded annually and based on their fiscal year 2005 baseline use (U.S. DOE 2009b).

The American Reinvestment and Recovery Act of 2009 stipulates numerous tax benefits and grants for alternative-energy projects including LFGTE. Under these rules alternatively fueled vehicles can receive a $0.50 per gallon equivalent tax credit as well as a 30 percent grant of low- to zero-interest bonds to finance prospective LFGTE projects (Obey, D. and 111th U.S. Congress 2009).

In addition to federal bills, laws, and mandates, two programs have been created to promote LFGTE projects within the United States and abroad, with the overall goal being a reduction in greenhouse-gas emissions as well as increased economic development.

Landfill Methane Outreach Program (LMOP)

One program created by the U.S. EPA, the Landfill Methane Outreach Program, is a voluntary assistance and partnership program that promotes the use of landfill gas as a renewable, green energy source. LMOP helps businesses, states, energy providers, and communities protect the environment and build a sustainable future through the development of landfill gas energy projects (U.S. EPA 2009a).

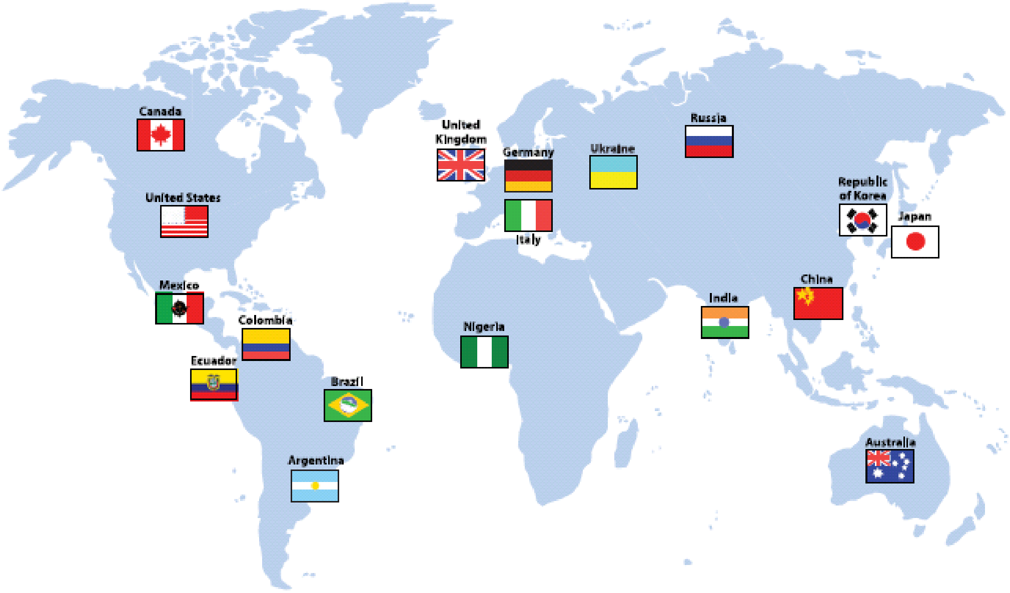
Methane to Markets

The U.S. EPA in 2004 created a program called Methane to Markets (M2M). This program committed the United States, along with 13 other countries, to advancing cost-effective, near-term methane recovery and use as a clean energy source. It enables both public- and private-sector organizations from around the world to work together with government agencies to facilitate project development of agricultural operations, coal mines, landfills, and oil and gas systems. This collaboration is yielding important benefits, including enhanced economic growth and energy security, improved air quality and industrial safety, and reduced greenhouse-gas emissions.

To date, M2M resources have been used in creating the foundation for future project development as well as advancing near-term methane recovery and use opportunities. The United States supports technology demonstrations and pre-feasibility and feasibility studies at potential project sites; addressing market, institutional, and other barriers to project development; and building capacity through technology transfer and training. These efforts are directly leading to the future implementation of full-scale projects in numerous countries, which, if fully implemented, will result in estimated annual emission reductions of approximately 5 million metric tons of carbon dioxide equivalent ($MMTCO_2E$).

In the landfill sector, the U.S. government is developing a global database of LFG project opportunities to help countries and project developers from around the world identify potential project sites. In addition, the United States has trained Russian professionals in LFG project development and provided seed funding for LFG projects in Mexico and Brazil. These projects are expected to reduce emissions by 45,000 and 500,000 $MTCO_2E$ per year, respectively.

Sustained effort and focus on methane recovery and use by the U.S. government, partner countries (see Figure 17), and the project network will lead to significant, near-term progress in reducing emissions. By working collaboratively with the public and private sectors, proponents can reduce global methane emissions while developing new sources of clean energy that provide economic, environmental, and health benefits.



Methane to Markets Partner Countries represent more than 60 percent of the world's anthropogenic methane emissions.

Figure 17: Methane to Markets Partner Countries (U.S. EPA 2009a)

LFGTE Projects

As of 2008, more than 480 landfill gas energy projects were operational in the United States. Those landfills have transformed their decaying garbage into a renewable energy resource. In doing so, the sites are helping to generate 12 billion kilowatt-hours (kWh) of electricity per year and deliver 255 million cubic feet per day of LFG to direct-use applications. An additional 520 landfills still present attractive opportunities for project development (see Figure 18) (U.S. EPA 2009b).

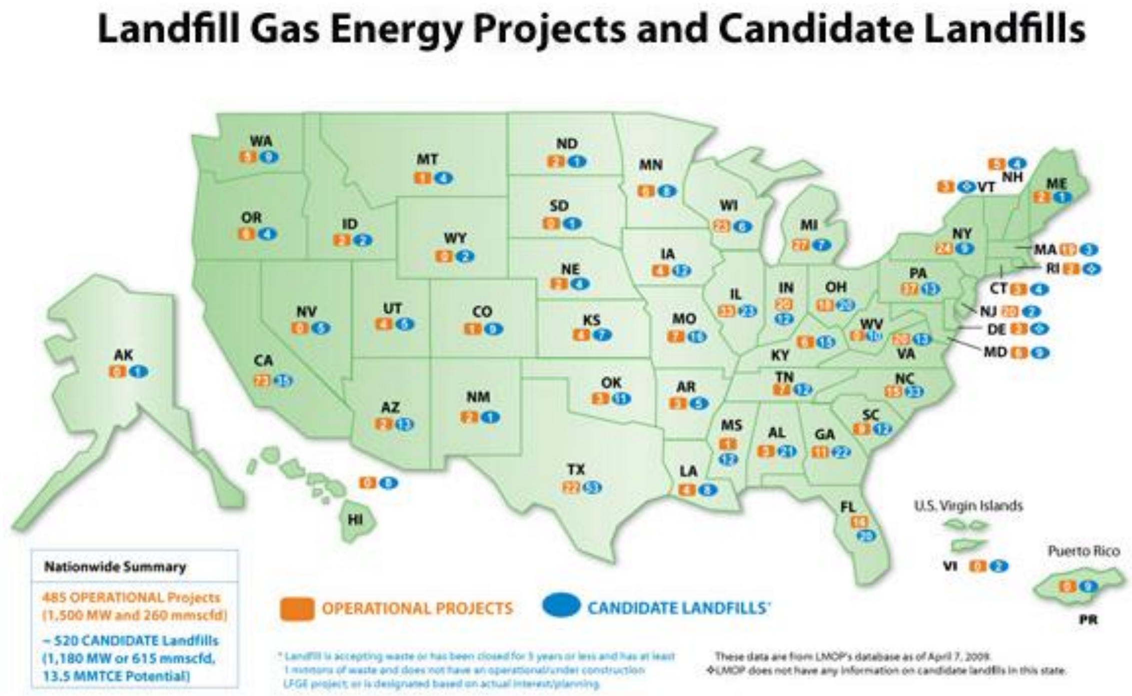


Figure 18: LFGTE Projects and Candidate Landfills (U.S. EPA 2009b)

Texas Projects

In 1996, Browning-Ferris Industries began generating electricity from LFG at its Sunset Farms Landfill in Austin (Figure 19). The installation uses three 1,500-horsepower engines fueled directly by LFG without any cleaning process. The engines that are used are similar to large diesel engines and are relatively expensive at $1,200 per kWh, which is three times the cost of an ordinary natural-gas-fueled power plant. The company offsets these costs by using the LFG. The savings earned by not purchasing natural gas allows the electricity to be extremely cost-competitive versus natural gas. Landfill-gas-powered units are highly reliable, producing full power for 90 to 95 percent of the year, which is more efficient than fossil fuels or nuclear power. Due to its size, the Sunset Farms project can distribute electricity directly to the local power grid whenever it produces a surplus of electricity (SECO 2006).

SOURCE: US DEPARTMENT OF ENERGY

LANDFILL GAS INTO ELECTRICITY *This small power plant located at a landfill produces low cost, reliable electricity.*

Figure 19: Landfill-Gas-to-Electricity Plant (SECO 2006)

San Antonio CNG Refuse Fleet

The Environment News Service published an article in January 2009 praising the City of San Antonio for incorporating CNG refuse trucks into their fleet. The City of San Antonio and Clean Energy Fuels Corporation in a cooperative effort designed and constructed a new refuse truck fueling station located at the Northeast Service Center. Clean Energy was co-founded by T. Boone Pickens, who has been an advocate for natural gas vehicles in the United States, receiving his greatest attention when gasoline prices reached $4 in the summer of 2008. The fleet currently has 30 CNG-powered refuse trucks with plans to purchase more, making it the largest refuse fleet comprised of CNG vehicles in Texas. The $0.50 per gallon tax credits as well as additional federal funding helped to assist with vehicle and fueling station costs, while a grant from TCEQ helped to offset station construction costs. It is estimated that two-thirds of the nation’s 700 refuse trucks operate using LNG, while the rest operate on CNG (Environment News Service 2009).

Natural Gas Vehicles (NGVs)

NGVs can be refueled either by quick fill or timed fill. Quick fill is used when vehicles need to be refueled in a time period similar to that of gasoline vehicles, about 3 to 7 minutes. At a quick-fill station, a compressor stores natural gas in a high-pressure tank. Refueling is done at the tank while the compressor replenishes the tank's supply. The system shuts off when the cylinder capacity of the vehicle is reached, or at whatever point the user desires.

A time-filled system eliminates the need for a high-pressure storage tank at the station. Natural gas is pumped by the compressor directly into the onboard cylinders over the course of 6 to 8 hours. Timed fill is usually for fleet vehicles that return to a specific location at the end of a working day.

While natural gas stations are still few and far between compared to gasoline stations, natural gas suppliers are proving themselves more accommodating in meeting the needs of their users. If a home or business already has a natural gas hook-up (for heating, cooking, etc.), the local gas utility can install an on-site refueling system, making the user independent of outside filling stations. There are also a variety of portable fuel delivery systems that use over-the-road transportation of CNG in tube trailers. For interstate travel, the NGV Coalition offers a free booklet, "The Pocket Guide to NGV Fueling Stations in the U.S.," for planning purposes (Spaulding 1997).

Safety

NGVs have a remarkable safety record. In 1992, an American Gas Association (AGA) survey of more than 8,000 fleet-based vehicles found that in 278.3 million miles driven, NGV injury rates per vehicle miles traveled were 37 percent lower than the rate for gasoline fleet vehicles and 34 percent lower than the rate for the entire nation, and were without a single fatality as opposed to 2.2 fatalities per 100 million miles for gasoline vehicles.

This safety record is due at least in part to the chemical properties of natural gas. Leaked natural gas dissipates into the atmosphere, instead of pooling on the ground. Its ignition temperature is 1,200°F, as opposed to 600°F for gasoline. It will burn only when the proper air-to-fuel ratio is reached. It will not ignite when the air concentration is below 5 percent or above 15 percent. Natural gas contains only trace amounts of toxic substances and is neither carcinogenic nor caustic. Another reason may be the stringent standards for onboard storage cylinders.

Susan Jacobs, a representative of the NGV Coalition, in 1997 stated that ever since the early 1990s, the federal government has been offering money and incentives at all levels of the industry. The two main reasons for this are that natural gas is friendly to the environment and can play a major role in reducing U.S. dependence on foreign oil.

Factory-built dedicated NGVs have the potential to reduce exhaust emissions of CO by 70 percent, NMOCs by 89 percent, nitrogen oxides (NO_x) by 87 percent, and CO_2 by 20 percent. Natural gas qualifies as a “clean fuel” under the Clean Air Act Amendment of 1990. Provisions of this same amendment require fleet operators of 10 or more automobiles or light duty trucks and vans to begin purchasing clean-fuel vehicles by model year 1998 (Spaulding 1997).

Carbon Credit Trading

Carbon credit trading has also become an issue to consider when looking at potential benefits for LFGTE projects. Legislators in the U.S. government have discussed the idea of placing a cap-and-trade program for industries within the country. Under this scenario, all manufacturing plants and some municipalities would be given a specific allocation of carbon credits (metric tons of CO_2 equivalent) that they would be allowed to pollute per year. If they were to exceed this limit, they would be forced to purchase carbon credits either from the government, from another company, or through a market system (like buying a stock). The idea is that these credits would become more valuable as time goes on because the government would allocate fewer and fewer credits to each company and municipality in order to decrease total nationwide emissions over time.

Recipients would be forced to purchase cleaner ("greener") equipment or buy more carbon credits. Companies that took an initiative and spent the money to reduce their overall emissions would be able to sell their additional certified emission reduction (CER) credits to others for profit.

Two markets within the United States have already begun to proactively trade CER credits, the Regional Greenhouse Gas Initiative (RGGI) and the Chicago Climate Exchange (CCX). The RGGI is a semi-voluntary cooperative by 10 Northeast and Mid-Atlantic States (Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Rhode Island, and Vermont) to limit greenhouse-gas emissions. These 10 states will cap CO_2 emissions from the power sector and then require a 10 percent reduction in these emissions by 2018. Regulations in these 10 states require the power companies to lower their emissions based on their given allotment or purchase additional credits, with the RGGI being the sole intermediary party of credit trading (RGGI 2009a). The CCX is a global market platform that sells CERs as well as European Union Allowances (EUAs) (CCX 2009). Futures prices for carbon financial instruments (CFIs), which are equal to CERs, are much lower on the CCX because of the low volume of trading in the United States due to no true federal regulations or cap-and-trade programs. When viewed on June 1, 2009, the CCX was selling futures for December 2009 at $1/metric tonne, while the RGGI was selling the same futures for $3.51/U.S. ton ($3.87/metric tonne).

The European Union and India each have their own carbon credit markets. The European Union has capped emissions and provides EUAs to various industries, with credits averaging roughly $25/metric ton. India's market is called the Multi-Commodity Exchange (MCX), where carbon credits sell for roughly $15/metric ton (MCX 2009a).

CHAPTER III

METHODOLOGY

This chapter outlines the methodology that is the framework behind the feasibility analysis of choosing which LFGTE project may be best for the person using it. The integral equations that act as the framework for methane generation rates are provided in this section along with various scenarios.

The introductory section of this thesis discussed in general terms the most common options for collecting and disposing of or making use of landfill gas. For conducting a pre-feasibility analysis that involves looking at costs and benefits, a total of six scenarios were chosen to examine which option is most financially viable, and to compare the LFG to natural gas for transportation fuel options versus other possibilities.

Landfill-Gas-to-Energy Scenarios

The six scenarios considered are as follows:

1. convert the LFG to LNG to use as a transportation fuel (LFG → LNG),
2. convert the LFG to CNG to use as a transportation fuel (LFG → CNG),
3. convert the LFG to pipeline-grade natural gas (LFG → pipeline),
4. convert the LFG to electricity (LFG → electricity),
5. cap the landfill and flare the LFG (closed flare), and
6. do nothing (nothing).

Numerous costs and benefits are associated with each option, and some of them are common to more than one scenario. Table 7 summarizes the types of benefits and costs associated with each of the scenarios. The analysis period considered for all the scenarios was 20 years.

Table 7: Summary of Costs and Benefits Associated with Each Scenario

Description	**Scenario**					
	LFG → LNG	**LFG → CNG**	**LFG → Pipeline**	**LFG → Electricity**	**Closed Flare**	**Nothing**
Benefits						
Diesel or natural gas savings	X	X	X			
Electricity conversion				X		
Carbon credits	X	X	X	X	X	
Fleet turnover emissions reduction	X	X				
Costs						
Landfill capping costs	X	X	X	X	X	X
CNG/LNG facility and operation cost	X	X				
Pipeline natural gas facility and operation cost			X			
Electricity plant and operation cost				X		
Flaring system and operation costs					X	
Fleet Turnover	X	X	X	X	X	X

The reasons to consider each of these costs and benefits, and the methods used to calculate them, are provided in the following benefits and costs sections. Before considering individual costs and benefits, it is necessary to estimate the quantity of gas generated for each landfill since this forms the basis for all other calculations.

Estimating Landfill Biogas Generation

Estimating landfill gas production from landfills and the methane potential from that LFG quantity is extremely difficult. The methodology for acquiring an estimate of the landfill gas potential was developed using the U.S. EPA's 1997 modeling equation for closed landfills (Equation 2).

$$Q_t = 2 * L_o * m_o * (e^{k*t_a} - 1) * e^{-k*t} \tag{2}$$

Where:

Q_t = expected gas generation rate in the tth year, meters^3/year;
L_o = methane generation potential, meters^3/year;
m_o = constant or average annual solid waste acceptance rate, Megagrams/year;
k = methane generation rate constant, year^{-1};
t = age of the landfill, year; and
t_a = total years of active period of the landfill, year.

The equation for closed landfills was chosen because all of the LFGTE options require the landfill to be capped or closed. A large societal cost is incurred if landfills are not capped, which is why it is mandatory for most U.S. landfills to be capped. For the purposes of this thesis it was assumed that construction for the capping and landfill gas collection systems would occur after the landfill or a portion of it has been closed.

The methane generation potential, L_o, is typically available after sufficient pump test data have been collected at a landfill (Figure 20). In order to obtain this value, LFG is extracted from a test well at a steady-state flow rate. This value is then adjusted based on the landfill depth and the radius of influence. The radius of influence is the volume of waste surrounding the extraction well that is contributing to the LFG generation on site (Qian et al. 2002). Therefore, if you have results on the quantity of gas that is coming out of the area you are extracting it from, you can estimate the volume of gas that will be present over time.

Figure 20: Operator Performing a Pump Test (World Bank 2002)

The methane generation rate constant, k, is derived based on the composition of the waste in place (WIP) and average climate at the landfill. The composition of the waste has a dramatic effect on how much methane can be produced as well as how quickly it can break down. For example, food waste will decompose much faster than a tire over time. Likewise, the climate has an effect on how quickly those items degrade. In an arid, dry climate at high altitude, food waste will not decompose as quickly as it would in a hot, humid area at sea level. The elevation above sea level of a landfill impacts the oxygen level that will be naturally present at a landfill. The absence of oxygen requires the aerobic microbial digestion of the food waste to occur at a slower pace than would be possible in an oxygen-rich location. The presence of moisture or rainwater at a landfill typically settles at the bottom of the liner system and is referred to as leachate. Leachate aids in decomposition in that fully saturated waste decomposes quicker than dry waste. For these reasons, moisture and oxygen affect the methane generation rate constant very differently based on the location and waste composition of the selected landfill. Typical ranges of L_o and k values can be seen in Table 8.

Table 8: Range and Suggested Values for L_o and k (Qian et al. 2002)

Parameter	Range	Suggested Values	
L_o (feet^3/pound)	0 ~ 5	2.25 ~ 2.88	
L_o (meter^3/Mg)	0 ~ 310	140 ~ 180	
k (year^{-1})	0.003 ~ 0.40	Wet Climate	0.10 ~ 0.35
		Medium Moisture Climate	0.05 ~ 0.15
		Dry Climate	0.02 ~ 0.10

The average acceptance rate per year, m_o, is calculated by taking the measured WIP and dividing by the number of years the landfill has been in existence. This method is preferred when waste acceptance values for each year of the landfill's life are not available. For convenience, this method was used with its corresponding equations as opposed to finding the gas generation rate for each individual year based on that corresponding year's waste acceptance rate in metric tons (Mg).

Based on all these components, the U.S. EPA gas generation modeling equation can be applied to estimate the potential gas generation for each year (post-closure) for a landfill. This equation estimates the total amount of landfill gas that will be generated from the site itself. In most instances, when a landfill gas collection system is installed, the collection system will not be 100 percent efficient in collecting the emitted LFG.

A 75 percent landfill gas collection efficiency was assumed in the calculations for this report, which is the standard used by the EPA (Leatherwood 2004). An additional report by Huitric and Kong states that LFG collection systems frequently operate at efficiencies of 95 to 100 percent. Huitric and Kong also state that the EPA uses the 75 percent value to be conservative in their LFG assessments. If the EPA is wrong in their assessment and the collection systems do operate at 95 to 100 percent, then no harm is done to the environment. Using the 75 percent value is thought to skew data toward the side of caution at the expense of the landfill owner/operator when conducting pre-feasibility analysis, yet the standard U.S. EPA value of 75 percent was used for all calculations (Huitric and Kong 2006). Taking the landfill gas generated each year and multiplying by the landfill gas collection efficiency gives the total amount of landfill gas that can be captured in a given year, as shown in Equation 3.

$$\text{Recoverable biogas} = \text{LFG per year}\left(\frac{\text{m}^3}{\text{yr}}\right) * \text{LFG efficiency (\%)} = Q_t * 0.75 \tag{3}$$

Estimating Natural Gas/Methane Recovery

From the recoverable biogas (LFG captured by the collection system) estimated for each year, the quantity of natural gas equivalent to this can be calculated. Landfill biogas is considered to have an energy content of approximately 500 Btu per cubic foot due to the consensus that LFG is typically comprised of 50 percent methane. Natural gas (i.e., natural gas from petroleum engineering) has a Btu value of 1,028 per cubic foot (U.S. EIA 2008). This value was used because it is the standard when selling natural gas commodities on the New York Stock Exchange (NYSE) floor. It is assumed that when one purchases 1 mcf of natural gas, he or she is receiving approximately 1,000,000 Btu of energy. The approximate nomenclature is because 1 mcf of natural gas is not exactly the same from well to well. The U.S. EPA has set the energy use equivalent from 1 mcf of natural gas to be 1,028,000 Btu, and therefore that was the Btu value selected for comparing 1 mcf of natural gas with other natural gas prices shown on the stock exchange. The abbreviation mcf is the equivalent of 1,000 feet^3 of gas. The use of the letter M instead of K, which is typically used for 1,000 units of something, has been common practice in the oil fields and sequentially on the trading floor of that commodity for years. By equating the energy content of LFG and natural gas, and using simple unit conversions, an equivalent mcf (1,000 feet^3) of natural gas produced can be calculated (see Equation 4).

$$\text{mcf of natural gas produced} = \text{recoverable LFG}\left(\frac{\text{m}^3}{\text{yr}}\right) * \left(35.315\,\frac{\text{ft}^3}{\text{m}^3}\right) \div 1{,}000\,\frac{\text{ft}^3}{\text{mcf}} * \left(\frac{500\text{ Btu}}{1028\text{ Btu}}\right) \tag{4}$$

The need for the unit conversion from cubic meters to cubic feet could be avoided if LFG generation values are calculated in cubic feet rather than cubic meters. Cubic meters were used in this instance because the use of cubic meters is more commonly used as a measure of volume when referring to landfill gas.

The LFG produced has been equated to natural gas in terms of Btu values. Methane comprises more than 80 percent of the total composition of natural gas (typically more than 95 percent), which allows the use of both terms with relatively equal values and terminology in this study. It should also be stated that natural gas in pipelines that lead directly to your home for cooking and the operation of various appliances is typically 100 percent methane, which is why this conversion was completed (Spaulding 1997). Thus, the pure methane gas that is being produced is considered equivalent to natural gas and is the sole comprising component in LNG and CNG. By placing a cost on each mcf of natural gas produced, based on market conditions, the value of the natural gas produced per year can be estimated as shown in Equation 5. This calculation for the value of natural gas produced will be considered while looking at the benefits of the various scenarios in the pre-feasibility analysis.

$$Annual\ mcf\ of\ methane * cost\ of\ 1\ mcf\ of\ natural\ gas\ (\$) = annual\ value\ (\$) \tag{5}$$

CHAPTER IV
ANALYSIS

This chapter includes an analysis, including costs and benefits, of the six LFGTE scenarios under investigation. Background information pertaining to the case study being used, the Clint landfill, is provided. An example of each calculation was provided using the Clint landfill data for explanatory purposes.

Study Location

The Clint landfill, which is located in El Paso, Texas, and operated by the City of El Paso's Solid Waste Management (SWM) Department, was used for collecting data on drive cycles. It is a large landfill with WIP of approximately 5 million U.S. tons and an annual waste acceptance rate (WAR) of 500,000 U.S. tons. The landfill is considered fairly typical, with El Paso being the sixth largest city in Texas (City of El Paso 2009).

Operations at Clint Landfill

The SWM Department at the Clint landfill performs residential as well as commercial collection of municipal waste. The residential collection is performed over four 8-hour days. It has 46 daily routes using fully automated refuse trucks and nine daily routes using semi-automated refuse trucks. These routes change by day of the week, covering the entire city during a week. The average route size for a fully automated residential route is approximately 800 containers. This falls perfectly within the industry range of 700 to 900 containers. The average route size for a semi-automated residential route is 645 containers, which is also within the industry range of 600 to 800 containers. The commercial collection service is provided between 1 to 7 days per week. The service is provided to commercial customers (55 percent) and governmental customers (45 percent). The SWM Department has to compete with private operators for providing commercial collection services. The collection service is provided with fully automated as well as semi-automated refuse trucks. The collection service provided by the SWM Department of the City of El Paso is consistent with other cities in Texas (R. W. Beck, Inc. 2004).

Sampling for Data Collection

The fleet operated by the SWM Department consists of side loaders (53), rear loaders (31), front loaders (5), and roll-off compactors (5). The fleet make includes manufacturers such as Peterbilt and International. The manufacturing date of the fleet varies from 1995 to 2005. All the trucks operated by the SWM Department are currently fueled by diesel.

Clint Landfill Site Characteristics

The Clint landfill located 26 miles east of downtown El Paso, Texas, was selected as a pilot landfill for feasibility of LFG-to-LNG/CNG conversion in refuse trucks due to the city's interest in cutting operating costs in conjunction with the closure of a portion of the landfill (R. W. Beck, Inc. 2004). Two new phases of the landfill have begun to be used for new refuse collection, while the pre-existing phase is considering various closure/capping options. The Department of Environmental Services in El Paso has not conducted pump tests on the landfill but estimates the methane generation potential, L_o, to be 100 m^3/Mg. This value is much lower than the 140 to 180 m^3/Mg that is assumed to be the average range for methane generation potential but is appropriate based on the average climate conditions for El Paso. Since El Paso is a dry, arid region, the absence of humidity or rainwater will not allow the leachate to build and aid in the decomposition of the existing waste, therefore creating a lower quantity of methane gas than in a region with high rainfall or moisture. Likewise, the methane generation rate constant is the most conservative value available for a dry climate at 0.02 $year^{-1}$. The portion (phase) of the landfill that has been closed and is being considered for this analysis measures 280 acres in size, accepted over 290,000 U.S. tons annually (265,604 Mg/year), and was opened in 1983 (see Table 9).

Table 9: Clint Landfill Input Values

Name of Value	Value
Methane generation potential	100 m^3/Mg
Methane generation rate constant	0.02 $year^{-1}$
Landfill opening date	1983
Average waste acceptance rate per year	265,600 Mg/year (calculated from WIP)
Landfill size (Ha)	113
Methane content	50% (assumed)
Waste in place	6,905,704 Mg

Do-Nothing Scenario

In this analysis, the baseline is considered to be the “do-nothing” scenario. The do-nothing scenario assumes that all landfills will have to be capped due to EPA regulations once they reach the end of their design life or reach capacity. This is the point at which landfill owners/operators consider various post-closure strategies via LFGTE projects or just capping the landfill. The capping costs, operation and maintenance costs, and yearly purchasing of new vehicles for the landfill totals $94 million for the Clint landfill. This is the base case or “do-nothing” scenario against which all other benefits and costs are measured.

Estimation of Benefits for Pre-feasibility Analysis

The scenarios considered for this analysis include a variety of LFGTE projects. The benefits of such projects include reduced emissions, reduced costs from fuel savings, or earnings from energy production and carbon credits. The monetization of these benefits is discussed here. Since many of the benefits occur on an annual basis over the 20-year analysis period, the total net present value (NPV) of these is generally of interest for analysis purposes. It should be noted here that for all estimates, the values are brought to NPV for the year the landfill is to be closed (in this case 2009) by discounting each year by a 3.05 percent inflation rate. Since 1988, the U.S. Bureau of Labor Statistics has estimated an average inflation rate of 3.05 percent (U.S. BLS 2009).

Natural Gas Generation for Landfills

Based on the methodology presented in Chapter III, the quantity of methane or dry natural gas that can be extracted from a landfill was calculated for a 20-year period after closure. Technically, the analysis is for 21 years, with year 0 being the first year of closure (assumed as 2009, although any year that is input as the closure date into the calculator provided with this thesis will update automatically). The calculator described in Appendix B provides a summary of the calculated LFG generation, recoverable LFG, and methane equivalent which can all be seen in Appendix C. These values can be equated with monetary values to decide upon feasibility for the various LFGTE projects. For example, if LNG is used as a transportation or trucking fuel source, the first benefit received would be the cost savings from no longer needing to purchase an equivalent amount of diesel fuel over the next 20 years.

Equations 2 and 3 are used to determine the quantity of recoverable dry natural gas. They are used below to estimate recoverable dry natural gas for the Clint landfill.

$$Landfill\ gas\ generated = 2 * 100 * 265{,}604.0132 * \left(e^{0.02*(2009-1983)} - 1\right) * e^{-0.02*26} = 21{,}539{,}393.94\ \mathrm{m}^3/\mathrm{yr}$$

$$Recoverable\ dry\ natural\ gas\ = 21{,}539{,}393.94\,\frac{\mathrm{m}^3}{\mathrm{yr}} * 0.75\ (\text{collection efficiency}) = 16{,}154{,}545.46\,\frac{\mathrm{m}^3}{\mathrm{yr}} * 35.31466746\,\frac{\mathrm{ft}^3}{\mathrm{m}^3} \div 1{,}000\,\frac{ft^3}{mcf} * \frac{500}{1028}\,(BTU/ft^3) = 277{,}476.85\ mcf\ NG\ for\ year\ 1$$

When these calculations are summed over a 20-year period, only changing the t value (for time from Equation 2), the Clint landfill will accumulate 4,805,818 mcf of recoverable dry natural gas over its 20-year analysis period.

Diesel Savings

When the natural gas recovered from LFG is used as a transportation fuel (scenarios 1, 2, and 3), the savings due to either not purchasing diesel or through the sale of natural gas can be estimated as benefits. Since future energy prices are hard to predict, historical rates for natural gas and diesel were sought for guidance. The price associated with each mcf of gas and each gallon of diesel should be estimated based on the average cost of that commodity over the next 20 years. Based on historical market prices for natural gas and diesel, an average price of $4.57 per mcf for gas and $2.60 per gallon of diesel was used (U.S. EIA 2009a, 2009b). The natural gas price was chosen because it has been the average U.S. market price for 1 mcf of natural gas since 1994 (U.S. EIA 2009a). Likewise, $2.60 has been the average market price of all types of diesel over the past 5 years (U.S. EIA 2009b). Market conditions can change dramatically and should be cautiously considered when selecting appropriate commodity prices. The user can adjust these values in the feasibility tool (spreadsheet) that is included with this thesis.

In order to calculate the savings from not purchasing diesel, natural gas was equated to diesel quantities in terms of energy equivalency. One mcf of natural gas was thus estimated to produce the equivalent of 7.39 gallons of diesel since 1 gallon of diesel equals 139,000 Btu while 1 mcf of natural gas equals 1,028,000 Btu (U.S. EIA 2008) (see Equation 6).

$$1{,}028{,}000\ Btu\ (NG) \div 139{,}000\ \left(\frac{Btu\ diesel}{gallon}\right) = 7.3957\ gallons\ equivalent \tag{6}$$

$$mcf\ of\ NG\ present\ in\ year\ 1 = 277{,}476.85$$

$$277{,}476 * 7.3957\,\frac{gallons}{mcf} * \left(\frac{\$2.60}{gal}\right)$$
$$= \$5{,}335{,}540\ savings\ in\ diesel\ for\ year\ 1$$

Using the present-value Equation 7, the savings from not purchasing diesel over 20 years are summed.

$$Present\ value = \sum_{t=0}^{n} \frac{FV_t}{(1+i)^t} \tag{7}$$

Where:

n = number of time periods,
i = rate of inflation (3.05 percent),
t = number of years, and
FV = future value.

$$\$71{,}091{,}615 = \sum_{t=0}^{20} \frac{FV_t}{(1+0.0305)^t} = sum\ of\ diesel\ savings\ over\ 20\ years$$

The savings in not purchasing diesel fuel for the Clint landfill when brought to NPV at 3.05 percent (the 20-year U.S. Bureau of Labor Statistics average inflation) over 20 years is $71,091,615 (in 2009 dollars).

Tax Credits from Alternative Fuels

The 2008 Omnibus Financial Rescue Package extended a tax credit until the end of 2009 on alternative fuels, specifically propane, which provides a $0.50 per gallon equivalent fuel tax credit. President Obama has extended this credit indefinitely under the American Recovery and Reinvestment Act of 2009. Under the provisions as they are currently written, landfill gas that is converted into natural gas (not propane) will still qualify for this tax credit until stated otherwise by the federal government (NPGA 2009). Because of this, the additional tax credit benefit was included in this feasibility analysis. For the Clint landfill the tax benefits will enable an additional $13.67 million (in 2009 dollars) adjusted for NPV over the 20-year feasibility period (if the tax credit remains in place over the life of the project).

$$Gallons\ of\ diesel\ equivalent = 2{,}052{,}130 * \frac{\$0.50}{gallon} = \$1{,}026{,}065\ in\ year\ 1$$

$$\$13{,}671{,}464 = \sum_{t=0}^{20} \frac{FV_t}{(1+0.0305)^t} = sum\ of\ tax\ benefits\ over\ 20\ years$$

Pipeline Natural Gas

For the alternative of selling natural gas, as stated previously, the value associated with 1 mcf of natural gas was taken as $4.57. This value was used to calculate earnings from an LFGTE project in which the LFG was sold as pipeline-grade natural gas. This is also presented in a detailed table in Appendix C. The NPV of the earnings for the Clint landfill over the entire analysis period was $16.90 million (in 2009 dollars).

$$mcf\ of\ NG\ produced = 277{,}477 * \$4.57/mcf = \$1{,}268{,}069\ in\ year\ 1$$

$$\$16{,}895{,}962 = \sum_{t=0}^{20} \frac{FV_t}{(1+0.0305)^t} = sum\ of\ NG\ earnings\ over\ 20\ years$$

Tax Credit from Pipeline-Grade Natural Gas

The Resource Conservation and Recovery Act of 2009 also provides a $1 per mcf production tax credit when produced from LFGTE facilities. Earnings from the quantity of natural gas that could be produced were $3.70 million (in 2009 dollars).

$$mcf\ of\ NG\ produced = 277{,}477 * \$1.00/mcf = \$277{,}477\ in\ year\ 1$$

$$\$3{,}697{,}147 = \sum_{t=0}^{20} \frac{FV_t}{(1+0.0305)^t}$$
$$= sum\ of\ tax\ credit\ earnings\ over\ 20\ years$$

Earnings from Electricity Conversion

Conversion of landfill gas to electricity is also a possible LFGTE project solution. As in the previous case for calculating diesel/natural gas equivalencies and costs, the Btu values were equated to estimate electricity generation. One cubic foot of LFG was equated to 500 Btu, and 1 Btu equals 0.000293 KWh of electricity. By assuming a price of $0.1 per KWh of electricity, the value of the electricity generated was calculated (U.S. EIA 2009c). Again, these calculations were performed for a 20-year period, and the NPV calculated for the Clint landfill was found to be $103.34 million (in 2009 dollars).

$$\frac{Btu}{yr} * 0.000293\,\frac{kWh}{Btu} * \frac{Cost\,(\$)}{kWh} = \frac{revenue}{yr} \tag{8}$$

$$\begin{aligned}\frac{Btu}{yr} &= 16{,}154{,}545\ (m^3\ recoverable\ LFG) * 35.3146667\,\frac{ft^3}{m^3} * 500\,\frac{Btu}{ft^3}\\ &= 2.85 * 10^{11}\end{aligned}$$

$$2.85 * 10^{11}\,\frac{Btu}{yr} * 0.000293\,\frac{kWh}{Btu} * \frac{\$0.10}{kWh} = \$8{,}357{,}713.49\ in\ year\ 1$$

$$\begin{aligned}\$103{,}341{,}657 &= \sum_{t=0}^{20} \frac{FV_t}{(1+0.0305)^t}\\ &= sum\ of\ electricity\ earnings\ over\ 20\ years\end{aligned}$$

Tax Credits for Electricity

The same American Recovery and Reinvestment Act of 2009 that provides a $0.50 per gallon tax benefit for alternative fuels also provides a $0.01 per kilowatt-hour tax credit for landfill-gas-to-electricity projects. This tax benefit can apply for landfill owners until 2013. Once approved, landfill owners will be able to receive this credit for the first 10 years of the LFGTE project's life (U.S. Government 2009). Again, a disclaimer must be placed with this tax credit because laws and regulations are constantly changing based on various political decisions. If it is assumed that the Clint landfill receives 10 years of this credit, the total tax credit received would total $7.73 million (in 2009 dollars).

$$83{,}577{,}135\,\frac{kWh}{yr} * \$0.01 = \$835{,}771\ in\ year\ 1$$

$$\begin{aligned}\$7{,}730{,}248 &= \sum_{t=0}^{20} \frac{FV_t}{(1+0.0305)^t}\\ &= sum\ of\ tax\ credit\ earnings\ over\ 20\ years\end{aligned}$$

Carbon Credits

Due to emerging political and societal requests for a reduction in global greenhouse emissions, carbon credit trading has emerged as a potential solution to this global issue. Thousands of tons of various emissions, most notably carbon dioxide, methane, and nitrogen oxides, are emitted from landfills each year. Some countries have passed cap-and-trade legislation that requires their industries to limit the amount of emissions that they produce each year. The implication this has on industries is very simple: either purchase new scrubbing equipment or new technology that is more environmentally friendly, or purchase offset emissions credits for the number of tons that you expect to exceed your imposed limit by. A company is essentially faced with which option is most economical, and in many instances, buying credits is the best option.

The positive side of those same regulations is that if an owner decides to upgrade his facilities and equipment and therefore is producing fewer emissions than he was originally allocated by the government, he can sell his additional emissions credits, typically known as carbon credits, to whomever he pleases. Based on traditional concepts of supply and demand, the price of these carbon credits will increase over time as the regulations and allotted carbon credits decrease. The ability to cap a landfill and sell its carbon credits creates an economic return for landfill owners wishing to curb their greenhouse-gas emissions and immeasurable societal benefits for the local communities.

The United States currently has two markets for carbon credit trading, the Regional Greenhouse Gas Initiative and the Chicago Climate Exchange. Both markets hold auctions and sell certified emission reduction credits. One certified emission reduction credit is equivalent to 1 metric ton of CO_2 equivalent (RGGI 2009a; CCX 2009). Therefore, contaminants that are much more detrimental to the environment such as methane would trade at their global warming potential (United Nations 1995). Global warming potential is considered to be the standard for converting other pollutants such as methane into a carbon equivalent. Methane's GWP is 21, meaning that it is 21 times more harmful than CO_2. The RGGI in its most recent auction (March 18, 2009) sold its CO_2 credits for $3.51 per ton (RGGI 2009b). It is important to mention the differences in the unit systems being used. The RGGI sells its credits based on a ton, which is 2,000 pounds, where all other trading platforms sell their credits based on a metric ton or tonne, 2,204.6226 pounds. To convert the price to a metric ton, the given price was interpolated to provide a value of $3.87 to equate 1 CER credit with each ton of pollution that comes from a landfill. For the purposes of this analysis it was assumed that 50 percent of the emissions were from methane and the other 50 percent were from CO_2. Much more in-depth analysis would be required in order to give more accurate estimates, but these values provide a conservative estimate of the earnings that would be produced from an LFGTE project.

In order to convert the estimated LFG into potential emitting metric tons to calculate the CER equivalent, principles of basic chemistry were used. The density of CO_2 and CH_4 at standard temperature and pressure (1 atmosphere at 25°C) are 1.799 and 0.656 kg/m^3, respectively. The calculations are shown in Equations 9 and 10 below.

$$\text{Molecular weight of } \mathrm{CO_2} = 44.01 \frac{\mathrm{g}}{\mathrm{mol}}$$

$$\text{Volume at standard tempurature and pressure} = 24.4658 \frac{\mathrm{L}}{\mathrm{mol}}$$

$$\rho = \frac{\mathrm{MW}}{\mathrm{V}} = \frac{44.01}{24.4658} = 1.799 \frac{\mathrm{g}}{\mathrm{L}} = 1.799 \frac{\mathrm{kg}}{\mathrm{m}^3} \tag{9}$$

$$MW \ of \ CH_4 = 16.042$$

$$\rho = \frac{\mathrm{MW}}{\mathrm{V}} = \frac{16.042}{24.4658} = 0.656 \frac{\mathrm{g}}{\mathrm{L}} = 0.656 \frac{\mathrm{kg}}{\mathrm{m}^3} \tag{10}$$

Splitting the volume of carbon dioxide and methane into two equal halves (since it was assumed that the composition was 50 percent methane and 50 percent CO_2) enables the landfill gas generated (cubic meters per year) to be multiplied by the densities of CO_2 and

CH_4 and then divided by 1,000 to provide the megagrams (Mg) of emissions per year (Equations 11 and 12).

$$1.799\,\frac{kg}{m^3} * LFG\ generated\ \left(\frac{m^3}{yr}\right) * 50\%\ CO_2 \div 1{,}000\,\frac{kg}{Mg} = \frac{Mg}{yr},\ (metric\ tons) \tag{11}$$

$$0.656\,\frac{kg}{m^3} * LFG\ generated\ \left(\frac{m^3}{yr}\right) * 50\%\ CH_4 \div 1{,}000\,\frac{kg}{Mg} = \frac{Mg}{yr},\ (metric\ tons) \tag{12}$$

Based on the methodology outlined here, the NPV earnings from carbon credits over a 20-year period for the Clint landfill was \$7.48 million. The detailed results are presented in Appendix C.

$$\left(16{,}154{,}545.46\,\frac{m^3}{yr}\,(recoverable\ LFG) * 1.799\,\frac{kg}{m^3} \div 1{,}000\,\frac{kg}{Mg} * \frac{50}{100}\,(\%\ CO_2)\right) + \left(16{,}154{,}545\,\frac{m^3}{yr} * 0.656\,\frac{kg}{m^3} \div 1{,}000\,\frac{kg}{Mg} * \frac{50}{100}\,(\%\ CH_4)\right) = 19{,}829.70\ Mg$$

$$(19{,}829.70\ Mg * 50\%\ methane * 21) + (19{,}829.70\ Mg * 50\%\ CO_2 * 1) = 218{,}126.75\ equivalent\ metric\ tons\ of\ CO_2$$

$$218{,}126.75\ Mg\ CO_2 * \$3.87\ per\ CER = \$844{,}150.53\ \text{in year 1}$$

$$\$7{,}484{,}850 = \sum_{t=0}^{20} \frac{FV_t}{(1+0.0305)^t} = sum\ of\ carbon\ credit\ earnings\ over\ 20\ years$$

The tool included with this thesis allows the user to change the percentage of methane at the landfill. The rest of the emissions from the landfill are all assumed to be carbon dioxide, but the equations will be computed according to the user's input methane percentage.

Using LNG/CNG as Transportation Fuel—Fleet Turnover Emissions Reduction

In the scenario where the landfill gas is captured and converted to LNG/CNG for use as transportation fuel, there would also be emissions benefits from the replacement of older, higher-emitting refuse trucks with more efficient (and lesser-emitting) LNG or CNG vehicles. Miguel Parra, Engineering Division manager with the City of El Paso, is in charge of the Clint landfill and stated that refuse trucks were replaced by the city on a need basis; therefore, if five trucks needed to be replaced, then five new trucks would be purchased and put into service to replace the older trucks. He stated that if the landfill were to convert its fleet to LNG/CNG, it would be able to do so at a rate of five refuse trucks per year based on current budget constraints. The five refuse trucks per year is the same number of diesel trucks he would be able to purchase if needed during a given year. Since five refuse trucks could be purchased per year, this was the fleet turnover number used.

In order to estimate the emissions benefit due to the fleet turnover from older trucks to new LNG trucks, a baseline emissions estimate is needed for the existing refuse truck fleet, as well as an estimate of emissions from CNG or LNG trucks.

Natural Gas Refuse Truck Emissions

With the emissions data for each of the refuse trucks being used for collection, the total annual emissions from the city refuse trucks that operate the Clint landfill were generated. These emissions were then converted to a dollar value based on CER values. For this analysis, carbon monoxide (CO) was given the same GWP as CO_2 because it is not a greenhouse gas but does hinder the breakdown of methane in the atmosphere. Through natural courses it will eventually turn into CO_2. “Oxides of nitrogen” is a generic term given to all pollutants that are solely comprised of nitrogen and oxygen. NO_x were equated with a global warming potential of 310 in this study as designated by numerous environmental regulatory agencies for the compound N_2O (United Nations 1995). Although not all of the NO_x that will be formed is N_2O, the GWP of N_2O was paired with those pollutants. Hydrocarbons and particulate matter were not given global warming potential factors since they are not pollutants that can be traded, nor do they have consistent estimated GWP values. Since they were unable to meet these criteria, no true value can be associated with them, and therefore they were not given a cost.

In order to estimate the cost savings from emissions due to using natural gas refuse trucks instead of a diesel trucks, emissions results from a test completed by the Texas Transportation Institute (TTI) in conjunction with the Texas State Energy Conservation Office (SECO) were used. These results were preliminary results from a study to be published by Dr. Zietsman of TTI and SECO in January of 2010. CNG vehicle emissions are nearly identical in every way to those of LNG vehicles, which is why LNG and CNG refuse trucks are given the same emissions benefits in this analysis.

For the SECO/TTI testing, five diesel and five CNG refuse trucks were equipped with portable emissions measurement systems (PEMSs) while completing various tasks that were simulated at the Northeast Service Center in San Antonio, Texas. This site was chosen because the City of San Antonio, in conjunction with Clean Fuel Technologies (a Boone Pickens company), installed a CNG fueling station for all of its newly purchased refuse trucks. The City of San Antonio was still utilizing some of its diesel refuse trucks with the exact same dimensions, engine size, etc., except for the fuel injection systems and fuel type used, which provided equal testing subjects to determine emissions differences. Standard daily operations including collection, high-speed driving, and compaction were simulated using both the CNG and diesel trucks at the same locations. Two refuse trucks were also used to collect real-world data. This occurred while a researcher from TTI rode along with a solid waste department employee during his daily route to record the emissions from a single service route. This was done with one CNG and one diesel truck.

The preliminary results from this test are shown in Tables 10 and 11.

Table 10: Diesel Emissions Based on 2009 SECO Testing

	DIESEL				
	No$_x$	**CO$_2$**	**CO**	**HC**	**PM**
	Average of Emissions from All 5 Trucks (grams/second)				
HIGH-SPEED DRIVING					
Driving—empty	0.1200	26.2000	Ng*	Ng*	Ng*
Driving—loaded	0.1400	30.8000	Ng*	Ng*	Ng*
Average of driving	**0.2766**	**26.7600**	**Ng***	**Ng***	**Ng***
COLLECTION					
Uphill—empty	0.2100	43.4000	0.0140	Ng*	Ng*
Uphill—loaded	0.2000	43.6000	Ng*	Ng*	Ng*
Short-dist. accel.—empty	0.2400	34.3000	0.0150	Ng*	Ng*
Short-dist. accel.—loaded	0.2300	37.0000	Ng*	Ng*	Ng*
35 steady—empty	0.8300	15.2000	Ng*	Ng*	Ng*
35 steady—loaded	0.0930	18.0000	Ng*	Ng*	Ng*
Compaction & idle	0.1100	8.2000	Ng*	Ng*	Ng*
Collection—stretch	0.1038	8.0209	0.0037	0.0000	0.0003
Collection—dummy	0.0966	7.6476	0.0034	0.0000	0.0000
Collection—loaded					
Average of collection	**0.2348**	**23.9298**	**0.0090**	**0.0000**	**0.0002**

Table 11: CNG Emissions Based on 2009 SECO Testing

	CNG				
	No$_x$	**CO$_2$**	**CO**	**HC**	**PM**
	Average of Emissions from All 5 Trucks (g/s)				
HIGH-SPEED DRIVING					
Driving—empty	0.0017	22.4000	0.1300	0.0110	Ng*
Driving—loaded	0.0025	26.2000	0.1700	0.0330	Ng*
Average of driving	**0.0021**	**24.3000**	**0.1500**	**0.0220**	Ng*
COLLECTION					
Uphill—empty	0.0026	31.9000	0.3200	0.0440	Ng*
Uphill—loaded	0.0029	32.1000	0.3800	0.0310	Ng*
Short-dist. accel.—empty	0.0034	31.0000	0.3900	0.0560	Ng*
Short-dist. accel.—loaded	0.0037	31.0000	0.4400	0.0480	Ng*
35 steady—empty	0.0026	13.8000	0.0530	0.0047	Ng*
35 steady—loaded	0.0032	15.2000	0.0570	0.0056	Ng*
Compaction & idle	0.0016	7.3000	0.0230	0.0044	Ng*
Collection—stretch	0.0019	6.3911	0.0317	0.0043	Ng*
Collection—dummy	0.0019	5.7527	0.0237	0.0051	Ng*
Collection—loaded					
Average of collection	**0.0026**	**19.3826**	**0.1909**	**0.0226**	**Ng***

The actions listed in Tables 10 and 11 are broken into both high speed driving and collection for the purpose of taking a weighted average of emissions based on the percentage of the total time that is spent on that specific action.

The driving portion of service was broken into various situations that would occur during a typical route. "High speed driving" reflects the emissions results when the refuse truck was traveling at 55+ mph on an urban arterial; "35 steady" reflects driving at 35 mph. "Uphill" is the emissions results from driving the refuse truck up a steep incline, roughly more than 3.5°. "Empty" and "loaded" listed after each of the actions reflect the refuse truck being completely empty or loaded with roughly 14,600 pounds of concrete. During testing this was kept consistent with pallets of concrete, with bales of hay acting as a protective barrier, but 20,000 pounds was recorded from the weight ticket of the refuse truck once it made its first trip to the collection site. The collection site acted as a transfer station between the refuse trucks and the landfill so that the refuse trucks themselves did not have to travel directly to the landfill.

Collection was broken into six actions: street driving (35 steady), uphill driving, collection-empty, collection-stretch, collection-dummy, and short distance acceleration. For testing purposes, 14- to 80-gallon refuse containers were placed along an abandoned road with a level grade. The spacing of the refuse containers varied from 15 to 90 feet to recreate the spacing that would be apparent in residential neighborhoods. The refuse truck picked up empty containers, which provided the results for the empty designation. The stretch emissions were obtained from the refuse truck extending its mechanical arm to pick up the containers. "Dummy" consisted of the refuse truck just stopping at each container but not picking up any of them. "Loaded" reflected the picking up of loaded containers, filled with bags of mulch and sand to consistently weigh roughly 200 pounds. This weight was chosen because the solid waste department stated that it was the average weight collected from each residential household from its estimates. During testing researchers felt that this value was much too dense for an average household, but the testing parameters had already been set. The results proved that the weight of the containers was never truly a factor since use of the mechanical arm created nearly the same quantity of emissions whether the container was loaded or empty. "Compaction & idle" provides the emissions results from operating the refuse compactor that is inside the refuse truck itself. This compaction pushes the refuse together to create less void space in order to pick up more refuse. The "short-distance acceleration" designation reflects the actions of a refuse truck traveling at 20 mph and stopping abruptly as one would while driving during collection from one refuse container to the next or from one street to another.

Emissions savings were calculated on the premise that each of the driving actions occurs the same percentage of time for other sanitation department vehicles as was observed during the SECO testing. In the testing, a scientist rode along with a sanitation department employee as he worked his collection route. These observations were conducted for both a diesel and CNG refuse truck. The scientist observed that the only two actions that needed to be recorded were high-speed driving and collection. The scientist noted that a typical daily route consisted of the driver getting into the refuse truck, checking his equipment, filling out a few forms, and leaving the station for collection. The drivers typically make one trip to a transfer station or dump and then continue the rest of their route, which will last around 6 hours. The scientist found that driving (without collection) consisted of 30 percent of the daily route, while the other 70 percent was spent on the collection itself. Based on this information a weighted average of the emissions found from the SECO testing can be used to produce the emissions benefits of using a CNG refuse truck versus a diesel truck over the course of a year. The calculations are outlined below.

For CO_2:

The difference in CO_2 emissions from a diesel refuse truck versus a CNG refuse truck is roughly 4.44 g/s (see Table 12). Assuming that the refuse truck is operated for 7 hours a day (routes typically run from 7 a.m. to 2 p.m.) for 260 days per year (5 days per week), using a CNG refuse truck produces a reduction of 33.45 Mg of CO_2 per truck per year. If carbon credits are selling for \$3.87/metric ton of CO_2, then this is an emissions savings of over \$112 per year per truck for the pollutant CO_2 alone.

Table 12: Difference in CNG versus Diesel Emissions in Refuse Trucks

	DIFFERENCE				
	No_x	**CO_2**	**CO**	**HC**	**PM**
	Average of Emissions from All 5 Trucks (g/s)				
HIGH-SPEED DRIVING					
Driving—empty	-0.1183	-3.8000	N/A	N/A	N/A
Driving—loaded	-0.1375	-4.6000	N/A	N/A	N/A
Average of driving	**-0.1279**	**-4.2000**	**N/A**	**N/A**	**N/A**
COLLECTION					
Uphill—empty	-0.2074	-11.5000	0.3060	N/A	N/A
Uphill—loaded	-0.1971	-11.5000	N/A	N/A	N/A
Short-dist. accel.—empty	-0.2366	-3.3000	0.3750	N/A	N/A
Short-dist. accel.—loaded	-0.2263	-6.0000	N/A	N/A	N/A
35 steady—empty	-0.8274	-1.4000	N/A	N/A	N/A
35 steady—loaded	-0.0898	-2.8000	N/A	N/A	N/A
Compaction & idle	-0.1084	-0.9000	N/A	N/A	N/A
Collection—stretch	-0.1019	-1.6298	0.0280	0.0043	N/A
Collection—dummy	-0.0947	-1.8949	0.0203	0.0051	N/A
Collection—loaded					
Average of collection	**-0.2322**	**-4.5472**	**0.1823**	**-0.0047**	**N/A**

$$Weighted\ average\ of\ CO_2 = (4.5472 * 0.30) + (4.2 * 0.70) = 4.44 \qquad (13)$$

$$Difference\ in\ CNG\ vs.diesel\ for\ CO_2 = 4.44\ g/s$$

$$4.44\frac{g}{s} * 60\frac{sec}{min} * 60\frac{min}{hr} * 7\frac{hr}{day} * 260\frac{days}{yr} \div 1{,}000{,}000\frac{g}{Mg} =$$
$$29.09\ Mg\ of\ CO_2\ per\ year \qquad (14)$$

An example for the first estimation of CO_2 is shown in Equations 13 and 14.

$$1\ CER = 1\ Mg\ of\ CO_2 = \$3.87 = 29.09\ Mg * \frac{\$3.87}{Mg} = \$112.58\ per\ truck$$

This analysis was also preformed for CO and NO_x since they are the only tradable pollutants (i.e., the only ones that can be sold) and then summed for the total number of CNG refuse trucks in the fleet, which can be seen in Appendix C.

For CO:

$$Difference\ in\ CNG\ vs.diesel\ for\ CO = -0.14\ g/s$$

$$-0.18\,\frac{g}{s} * 60\,\frac{sec}{min} * 60\,\frac{min}{hr} * 7\,\frac{hr}{day} * 260\,\frac{days}{yr} \div 1{,}000{,}000\,\frac{g}{Mg} =$$
$$-1.18\ Mg\ of\ CO\ per\ year \tag{15}$$

An example for the first estimation of CO is shown in Equation 15.

$$1\ CER = 1\ Mg\ of\ CO_2 = \$3.51 = -1.18\ Mg * \frac{\$3.87}{Mg} = -\$4.57\ per\ truck$$

It is shown that CO is increased through the use of CNG refuse trucks, but the impact is only $4.57 per truck per year if 1 ton of CO is assumed to be equal to 1 ton of CO_2.

For NO_x:

$$Difference\ in\ CNG\ vs.diesel\ for\ NO_x = 0.12\ g/s$$

$$0.20\,\frac{g}{s} * 60\,\frac{sec}{min} * 60\,\frac{min}{hr} * 7\,\frac{hr}{day} * 260\,\frac{days}{yr} \div 1{,}000{,}000\,\frac{g}{Mg} =$$
$$1.31\ Mg\ of\ NO_x\ per\ year \tag{16}$$

An example for the first estimation of CO is shown in Equation 16.

$$1\ CER = 1\ Mg\ of\ CO_2 = \$3.87 = 1.31\ Mg * 310\ GWP * \frac{\$3.87}{Mg}$$
$$= \$1{,}571.61\ per\ truck$$

The benefit in the reduction of NO_x is shown to be $1,571.61 per truck if the global warming potential associated with NO_x is assumed to be 310, as indicated by the Kyoto Protocol. It must be mentioned again that NO_x is not N_2O, which is what the 310 GWP multiplier is added into the calculations for. The N_2O that would be present in NOx would be very small, yet as stated previously no research has shown the GWP of NO_x as a whole; therefore, the 310 GWP multiplier for N_2O was applied to NO_x as a whole.

This methodology was used for each pollutant. The cost savings from using a CNG/LNG vehicle versus a diesel vehicle were then calculated. The emissions cost savings from switching from diesel to LNG vehicles exceeds $1.32 million when brought to NPV over the course of 20 years.

Societal Benefits

Additional societal benefits that are difficult to quantify occur from reduced emissions. Many of these benefits are indirect benefits that will ultimately have monetary effects, but they were not considered in looking at the overall financial return or benefit-cost analysis.

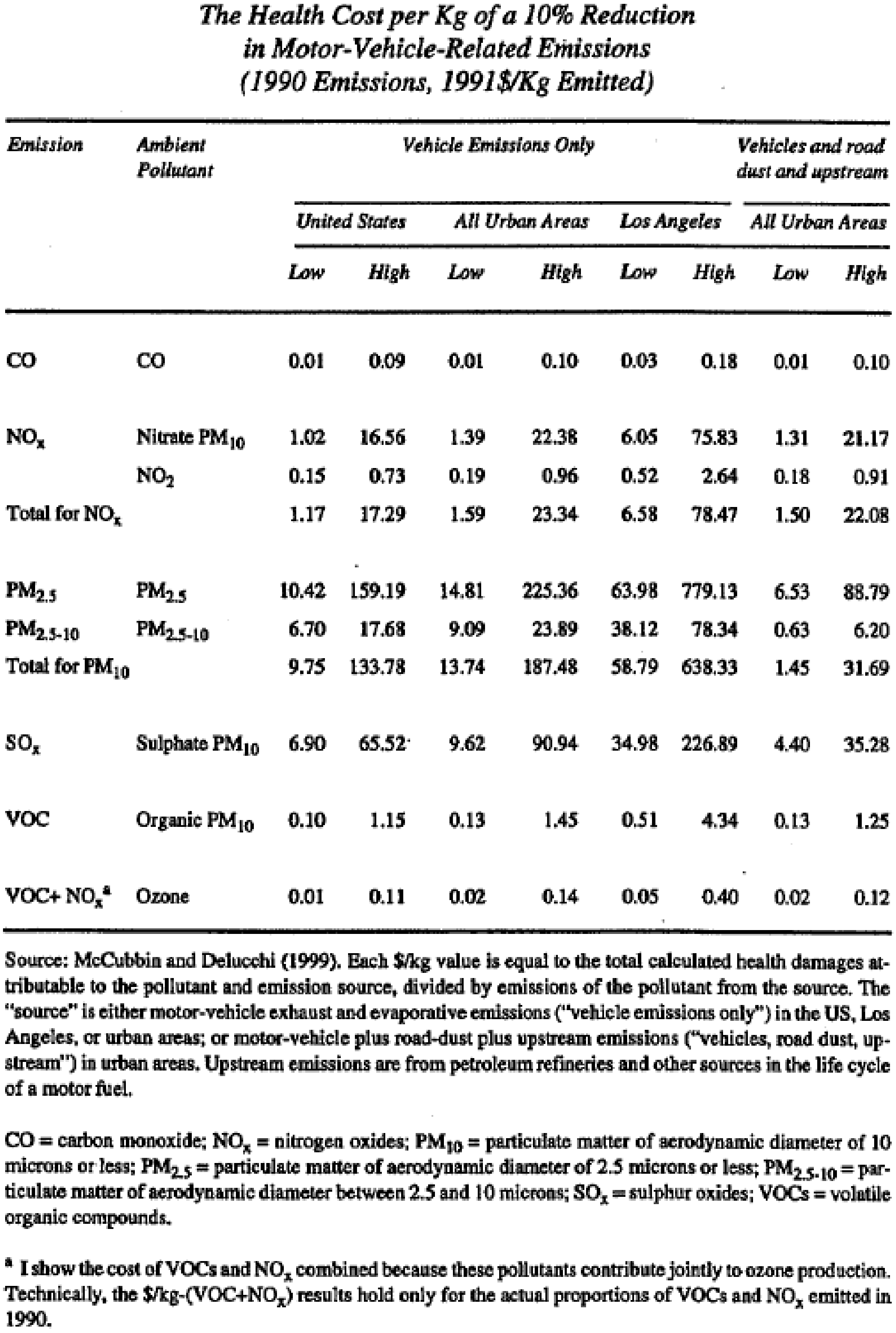
A study conducted by Mark A. Delucchi in 2000 categorized all environmental damages that are incurred from motor vehicles as externalities. He felt that air quality should be considered an externality because individual air molecules are not owned or bought and sold in markets. Ten years later this thought is beginning to come closer to fruition with the idea of carbon credit trading. Delucchi and McCubbin placed a monetary value on the major pollutants from motor vehicles including CO, NO_2, ozone, and PM (McCubbin and Delucchi 1996). The value of these emissions was found from a valuation of health effects from lung-related illness. The total cost that was incurred from lung-related illnesses (i.e., lost work time, direct illness costs, etc.) due to motor-vehicle emissions at a given source was divided by emissions produced from that source. Extensive research was placed into answering all questions that could arise about the estimation of these values, giving extensive reasoning behind dismissing many of their results based on outlying events that could skew data. They stated that CO, NO_x, sulfur oxide (SO_x), and ozone appear to have much smaller effects than PM does. Aside from their contribution to particulate formation, emissions of NO_x, SO_x, and volatile organic compounds (VOCs) are relatively unimportant to lung-related illness. The explanation of this is the truly unknown effects of the formation of ozone through the interaction of NO_x and VOCs

(Delucchi 2000).

Delucchi's results are presented in Table 13. The values are presented in dollars per kilogram. This thesis refers to pollutants valued by megagram; therefore, the prices provided by Delucchi must be multiplied by 1,000. Adjusting for inflation as well would require the user to multiply by 1,549 (not 1,000), in order to convert the pollutants to 2009 dollars. With present carbon credit prices, assuming that CO is considered equivalent to CO_2, then CO is undervalued by $75 according to U.S. trading. NO_x on the other hand would be equivalent to $1,088 today since it is 310 times more harmful and yet is quoted by numerous state agencies as being valued around $10,000 to $15,000. The $10,000 to $15,000 cost per ton of NO_x is the mitigation cost associated with NO_x and not the associated price that is given to 1 ton of the pollutant. The correct value that should be associated with each value will only be what the market chooses it to be if and only if emissions trading platforms are made commonplace in the economic trading of everyday operations in order for the decision-making tool included with this thesis to provide a relatively accurate pre-feasibility analysis.

It should also be noted that for the Clint landfill case, as with any other landfill, there will be societal costs incurred through the do-nothing scenario. By the landfill owner/operator not reducing the pollutants that are being emitted by the landfill, there is a societal cost that is being incurred by the surrounding communities. This cost was assumed to equal the cost of the total CO_2 equivalent tons being emitted times the market price of a carbon emission reduction credit. For the Clint landfill this societal cost amounted to just less than $13 million over the 20-year analysis period. This cost was not implemented into the benefit-cost analysis because it is only a societal cost. It does not cost the landfill owner/operator any amount of money to do nothing (unless he or she were fined); therefore, this cost was not included in the benefit-cost analysis.

Table 13: Health Care Costs per Kilogram of Emissions (McCubbin and Delucchi 1996)



The Health Cost per Kg of a 10% Reduction in Motor-Vehicle-Related Emissions (1990 Emissions, 1991$/Kg Emitted)

Emission	*Ambient Pollutant*	*Vehicle Emissions Only*						*Vehicles and road dust and upstream*	
		United States		*All Urban Areas*		*Los Angeles*		*All Urban Areas*	
		Low	*High*	*Low*	*High*	*Low*	*High*	*Low*	*High*
CO	CO	0.01	0.09	0.01	0.10	0.03	0.18	0.01	0.10
NO_x	Nitrate PM_{10}	1.02	16.56	1.39	22.38	6.05	75.83	1.31	21.17
	NO_2	0.15	0.73	0.19	0.96	0.52	2.64	0.18	0.91
Total for NO_x		1.17	17.29	1.59	23.34	6.58	78.47	1.50	22.08
$PM_{2.5}$	$PM_{2.5}$	10.42	159.19	14.81	225.36	63.98	779.13	6.53	88.79
$PM_{2.5\text{-}10}$	$PM_{2.5\text{-}10}$	6.70	17.68	9.09	23.89	38.12	78.34	0.63	6.20
Total for PM_{10}		9.75	133.78	13.74	187.48	58.79	638.33	1.45	31.69
SO_x	Sulphate PM_{10}	6.90	65.52	9.62	90.94	34.98	226.89	4.40	35.28
VOC	Organic PM_{10}	0.10	1.15	0.13	1.45	0.51	4.34	0.13	1.25
VOC+ NO_x[a]	Ozone	0.01	0.11	0.02	0.14	0.05	0.40	0.02	0.12

Source: McCubbin and Delucchi (1999). Each $/kg value is equal to the total calculated health damages attributable to the pollutant and emission source, divided by emissions of the pollutant from the source. The "source" is either motor-vehicle exhaust and evaporative emissions ("vehicle emissions only") in the US, Los Angeles, or urban areas; or motor-vehicle plus road-dust plus upstream emissions ("vehicles, road dust, upstream") in urban areas. Upstream emissions are from petroleum refineries and other sources in the life cycle of a motor fuel.

CO = carbon monoxide; NO_x = nitrogen oxides; PM_{10} = particulate matter of aerodynamic diameter of 10 microns or less; $PM_{2.5}$ = particulate matter of aerodynamic diameter of 2.5 microns or less; $PM_{2.5\text{-}10}$ = particulate matter of aerodynamic diameter between 2.5 and 10 microns; SO_x = sulphur oxides; VOCs = volatile organic compounds.

[a] I show the cost of VOCs and NO_x combined because these pollutants contribute jointly to ozone production. Technically, the $/kg-(VOC+$NO_x$) results hold only for the actual proportions of VOCs and NO_x emitted in 1990.

Estimation of Costs for Pre-feasibility Analysis

In general, the costs associated with LFGTE projects vary greatly and are based on size and need of the municipality or owner/operator. In the case of the six scenarios identified for this study, each scenario entails unique costs as indicated in Table 7. Each of these costs is described in this section. A majority of costs (such as capping, investment in LNG/electric conversion facilities, etc.) involve one-time investments for which the present value can be considered. Other costs may occur over the analysis period, and their present value is considered for discussion purposes. Thus, all costs mentioned here refer to their present value when considered over the total 20-year analysis period.

Landfill Capping Costs

All of the six analysis scenarios considered involve capping the landfill. Capping of a landfill is a necessity in the United States when a landfill has reached the end of its design life. Capping the landfill dramatically reduces the odor that is present as well as controls the emission of harmful gases. The capping process involves covering the entire landfill with geosynthetic liners, membranes, and topsoil. Throughout this covering or capping process, contractors may also drill gas extraction wells directly into the face of the landfill in order to extract the landfill gases that are below. This process not only helps to eliminate the harmful gases that would otherwise be emitted but also helps to keep the integrity of the landfill cap intact. If too much methane or any other gas builds up underneath the landfill cap, the cap could eventually tear, rip, or burst, defeating the purpose of the cap. Typically, the gas from each of these extraction wells is collected and flared, therefore removing more harmful pollutants from the atmosphere by just producing CO_2 and heat. Other approaches to using the collected gas include conversion to CNG/LNG, electricity, or natural gas. Data were obtained from various contractors in the United States that estimate landfill capping costs and collection system installation for a landfill the size of Clint’s, as shown in Table 14.

Table 14: Estimated Clint Landfill Capping Costs

No.	**Item Description**	**Cost ($ Million) Of Clint Landfill** (Area=113.3 Ha)
1	Landfill cap	54.6
2	Gas and leachate collection wells and collection system	22.4
3	Operation and maintenance (for 20 years)	3
	Total	80

Cost of LFG-to-LNG Conversion System

An LFG-to-LNG conversion system can be used to filter the LFG in order to produce LNG and food-grade CO_2. The harmful pollutants from the LFG are disposed or recycled back into the landfill, and the methane from the LFG ultimately produces a transportation fuel. While there is technology already in place to fuel vehicles on CNG, the biggest hindrance to the advancement of this technology has been the fuel storage tanks. LNG solves this issue since it takes up 1/600 the volume that natural gas (at standard temperature and pressure) does for the same energy output and is very similar to CNG in terms of overall fuel efficiency and emissions, taking only 1/6 the volume of CNG (Tusiani and Shearer 2007).

The Acrion Technologies, Inc., CO_2 WASH^{TM} (described in Appendix A) has been chosen as the technology of choice for cleaning landfill gas and ultimately converting it to liquefied natural gas. A pilot project in Burlington, New Jersey, proved the technology's reliability and functionality (see Figure 21). The study took landfill gas from the Burlington County landfill and converted it into liquefied natural gas, which then fueled refuse trucks (Cook et al. 2005).

Figure 21: Acrion System at Burlington, New Jersey, Testing Facility (Cook et. al 2005)

The costs associated with the installation of an LFG-to-LNG conversion system include the capping costs and LFG collection system costs (from Table 14), the cost of the Acrion CO_2 WASH^{TM} technology and the purchase of new fleet vehicles (both shown in Table 15). An additional cost to be considered is the purchase of LNG vehicles in phases over time. The Acrion system is estimated to cost roughly $12 million according to correspondence between Dr. Joe Zietsman of TTI and Dr. Bruce Smackey of Mack Trucks and Acrion Technology. Since this process is a refining process, prices will fluctuate based on market conditions for refining materials.

Fleet turnover from the purchase of new LNG/CNG refuse trucks versus the purchase of traditional diesel refuse trucks is also a cost incurred. The difference in operation and maintenance costs is also accounted for. Table 15 shows the marginal costs of installing the LNG conversion system and the fleet turnover costs. Any mathematical differences are a result of rounding.

$$((Cost\ of\ LNG\ or\ CNG\ truck +\ O/M) - (cost\ of\ diesel\ truck + O/M)) \\ * trucks\ purchased\ per\ year$$

$$Cost\ of\ LNG\ truck = \$147{,}824$$

$$Cost\ of\ CNG\ truck = \$144{,}174$$

$$O/M\ tost\ of\ \ LNG/CNG\ \ trucks = \$20{,}000\ per\ year$$

$$Cost\ of\ diesel\ truck = \$125{,}506$$

$$O/M\ cost\ of\ diesel\ trucks = \$15{,}000\ per\ year$$

For LNG:

$$\big((\$147{,}824 + \$20{,}000) - (\$125{,}506 + \$15{,}000)\big) * 5 = \$136{,}588\ in\ year\ 1$$

$$\$2{,}731{,}754 = \sum_{t=0}^{20} \frac{FV_t}{(1 + 0.0305)^t} \\ = marginal\ cost\ of\ LNG\ trucks\ over\ 20\ years$$

For CNG:

$$\big((\$144{,}174 + \$20{,}000) - (\$125{,}506 + \$15{,}000)\big) * 5 = \$118{,}340\ in\ year\ 1$$

$$\$2{,}366{,}792 = \sum_{t=0}^{20} \frac{FV_t}{(1 + 0.0305)^t} \\ = marginal\ cost\ of\ CNG\ trucks\ over\ 20\ years$$

Table 15: Marginal Cost of Acrion System plus Fleet Turnover

Landfill	**Clint**
Acrion system cost ($ millions)	12
Marginal cost of LNG trucks	2.7
Marginal cost of CNG trucks	2.4
Total with LNG trucks ($ millions)	**14.7**
Total with CNG trucks ($ millions)	**14.4**

Cost of Conversion of LFG to Pipeline-Grade Natural Gas

Converting LFG into pipeline-grade natural gas is a difficult task that requires almost as many resources as the LFG-to-LNG conversion. The CO_2 WASH^{TM} process must be used in order to truly rid the LFG of all contaminants in order to sell the LFG to a natural gas provider. Adding a lower grade of natural gas such as direct LFG, at 50 percent methane, would not only devalue the price of the natural gas but cause an extensive amount of corrosive damage to the existing pipeline. The additional contaminants that are contained within LFG along with the CO_2 would cause extensive corrosion and potential scaling within the pipe walls. Because of these reasons, the CO_2 WASH^{TM} process was chosen as the filtering process to convert LFG into pipeline-grade natural gas. Pure methane is produced from the CO_2 WASH^{TM} process.

The cost to convert LFG to pipeline-grade natural gas includes $12 million for the CO_2 WASH^{TM} process. There is also an operational cost of $2 per mcf associated with the treatment process as well, causing this scenario to total to the amounts seen in Table 16 for each of the landfills (SECO 2002).

Table 16: Cost of LFG to Pipeline-Grade Natural Gas

Landfill	**Clint**
Acrion system cost ($ millions)	12
Operational costs ($ millions)	9.61
Total ($ millions)	**21.61**

It should also be noted that the CO_2 WASH^{TM} process does not necessarily have to be used in order to use LFG as a heating fuel source. The reason the CO_2 WASH^{TM} process was selected as opposed to other, cheaper options (typically costing $2 million to $5 million) was due to the lack of reliability of these systems. Literature has shown that the capital costs for these projects are much less since the LFG is not cleaned of contaminants, but based on engineering principals from petroleum and mechanical engineering, CO_2 and moisture/water are the two biggest concerns for pipeline-grade natural gas. Carbon dioxide and water are extremely corrosive when present in a pipeline, which is why these elements are taken out of natural gas when it is transmitted to the end user through the pipeline. Petroleum engineers typically combat this corrosiveness by using stainless steel pipelines, which are extremely costly. Depending on the distance needed to connect the LFG with existing natural gas pipelines, costs could vary dramatically, which is why the CO_2 WASH^{TM} process was selected for its high level of contaminant removal. Literature is unavailable to discuss the maintenance costs of using direct LFG as a fuel/gas source, which is why this cheaper option was left out of the analysis.

Cost of Conversion of LFG to Electricity

The costs associated with converting LFG to electricity included the cost of the facility and the operational costs. The cost of the facility was determined first by the size of facility that could accommodate the landfill gas. In order to estimate electricity production capability from the landfill gas, the British thermal unit equivalent of the LFG produced was converted to kilowatt-hours using the conversion factor of 1 Btu = 0.000293 kWh. The kilowatt-hours that would be produced from the first year (the greatest LFG generation year) divided by the conversion factor of 8,928,000 gives the megawatts of electricity that could be produced at a given time.

This allows us to estimate the electricity generation needed based on the megawatt output. For this study, \$1.5 million was used per megawatt to determine the cost of the electric generation facility. An operational cost of \$0.05 per kilowatt was used (SCEC 2002). Based on these assumptions the cost at each of the landfills for an electricity generation facility is shown in Table 17.

Table 17: Cost of Conversion of LFG to Electricity

Landfill	**Clint**
Facility cost (\$ millions)	14.25
Operational costs (\$ millions)	72.38
Total (\$ millions)	**86.63**

Cost of Flaring LFG from Capped Landfill

The cheapest option of the capped landfill scenarios falls upon the use of a flaring system. With this scenario, the landfill is still capped, extraction wells are put in place, and the landfill gas is flared once collected. This action allows more of the pollutant emissions such as methane to be burned off as CO_2 and heat, instead of being emitted into the atmosphere with 21 times the GWP as CO_2 (John Zink Co. 2005). The equipment needed for this mitigation strategy is very simple. A flaring system collects the LFG from the landfill gas collection system and flares it (Figure 22). The costs of the flaring system and its operational costs are shown in Table 18.

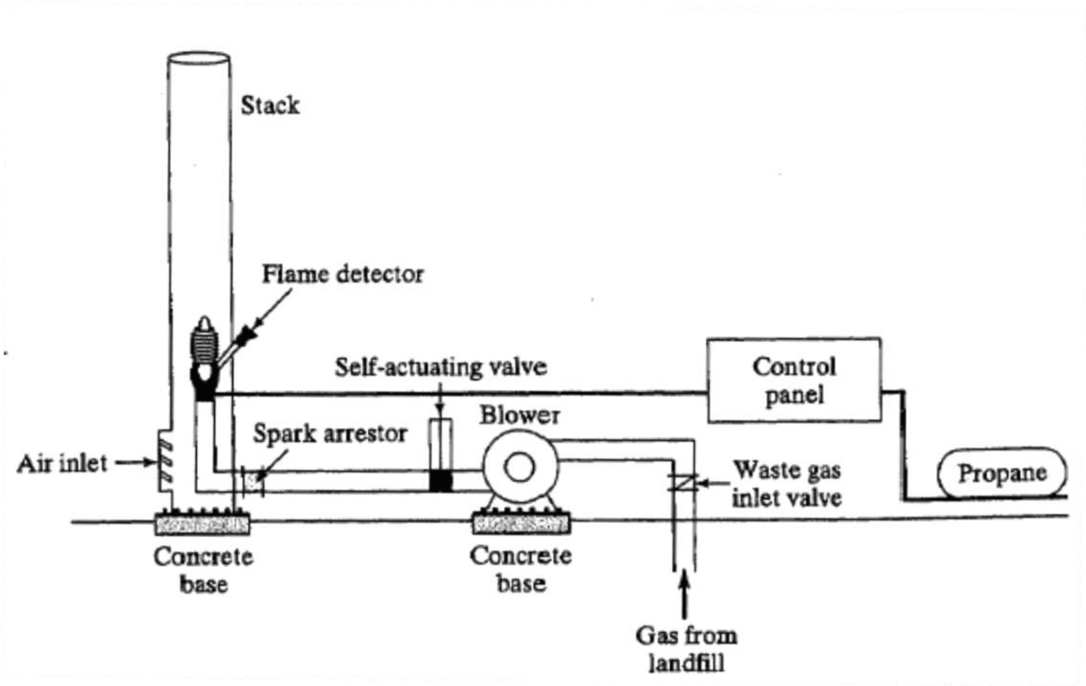


Figure 22: Schematic of LFG Flaring System with Blower (Qian et al. 2002)

Table 18: Cost of Flaring System for Capped Landfill

Landfill	**Clint**
Flaring system cost ($)	2,500,000
Operational costs ($)	1,800,000
Total ($)	**4,300,000**

The costs of flaring systems are nearly equal at all landfills because there is no real difference in total or operational costs. The total cost assumes the same size flare is good enough for all landfills, and the operational costs are equal because the time of operation on an equal size flare will also be equal. These values can be changed on the feasibility tool that is included with this thesis, but for conceptual analysis these were the values that were used.

Cost of the Do-Nothing Scenario

The cost of the do-nothing scenario includes capping, operation and maintenance, and fleet turnover costs. These are the costs associated with taking no action based on current landfill practices and represent the economic implications of capping and maintaining the capped landfill. An assumption that a cost of $150,000 per year for general operation costs (i.e., employees, electricity, etc.) is where the $3 million over 20 years originates. The cost of fleet turnover is also included in the do-nothing scenario. For the Clint landfill it was stated that five new refuse trucks replace five older trucks each year. The do-nothing scenario assumes that five diesel refuse trucks are being purchased each year. The present value of purchasing five new diesel trucks per year totals over $3.51 million. The values for each landfill are presented in Table 19.

$$(\$125,506\ per\ diesel\ refuse\ truck + \$15,000\ \ O/M) * 5\frac{trucks}{year} * 20\ years = \$14,050,600$$

Table 19: Cost of Do-Nothing Scenario

Landfill	**Clint**
Capping	$77 million
Operation and maintenance costs (assumed: $150,000/year)	$3 million
Fleet turnover cost	$14 million
Total	$94 million

The cost of the fleet turnover is also included in the do-nothing scenario. For the Clint landfill it was stated that five new refuse trucks replace five older trucks each year. The do-nothing scenario assumes that five diesel refuse trucks are being purchased each year. The present value of purchasing five new diesel trucks per year totals over $14 million.

Estimating the Benefit-Cost Ratio for Each Scenario

The costs and benefits described in this section of the report need to be combined and evaluated for each scenario. As indicated in Table 20, each scenario will incur a different set of costs and benefits. Depending on the efficiency of the LFGTE process under consideration and other details, different proportions of the costs and benefits may be considered to apply to a particular scenario. The estimation of the benefit-cost ratio for each of the scenarios is evaluated as shown in Equation 17.

$$\text{Benefit-cost ratio (B/C)} = \frac{\text{total NPV of benefits}}{\text{total NPV of costs}} \tag{17}$$

Table 20: Monetary Summary of Marginal Costs and Benefits Associated with Each Scenario

Description	**Scenario**					
	LFG →LNG	**LFG → CNG**	**LFG → Pipeline**	**LFG → Electricity**	**Closed Flare**	**Nothing**
			Benefits			
Diesel or natural gas savings	71,091,615	71,091,615	16,895,962			
Electricity conversion				103,341,657		
Carbon credits	7,484,850	7,484,850	6,162,648	5,718,937	5,191,264	
Tax subsidy earnings	13,671,464	13,671,464	3,697,147	7,730,248		
Fleet turnover emissions reduction	1,322,203	1,322,203				
			Costs			
CNG/LNG facility and operation cost	14,000,000	14,000,000				
Fleet turnover cost	2,731,754	2,366,792				
Pipeline natural gas facility and operation cost			27,611,636			
Electricity plant and operation cost				86,626,575		
Flaring system and operation costs					6,300,000	

All values are in 2009 dollars based on the 20-year analysis period.

The details of the costs and benefits considered for each scenario are summarized in the following subsections.

Scenario 1: Conversion of LFG to LNG for Use as a Transportation Fuel

In this scenario, the costs incurred for each landfill include the cost of the Acrion system as shown in Table 15. In addition to this, the operational cost of the LNG facility, as well as the NPV of the cost of investing in new trucks (fleet turnover), is also considered. In terms of the benefits, these include the NPV of savings due to not purchasing diesel, carbon credits (assuming 95 percent efficiency), and the emissions benefits due to the use of LNG trucks instead of diesel.

Scenario 2: Conversion of LFG to CNG for Use as a Transportation Fuel

The costs incurred with this scenario are equal to scenario 1 except for the cost of the refuse trucks. The CNG refuse trucks were slightly cheaper than the LNG trucks.

Scenario 3: Conversion of LFG to Pipeline-Grade Natural Gas

The costs for this scenario include the facility and operational costs as listed in Table 16. The benefits considered include the NPV of earnings from the natural gas sales and carbon credits, assuming 95 percent conversion efficiency.

Scenario 4: Conversion of LFG to Electricity

The costs for this scenario include the electricity plant cost and operational costs (as shown in Table 17). The benefits considered for this scenario include the NPV of benefits from the sale of electricity and carbon credits. Efficiency losses in electricity lines are known to exist and were assumed to be 7.2 percent from a report by the U.S. Climate Change Technology Program (U.S. CCTP 2003); therefore, 7.2 percent of the electricity produced was assumed to be lost, which caused that percentage of earnings from carbon credits and electricity to be reduced.

Scenario 5: Flaring of Capped Landfill

The costs of this scenario include the costs of installing and operating the flaring system (shown in Table 18). The only benefit for this scenario comes from the NPV of carbon credit earnings, for which 95 percent efficiency is assumed.

Scenario 6: Do Nothing

The costs associated with the do-nothing scenario assume that the landfill must be capped due to EPA regulations once it has reached the end of its design life or its maximum capacity. In the do-nothing scenario the landfill capping costs, fleet turnover costs for diesel vehicles that would have been purchased and operational and maintenance costs that will be incurred throughout the 20-year lifetime of the project analysis are included. A cost of $150,000 per year was assumed to be the operation and maintenance cost. The total cost of the do-nothing scenario amounts to $94 million. These are real costs and benefits but are included in all scenarios. Therefore the marginal costs and benefits of all scenarios are relative to this, which is why the do-nothing scenario has no benefit-cost ratio.

$$\frac{Benefits}{Costs - do\text{-}nothing\ scenario} = B/C\ ratio$$

CHAPTER V

RESULTS

This chapter details the results of the benefits and costs analyses, providing additional information on the outputs that were created.

Using the methodology in the analysis section, all of the benefits and costs were accumulated for each scenario (see Table 7). The results can be calculated quickly using the feasibility tool included with this thesis. The tool is a Microsoft Excel® spreadsheet that enables the user to input all of the discussed values needed for LFGTE analysis and create an output with relative ease (see Appendix B). The output will provide the user with the return on investment as well as a benefit-cost ratio according to the various input values placed into the tool.

For the Clint landfill, the tool was used to create the output shown in Table 21. The analysis shows that LNG to CNG is the best option with a 5.63 benefit-cost ratio. The worst option appears to be selling the landfill gas as pipeline-grade natural gas with a benefit-cost ratio of just less than 1.0 (0.97). The initial hypothesis stated that conversion of LFG to CNG/LNG has been found to be more economically viable than other LFGTE projects, and in this case study, that hypothesis has been confirmed. This option provides promising results when compared to the other available options.

Landfill capping requires enormous capital upon closure of the landfill. As stated in Table 21, the landfill capping costs for this landfill are assumed to be $77 million, operation and maintenance $3 million, and the purchase of refuse trucks over the 20-year lifetime $14 million. The costs associated with each of the options shown assume that they are marginal costs. The landfill must be capped no matter what happens once the landfill reaches the end of its design life or reaches full capacity. For this reason, the do-nothing scenario was assumed to equal the cost of capping the landfill, operation and maintenance, and fleet turnover (for 20 years) ($94 million). If owners/operators have the available capital, they should carefully consider LFGTE projects, specifically LFG to natural gas for use in refuse trucks. The emissions benefits of each truck over the course of the truck's lifetime provide a minimal financial return and will lose money over the course of their lifetime, but the fuel savings from using natural gas at roughly $3 to $5 per mcf will offset diesel prices. With 1 mcf producing over 7 gallon equivalents of diesel based on Btu, each gallon of fuel of natural gas roughly costs $0.40 to $0.70 per gallon. This is a $2 savings for each gallon of fuel that is used. These trucks use roughly 100 gallons of diesel per day. With $200 per day being saved, these trucks could pay for themselves depending on how many and how quickly the CNG trucks are phased into the fleet. Apart from landfill gas collection, this method should be investigated by all municipal solid waste management departments. When used in conjunction with solid waste collection and disposal at landfills, methane collection for use as a transportation fuel appears to create an environmentally, financially, and economically sound investment.

Landfill-gas-to-electricity conversion is the option most commonly read about in newspaper and journal articles, yet in this analysis it appears to yield a 1.35 benefit-cost ratio. This shows that conversion of LFG to electricity is still a viable option for those that are using it, but for a landfill the size of the Clint landfill (approximately 280 acres); projects that incorporate savings from using refuse trucks with natural gas from landfills provide the greatest financial return.

Flaring of landfill gas is typically used as a mitigation strategy to destroy harmful pollutants such as PM, HC, NO_x, and SO_x, which are much more harmful that CO_2 or CH_4 and are therefore regulated by the U.S. EPA. Flaring is also the cheapest method of the scenarios examined. The main issue with flaring is that although it is conducted at various landfills, the gas is being flared only because there is no other use for it. With the CO_2 WASH^{TM} process, the methane that would also be destroyed during this flaring can be used for positive purposes such as its conversion to a transportation fuel. The CO_2 WASH^{TM} process fills the gap in landfill-gas-to-energy projects. It provides a scrubbing system to rid pollutants from landfill gas and provides a useful end product in clean, dry natural gas.

Table 21: Results from Feasibility Tool for All Six Scenarios

	Scenarios	Cost**	Diesel/Natural Gas/Electricity	Carbon Credit	Tax Credits	**Net**	B/C Ratio
1	LFG to LNG refuse trucks	$16,731,754	$71,091,615	$7,387,626	$13,671,464	$75,418,952	5.508
2	LFG to CNG refuse trucks	$16,366,792	$71,091,615	$7,387,626	$13,671,464	$75,783,914	5.630
3	LFG to pipeline-grade natural gas	$27,611,636	$16,895,962	$6,162,648	$3,697,147	$(855,879)	0.969
4	LFG to electricity	$86,626,575	$103,341,657	$5,718,937	$7,730,248	$30,164,267	1.348
5	Cap landfill & flare	$4,300,000	-	$5,191,264	-	$891,264	1.207
6	Do nothing*	$94,050,646	-	-	-	$(94,050,646)	N/A*

*Do-nothing scenario is baseline for all scenarios; benefits = 0, costs = landfill capping cost + operation and maintenance (over 20 years)

**All costs are marginal costs above the do-nothing scenario

CHAPTER VI

CONCLUSIONS

The goal of this research was to create a methodology that landfill owners/operators could follow to examine the feasibility of various landfill-gas-to-energy projects. This research created a useful feasibility tool in the form of a Microsoft Excel® spreadsheet that computes all of the equations in this thesis using the explained methodology. Users need to input only the values that are indicated by yellow cells. Cells indicated in pink provide average values to use if input values are unknown. All results are computed in the spreadsheet in a results section that looks similar to Table 21.

The methodology created is the most important achievement of this thesis. It combines emissions values from refuse trucks and landfill gas modeling equations created by the EPA with monetary values that are pivotal to decision makers who are looking to make informed decisions based on fiscal values in combination with environmentally conscious ideology. If LFGTE projects can be proven to be economically viable, more of them will be placed into service, which benefits the environment, society, and the operating company or municipality. Without providing evidence of their economic benefit, the stereotypes that are labeled with most alternative-energy projects that they are expensive and do not provide any true benefits will be placed with these scenarios as well. Providing evidence in the form of facts and economics, as this thesis does, can not only further the science but the implementation of LFGTE projects across the nation and across Texas.

It should be noted that the conclusions are based on numerous assumptions. Those assumptions are as follows:

- *Cap and trade legislation will be passed in Congress:* Once laws, rules, and regulations are put into place to assess the emissions from various companies, a finite number of carbon credits will be purchased and sold on numerous commodity trading platforms based on economic supply and demand principles.
- *U.S. EPA LFG modeling equations accurately represent LFG generation volumes:* This thesis assumes that the 1997 U.S. EPA equations, still used in practice, continue to

accurately represent the quantity of landfill gas that can be created at a landfill. Since very little research is available on landfill gas estimation rates over time (modern-day landfills have only existed a short period of time, approximately 30 years), it is difficult to accurately predict LFG generation rates.

- *Tax benefits that are currently indefinite will remain indefinite:* As of October 2009, there have been two major economic stimulus bills that have been signed into law. Within each of them lie numerous tax credits and benefits that are also associated within this thesis. This thesis makes the assumption that the tax credits that are in effect indefinitely will remain that way, while the benefits that are definite will terminate on their set dates.

Both LFG-to-LNG and LFG-to-CNG conversions are extremely feasible options, with benefit-cost ratios over 5.5 each. LFG-to-LNG conversion provided a 5.51 B/C ratio, while LFG-to-CNG conversion provided a 5.63 B/C ratio. In comparison to the other options that were presented, converting LFG to natural gas (LNG or CNG) for use as a transportation fuel proves to yield the highest economic returns. The two most common forms of LFGTE projects, LFG to electricity and LFG to flaring, yielded modest 1.35 and 1.21 B/C ratios, respectively. The only scenario in which costs exceeded benefits was the conversion of LFG to pipeline-grade natural gas, which provided a B/C ratio of 0.97.

The Texas State Energy Conservation Office testing conducted in San Antonio, Texas, provided extremely promising results. Very few studies have shown the emissions difference between natural gas vehicles and diesel or gasoline vehicles. This research may be the first to test these vehicles using real-world data. The data included in this thesis are only preliminary data, but when the final SECO/TTI report is published, researchers at the Texas Transportation Institute say the reduction in emissions for NO_x could be as much as 95 percent. The ability to reduce NO_x from heavy-duty diesel vehicles (HDDVs) by using compressed natural gas could mark an important turning point in how municipalities operate their vehicles in order to meet air quality regulations.

This research has created a platform from which to study in greater detail the economics of various LFGTE projects. This thesis is merely a pre-feasibility study to assess the various LFGTE options that are available to a landfill owner/operator. Future research will be able to build upon this research by expanding upon the existing feasibility tool and methodology. In time more knowledge and research will be gathered on landfills in order to have a more accurate landfill gas generation rate. More landfills are implementing LFGTE projects, and future researchers will be able to assess the pros and cons associated with each of the options that have been implemented. Transportation-related emissions (via refuse trucks) will also change over time as the technology becomes more refined with more municipalities and landfill owners using compressed or liquefied natural gas over their fossil-fuel counterparts. The carbon credit market will have evolved based on legislation passed around the world or nationally, which will also influence the results of this thesis. International researchers have the ability to modify this thesis for use in their country where carbon credit trading may already be in place, such as in European countries or India. Numerous options are available for advancing the science in this field, yet this thesis is the first to lay the groundwork for combining the benefits and costs associated with various landfill-gas-to-energy projects.

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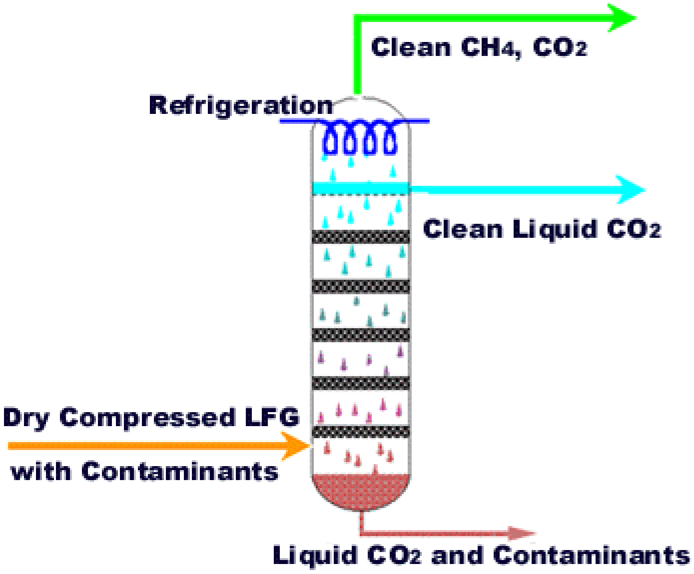
APPENDIX A

CO_2 WASH^{TM} PROCESS DETAILS

The CO_2 wash process developed by Acrion Technologies is used to clean landfill gas of its contaminants to produce clean methane as well as food-grade CO_2. The wash process has been used with success to produce clean gas that can be used for various purposes. Further details about this process are available at http://www.acrion.com/ . The schematic diagram below shows the CO_2 wash process.



Source: **http://www.acrion.cobm/**

APPENDIX B

LANDFILL-GAS-TO-ENERGY FEASIBILITY CALCULATOR

Included with this thesis is the landfill-gas-to-energy feasibility calculator that has produced the results found within this thesis based on the methodology presented. The user may follow the methodology section of this thesis to input the selected values needed to produce a feasibility summary.

The cells colored yellow are cells that need to have information input into them. These values are based on the specific attributes of the landfill being evaluated. Values in the pink-colored cells are suggested default values that can be used if no input value is available. Green cells are summary cells that provide a sum of the various values being viewed (i.e., total emissions reduced, NPV of each option, etc.). The summary of all results is also colored green. This summary provides the overall costs and benefits of each option as well as the overall benefit-cost ratio.

The additional tabs that are placed in this spreadsheet provide some values that are referenced in the main spreadsheet, including the emissions savings from using CNG/LNG refuse trucks versus diesel refuse trucks.

(See Microsoft Excel® spreadsheet.)

APPENDIX C
CALCULATION OF SPREADSHEET

The inputs that were placed into the calculator are shown below for reference. They can also be found in the methodology section of this thesis.

L_o	100 m^3/Mg	Methane generation potential
k	0.02 $year^{-1}$	Methane generation rate constant
t	Time in years	
m_o	Average waste acceptance rate per year	Mg/year
m_o	265604.0132 Mg/year i.e., 6,905,704.342 Mg/(2009-1983)	Found by WIP/life of landfill (i.e., WIP/(closing date-opening date)
Landfill opening date	1983	
Landfill closing date	2009	
Methane content	50%	Assumed value by consensus
Landfill size	113.3118 Ha	280 acres * 0.404685 Ha/acre
1 CER	$3.87/metric tonne	$3.51/U.S. ton * (2204.6226 (pounds/metric ton)/2000 (pounds/U.S. ton))
1 kWh	$0.10	Assumed value
1 mcf of natural gas	$4.57	*See thesis for explanation
1 gallon of diesel	$2.60	*See thesis for explanation
Recoverable LFG	75%	*See thesis for explanation (U.S. EPA value)

The total recoverable LFG must first be evaluated; the evaluation used the equations stated in this thesis, which are provided by the U.S. EPA landfill gas generation models. The results of those equations are outlined below.

	Landfill Age (t)	**Year**	**Landfill Gas Generated Post-closure (m^3/Year)**	**m^3/Minute**	**m^3 Recoverable LFG/Minute**	**m^3 Recoverable LFG/Year**	**Total Reduction in Emitting Tonnes after Recovery LFG/Year**	**CO_2 Equivalent (Tonnes)**
Time since Closure Date								
0	26	2009	21,539,393.94	40.98	30.74	16,154,545.46	19,829.70	125,803.52
1	27	2010	21,112,885.37	40.17	30.13	15,834,664.02	19,437.05	123,312.45
2	28	2011	20,694,822.23	39.37	29.53	15,521,116.67	19,052.17	120,870.70
3	29	2012	20,285,037.29	38.59	28.95	15,213,777.97	18,674.91	118,477.30
4	30	2013	19,883,366.64	37.83	28.37	14,912,524.98	18,305.12	116,131.29
5	31	2014	19,489,649.60	37.08	27.81	14,617,237.20	17,942.66	113,831.73
6	32	2015	19,103,728.68	36.35	27.26	14,327,796.51	17,587.37	111,577.72
7	33	2016	18,725,449.51	35.63	26.72	14,044,087.13	17,239.12	109,368.33
8	34	2017	18,354,660.77	34.92	26.19	13,765,995.57	16,897.76	107,202.69
9	35	2018	17,991,214.13	34.23	25.67	13,493,410.60	16,563.16	105,079.94
10	36	2019	17,634,964.22	33.55	25.16	13,226,223.17	16,235.19	102,999.21
11	37	2020	17,285,768.54	32.89	24.67	12,964,326.40	15,913.71	100,959.69
12	38	2021	16,943,487.39	32.24	24.18	12,707,615.54	15,598.60	98,960.56
13	39	2022	16,607,983.86	31.60	23.70	12,455,987.89	15,289.73	97,001.01
14	40	2023	16,279,123.74	30.97	23.23	12,209,342.81	14,986.97	95,080.26
15	41	2024	15,956,775.49	30.36	22.77	11,967,581.62	14,690.21	93,197.54
16	42	2025	15,640,810.17	29.76	22.32	11,730,607.63	14,399.32	91,352.11
17	43	2026	15,331,101.38	29.17	21.88	11,498,326.03	14,114.20	89,543.21
18	44	2027	15,027,525.23	28.59	21.44	11,270,643.92	13,834.72	87,770.14
19	45	2028	14,729,960.29	28.03	21.02	11,047,470.22	13,560.77	86,032.17
20	46	2029	14,438,287.54	27.47	20.60	10,828,715.65	13,292.25	84,328.62
		SUM	373,055,996.00	709.77		279,791,997.00	343,445	2,178,880

Scenario 1: LFG → LNG

This scenario required calculating the cost of purchasing new refuse trucks and phasing them in over time. It was assumed that five trucks would be purchased each year at a cost of $147,824/truck[1]. Operational costs were assumed to be $20,000 per year, which was added into the cost of the vehicles, therefore providing the $839,120 value shown. The cost of the trucks is assumed to increase at the inflation value used throughout this thesis (3.05 percent), which is why the NPV of the vehicles never changes. The cost of the diesel trucks was included within this analysis to show the difference in replacement costs, which is more than an additional $2.7 million dollars over 20 years (assuming five vehicles are purchased per year). The emissions reduced follow the formulas seen in the benefits section of the methodology. Any minor differences in the output versus the results in the benefits sections are because of rounding.

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[1] City of Dallas, Texas. <www.ci.dallas.tx.us/cso/caps/A17a.pdf> (April 5, 2009).

LNG Trucks					
Cost of New Trucks	NPV	Cost of Diesel Trucks	NPV	Emissions Reduced	NPV
$839,120	$839,120	$702,532	$702,532	2,182	$8,443
$864,713	$839,120	$723,960	$702,532	4,363	$16,387
$891,087	$839,120	$746,040	$702,532	6,545	$23,853
$918,265	$839,120	$768,795	$702,532	8,727	$30,862
$946,272	$839,120	$792,243	$702,532	10,909	$37,436
$975,133	$839,120	$816,406	$702,532	13,090	$43,594
$1,004,875	$839,120	$841,307	$702,532	15,272	$49,354
$1,035,524	$839,120	$866,966	$702,532	17,454	$54,735
$1,067,107	$839,120	$893,409	$702,532	19,636	$59,755
$1,099,654	$839,120	$920,658	$702,532	21,817	$64,429
$1,133,193	$839,120	$948,738	$702,532	23,999	$68,774
$1,167,756	$839,120	$977,674	$702,532	26,181	$72,806
$1,203,372	$839,120	$1,007,493	$702,532	28,363	$76,539
$1,240,075	$839,120	$1,038,222	$702,532	30,544	$79,987
$1,277,897	$839,120	$1,069,888	$702,532	32,726	$83,163
$1,316,873	$839,120	$1,102,519	$702,532	34,908	$86,082
$1,357,038	$839,120	$1,136,146	$702,532	37,089	$88,755
$1,398,428	$839,120	$1,170,799	$702,532	39,271	$91,195
$1,441,080	$839,120	$1,206,508	$702,532	41,453	$93,412
$1,485,033	$839,120	$1,243,307	$702,532	43,635	$95,418
$1,530,326	$839,120	$1,281,227	$702,532	45,816	$97,224
$22,662,496	$16,782,400	$18,973,610	$14,050,646	458,164	$1,224,979
		Difference	-$2,731,754		
		Reduction (Mg of CO_2 Equiv.)		503,981	

Scenario 2: LFG → CNG

This scenario also required calculating the cost of purchasing new refuse trucks and phasing them in over time. It was assumed that five trucks would be purchased each year at a cost of $144,174/truck[2]. Operational costs were assumed to be $20,000 per year, which was added into the cost of the vehicles, therefore providing the $820,872 value shown. The cost of the trucks is assumed to increase at the inflation value used throughout this thesis (3.05 percent), which is why the NPV of the vehicles never changes. The cost of the diesel trucks was included within this analysis to show the difference in replacement costs, which is nearly an additional $2.4 million dollars over 20 years (assuming five vehicles are purchased per year). The emissions reduced follow the formulas seen in the benefits section of the methodology. Any minor differences in the output versus the results in the benefits sections are because of rounding.

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[2] City of Dallas, Texas. <www.dallascityhall.com/committee_briefings/briefings0309/TEC_upcoming_agenda_032309.pdf> (April 5, 2009).

CNG Trucks					
Cost of New Trucks	NPV	Cost of Old Trucks	NPV	Emissions Reduced	NPV
$820,872	$820,872	$702,532	$702,532	2,182	$8,443
$845,908	$820,872	$723,960	$702,532	4,363	$16,387
$871,709	$820,872	$746,040	$702,532	6,545	$23,853
$898,296	$820,872	$768,795	$702,532	8,727	$30,862
$925,694	$820,872	$792,243	$702,532	10,909	$37,436
$953,928	$820,872	$816,406	$702,532	13,090	$43,594
$983,022	$820,872	$841,307	$702,532	15,272	$49,354
$1,013,004	$820,872	$866,966	$702,532	17,454	$54,735
$1,043,901	$820,872	$893,409	$702,532	19,636	$59,755
$1,075,740	$820,872	$920,658	$702,532	21,817	$64,429
$1,108,550	$820,872	$948,738	$702,532	23,999	$68,774
$1,142,361	$820,872	$977,674	$702,532	26,181	$72,806
$1,177,203	$820,872	$1,007,493	$702,532	28,363	$76,539
$1,213,108	$820,872	$1,038,222	$702,532	30,544	$79,987
$1,250,107	$820,872	$1,069,888	$702,532	32,726	$83,163
$1,288,236	$820,872	$1,102,519	$702,532	34,908	$86,082
$1,327,527	$820,872	$1,136,146	$702,532	37,089	$88,755
$1,368,016	$820,872	$1,170,799	$702,532	39,271	$91,195
$1,409,741	$820,872	$1,206,508	$702,532	41,453	$93,412
$1,452,738	$820,872	$1,243,307	$702,532	43,635	$95,418
$1,497,047	$820,872	$1,281,227	$702,532	45,816	$97,224
$22,169,661	$16,417,438	$18,973,610	$14,050,646	458,164	$1,224,979
		Difference	-$2,366,792		
		Reduction (Mg of CO$_2$ Equiv.)		503,981	

Scenario 3: LFG → Pipeline-Grade CNG

This scenario is unique in that it requires all of the same refining processes as LFG-to-CNG conversion as a transportation fuel, yet is only sold back to a utility provider. The reason it is unique is that major fuel savings can be received from natural gas (1 mcf ~ 7.4 gallons of diesel). The mcf of methane that can be obtained and its value are all explained in the methodology section of this thesis. A summary derived from the input values discussed above is listed below. Any minor differences in the output versus the results in the benefits sections are because of rounding.

Earnings from LFG If Upgraded to Pipeline-Grade NG				
Mcf of Methane/Year	Earned/Year	Tax Credit	NPV of Tax Credit	*NPV (2009)
277,476.85	1,268,069.20	$277,477	$277,477	1,268,069.20
271,982.44	1,242,959.75	$271,982	$263,932	1,206,171.51
266,596.83	1,218,347.49	$266,597	$251,049	1,147,295.21
261,317.85	1,194,222.60	$261,318	$238,795	1,091,292.82
256,143.41	1,170,575.41	$256,143	$227,139	1,038,024.04
251,071.44	1,147,396.46	$251,071	$216,052	987,355.44
246,099.89	1,124,676.49	$246,100	$205,505	939,160.11
241,226.78	1,102,406.40	$241,227	$195,474	893,317.32
236,450.17	1,080,577.29	$236,450	$185,933	849,712.23
231,768.15	1,059,180.43	$231,768	$176,857	808,235.61
227,178.83	1,038,207.25	$227,179	$168,224	768,783.57
222,680.39	1,017,649.37	$222,680	$160,013	731,257.29
218,271.02	997,498.56	$218,271	$152,202	695,562.76
213,948.96	977,746.77	$213,949	$144,773	661,610.58
209,712.49	958,386.08	$209,712	$137,706	629,315.68
205,559.91	939,408.77	$205,560	$130,984	598,597.18
201,489.55	920,807.23	$201,490	$124,590	569,378.13
197,499.79	902,574.02	$197,500	$118,509	541,585.33
193,589.03	884,701.86	$193,589	$112,724	515,149.18
189,755.71	867,183.59	$189,756	$107,222	490,003.43
185,998.29	850,012.20	$185,998	$101,988	466,085.12
4,805,818	$21,962,587	$4,805,818	$3,697,147	$16,895,962

Scenario 4: LFG → Electricity

The LFG-to-electricity option uses the methodology discussed in the thesis to formulate the results listed below. Any minor differences in the output versus the results in the benefits sections are because of rounding.

Electricity				
Btu Present	kWh Equivalent	Tax Credits	NPV of Tax Credits	NPV
2.85E+11	83,577,135	$835,771	$835,771	$8,357,713.49
2.80E+11	81,922,197	$819,222	$794,975	$7,949,752.23
2.74E+11	80,300,029	$803,000	$756,170	$7,561,704.60
2.69E+11	78,709,981	$787,100	$719,260	$7,192,598.56
2.63E+11	77,151,419	$771,514	$684,151	$6,841,509.53
2.58E+11	75,623,719	$756,237	$650,756	$6,507,558.04
2.53E+11	74,126,269	$741,263	$618,991	$6,189,907.58
2.48E+11	72,658,471	$726,585	$588,776	$5,887,762.44
2.43E+11	71,219,736	$712,197	$560,037	$5,600,365.78
2.38E+11	69,809,491	$698,095	$532,700	$5,326,997.68
2.34E+11	68,427,171	$684,272	$506,697	$5,066,973.37
2.29E+11	67,072,222	$670,722	$481,964	$4,819,641.51
2.24E+11	65,744,103	$657,441		$4,584,382.54
2.20E+11	64,442,282	$644,423		$4,360,607.17
2.16E+11	63,166,240	$631,662		$4,147,754.84
2.11E+11	61,915,464	$619,155		$3,945,292.37
2.07E+11	60,689,456	$606,895		$3,752,712.61
2.03E+11	59,487,724	$594,877		$3,569,533.16
1.99E+11	58,309,788	$583,098		$3,395,295.17
1.95E+11	57,155,177	$571,552		$3,229,562.17
1.91E+11	56,023,429	$560,234		$3,071,919.03
4.94E+12	1,447,531,504	$14,475,315	$7,730,248	$111,359,544

Scenario 5: LFG → Flare Closed Landfill

Flaring of LFG for a closed landfill assumes that 50 percent of the LFG is methane and the remaining emissions are all CO_2 (unless input otherwise by the user). The carbon credit earnings are earned based on the recoverable landfill gas generation. These calculations assume that the flaring of 1 metric ton of CO_2 produces 1 metric ton of CO_2. One metric ton of CH_4 that is flared will produce 1 metric ton of CO_2 as opposed to the 21 metric tons of CO_2 equivalent that methane would produce by being emitted into the atmosphere. Therefore, flaring enables CO_2 to still be emitted into the atmosphere, but to a lesser degree since it is burning off CH_4. Twenty carbon credits can be earned for every ton of CH_4 that is disposed of. Any minor differences in the output versus the results in the benefits sections are because of rounding.

	NPV
Carbon Credit Earnings (Flaring + Capped Landfill)	
$410,118.68	$410,118.68
$401,997.78	$390,099.74
$394,037.69	$371,057.98
$386,235.22	$386,235.22
$378,587.25	$345,956.90
$371,090.72	$329,069.87
$363,742.64	$313,007.13
$356,540.05	$297,728.45
$349,480.08	$283,195.57
$342,559.91	$269,372.07
$335,776.77	$256,223.34
$329,127.95	$243,716.43
$322,610.78	$231,820.01
$316,222.66	$220,504.28
$309,961.03	$209,740.91
$303,823.39	$199,502.92
$297,807.28	$189,764.68
$291,910.30	$180,501.78
$286,130.09	$171,691.03
$280,464.34	$163,310.35
$274,910.77	$155,338.76
$7,103,135	**$5,617,956**

Scenario 6: Do Nothing

The U.S. EPA model for active landfills was used to estimate the emissions for the open or active landfill. The do-nothing scenario is assumed to cost $80 million based on capping costs and operational and maintenance costs over the 20-year period, but there are still societal costs from doing nothing in the form of emissions. The value of those emissions is listed below.

Do-Nothing Scenario: Societal Cost of Emissions					
Year	Landfill Gas Generated without Closure (m^3/Year)	m^3/Minute	Total Potential Emitting Tonnes LFG/Year	CO_2 Equivalent	NPV of Emissions
2009	21,539,393.94	40.98	26,439.61	167,738.03	$ 649,146
2010	22,164,747.73	42.17	27,207.23	172,607.97	$ 648,222
2011	22,777,718.69	43.34	27,959.65	177,381.48	$ 646,433
2012	23,378,552.01	44.48	28,697.17	182,060.47	$ 704,574
2013	23,967,488.03	45.60	29,420.09	186,646.81	$ 660,066
2014	24,544,762.33	46.70	30,128.70	191,142.34	$ 655,958
2015	25,110,605.84	47.78	30,823.27	195,548.84	$ 651,218
2016	25,665,244.90	48.83	31,504.09	199,868.09	$ 645,902
2017	26,208,901.37	49.86	32,171.43	204,101.82	$ 640,062
2018	26,741,792.72	50.88	32,825.55	208,251.71	$ 633,747
2019	27,264,132.11	51.87	33,466.72	212,319.43	$ 627,002
2020	27,776,128.49	52.85	34,095.20	216,306.60	$ 619,870
2021	28,277,986.66	53.80	34,711.23	220,214.82	$ 612,392
2022	28,769,907.38	54.74	35,315.06	224,045.65	$ 604,605
2023	29,252,087.41	55.65	35,906.94	227,800.63	$ 596,543
2024	29,724,719.64	56.55	36,487.09	231,481.25	$ 588,240
2025	30,187,993.12	57.44	37,055.76	235,089.00	$ 579,727
2026	30,642,093.18	58.30	37,613.17	238,625.30	$ 571,031
2027	31,087,201.44	59.15	38,159.54	242,091.58	$ 562,179
2028	31,523,495.98	59.98	38,695.09	245,489.22	$ 553,197
2029	31,951,151.30	60.79	39,220.04	248,819.59	$ 544,106
	568,556,104.30		**SUM**	**4,427,631**	**$ 12,994,218**

VITA

Name: Stephen M. Sprague, EIT

Address: Halff Associates
1201 N. Bowser Road
Richardson, TX 75081

Email Address: smsprague@yahoo.com

Education: B.S., Civil Engineering, University of South Carolina at Columbia, 2007
M.S., Civil Engineering, Texas A&M University, 2009