Feasibility of Landfill Gas as a Liquefied Natural Gas Fuel Source for Refuse Trucks

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Josias Zietsman, Ph.D., P.E.*
Director, Center for Air Quality Studies
Texas Transportation Institute
The Texas A&M University System
College Station, TX 77843
(979) 458-3476 (voice)
E-mail: zietsman@tamu.edu

Bhushan Gokhale
Jacobs Engineering Group Inc.
6688 N. Central Expressway
Dallas, TX 75206-3914 U.S.A.
Phone: (214) 424-7500 (voice)
E-mail: b-gokhale@ttimail.tamu.edu

Dominique Lord, Ph.D., P.Eng.
Assistant Professor
Texas A&M University
College Station, TX 77843
979-458-3949 (voice)
E-mail: d-lord@tamu.edu

Ehsanul Bari
Graduate Research Assistant
Center for Air Quality Studies
Texas Transportation Institute
College Station, TX 77843
(979) 595-3305 (voice)
E-mail: M-Bari@ttimail.tamu.edu

Aaron J. Rand
Research Associate
Center for Air Quality Studies
Texas Transportation Institute
College Station, TX 77843
(979) 595-3305 (voice)
E-mail: a-rand@ttimail.tamu.edu

* Corresponding author
The purpose of this paper is to develop a methodology to evaluate the feasibility of using landfill gas (LFG) as a Liquefied Natural Gas (LNG) fuel source for heavy-duty refuse trucks operating on landfills. Using LFG as a vehicle fuel can make the landfills more self-sustaining, reduce their dependence on fossil fuels, and reduce emissions and greenhouse gases. Acrion Technologies Inc. in association with Mack Trucks Inc. developed a technology to generate LNG from LFG using the CO₂ WASH™ Process. A successful application of this process was performed at the Eco Complex in Burlington County, PA. During this application two LNG refuse trucks were operated for 600 hours each using LNG produced from gases from the landfill.

The methodology developed in this paper can evaluate the feasibility of three landfill gas options – do nothing, electricity generation, and producing LNG to fuel refuse trucks. The methodology involved the modeling of several components – landfill gas generation, energy recovery processes, fleet operations, economic feasibility, and decision-making. The economic feasibility considers factors such as capital costs, maintenance costs, operational costs, fuel costs, emissions benefits, tax benefits, and the sale of products such as surplus LNG and food grade carbon dioxide (CO₂).

Texas was used as a case study. The 96 landfills in Texas were prioritized and 17 landfills were identified that showed potential for converting LFG to LNG for use as a refuse truck fuel. The methodology was applied to a pilot landfill in El Paso, TX. The analysis showed that converting LFG to LNG to fuel refuse trucks proved to be the most feasible option and that the methodology can be applied for any landfill that considers this option.

This manuscript demonstrates that it is possible and potentially feasible to convert LFG to LNG to fuel refuse trucks. Practical implications could include for cities to develop LFG-to-LNG conversion plants and to acquire and operate LNG-fueled vehicles as opposed to diesel-fueled
vehicles. Finally, this approach can provide nonattainment areas with another method to reach attainment and meet conformity standards.

INTRODUCTION

Energy consumption throughout the world has increased substantially over the past few years and the trend is projected to continue well into the future. The primary sources of energy are conventional fuels such as oil, natural gas, and coal. The most apparent negative impacts of these conventional fuels are global warming, poor air-quality, and adverse health effects. Considering these negative impacts, it is necessary to develop and use non-conventional sources of energy.

LFG generated at landfills can serve as a non-conventional source of energy if cleaned of certain impurities and additionally as a transportation fuel if it is adequately cleaned. This fuel can then be used as a fuel source for the refuse trucks operating at landfills. The refuse trucks primarily operate in the residential and commercial areas and any fuel consumption and emissions improvements will have considerable positive environmental benefits for the community.

Mack Trucks Inc. in association with Acrion Technologies Inc have demonstrated that methane produced by landfills can be converted to commercial level LNG and can consequently be used as a fuel for refuse trucks. This is achieved through their CO₂ WASH™ process, which is a sophisticated chemical process that separates the CO₂ and oxygen (O₂) from methane providing clean landfill gas with a high methane content that can be liquefied to produce LNG for use as vehicle fuel. The process was demonstrated during a very successful application at the Eco Complex in Burlington County, NJ. During this application, two refuse trucks fueled with LNG produced by the landfill were tested for more than 600 hours and produced exceptional performance, maintenance, and fuel consumption results. This was the first application of this magnitude and it was shown that the process is transferable to other landfills.

Using the LFG for vehicular fuel applications has been much more recent as compared to other applications such as electricity and heating.¹,² There are, therefore, very limited studies on the economic feasibility of this option and the possible environmental benefits.
The purpose of this paper is to develop a methodology to evaluate the feasibility of using LFG as an LNG fuel source for heavy-duty refuse trucks operating at the landfill. The methodology developed in this paper can evaluate the feasibility of three landfill gas options – do nothing, electricity generation, and producing LNG to fuel refuse trucks. The methodology involved the modeling of several components – LFG generation, energy recovery processes, fleet operations, economic feasibility, and decisions making. The economic feasibility considers factors such as capital costs, maintenance costs, operational costs, emissions benefits, and sale of any products. Texas was used as a case study. The 96 landfills in Texas were prioritized and 17 landfills were identified that showed potential for converting LFG to LNG. The methodology was applied to a pilot landfill in El Paso, TX.

The paper is divided into the following four sections — introduction, overall approach, Texas case study, and concluding remarks.

OVERALL APPROACH

The overall approach involves the modeling of six distinct components that provide the city or landfill owner with enough information to make a decision whether to convert LFG to LNG to fuel refuse trucks. The approach was coded into a user-friendly analysis tool that can be used by cities and landfill owners to perform their own analyses. Figure 1 shows a flow chart of the analysis process. This figure shows that the process begins with the generation of the LFG. The gas may then be used in one of three ways – do nothing (flare), generate electricity, or produce transportation fuel.

If transportation fuel is produced, it will be necessary to have a replacement scheme where diesel-fueled trucks are replaced by LNG-fueled trucks over time. Regardless of the method, the refuse trucks will continue to operate, burn fuel, and produce emissions. All the costs and benefits associated with these options will be calculated to evaluate the relative economic feasibilities. This can lead to a decision or a repeat of the process while performing sensitivity analyses. The following sections describe each of the steps in more detail.
LFG Generation

LFG is primarily composed of methane (CH$_4$) and CO$_2$ along with some quantities of nitrogen (N$_2$) and O$_2$. A few trace compounds may also be found in the LFG. The composition of the gas depends upon various factors such as the type of waste in a landfill, climatic conditions at the landfill, and age of the landfill among others. 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. Table 1 presents a typical composition of LFG.

There are several models that can be used to estimate the amount of LFG generated at landfills. The accuracy of the estimates depends upon the type of model used and the underlying data used in the models. Equation 1 shows the model used to estimate the amount of LFG generated due to the incremental waste acceptance ratio (WAR) at the landfill.

\[ LFG = W \times OC \times L_0 \times k \times e^{-k(t-t_l)} \]  

(1)

Where,

- $LFG$ = annual LFG generation rate, cf/year;
- $W$ = waste acceptance rate, tons;
- $L_0$ = CH$_4$ generation potential, cf of CH$_4$ per ton of waste;
- $k$ = rate of decay, yearly;
- $t$ = time after waste placement, years;
- $t_l$ = lag time, years; and
- $OC$ = organic content, percentage.

This model requires information on the waste acceptance ratio at a landfill as well as additional parameters such as rate of decay of the municipal solid waste, CH$_4$ generation potential of the MSW, lag time, and time after placement. Lag time refers to the time difference between placement of MSW at a landfill and generation of the LFG. It should be noted that for this modeling purpose, the lag time was assumed to be zero. The values of ($L_0$) and ($k$) are
dependent upon the amount of rainfall and presence of a leachate re-circulation system at the landfill.

**Energy Recovery Processes**

U.S. landfills are responsible for a third of all methane emissions worldwide and methane is 21 times more powerful than CO₂ at warming the atmosphere. Depending on the amount of methane produced, U.S. Environmental Protection Agency (EPA) regulations require that the gas be allowed to escape into the atmosphere or has to be sucked out and burned, or captured in another way.⁶

Landfill gas is extracted from landfills using a series of wells and a blower/flare (or vacuum) system. This system directs the collected gas to a central point where it can be processed and treated depending upon the ultimate use for the gas. From this point, the gas can be simply flared or used to generate electricity, replace fossil fuels in industrial and manufacturing operations, fuel greenhouse operations, upgraded to pipeline quality gas, or developed into transportation fuel.

The most basic and least productive way of disposing of methane is to burn it in a flare. The other productive uses of the LFG require some of the components of the LFG to be removed, which is referred to as cleaning. The degree of cleaning depends on the intended application of the LFG.³,⁷ Each type of energy recovery project therefore, has a unique requirement for processing the gas. The LFG typically has heating values that range between 450-to-600 British thermal units (Btu) per standard cubic foot and is mostly saturated with water.¹ 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.⁷

**Electricity Generation**

Generating electricity from LFG comprises about two-thirds of the current operational projects in the U.S. Electricity for on-site use or sale to the grid can be generated using a variety of different technologies — internal combustion engines, turbines, microturbines, Stirling engines (external
combustion engines), Organic Rankine Cycle engines, and fuel cells. The vast majority of projects use internal combustion engines or turbines, with microturbine technology being used at smaller landfills and in niche applications. Certain technologies such as the Stirling and Organic Rankine Cycle engines and fuel cells are still in the development phase.\(^6\)

Vehicle Fuel Production

The CO\(_2\) WASH™ process is capable of effectively cleaning LFG so that it can be used as a fuel for refuse trucks. Figure 2 shows a diagram describing the CO\(_2\) WASH™ process. In simple terms, this process begins by the removal of unwanted substances such as hydrogen sulfide (H\(_2\)S) and water vapor. Refrigeration then separates the gas into methane and food grade CO\(_2\). The volatile organic compounds are burned in a flare. The contaminant free methane can then be taken through the liquefaction process to produce adequately cleaned LNG that can be used as transportation fuel.

The capture rate at landfills is approximately 80% of raw LFG.\(^8\) As shown in Table 1, approximately 50% of this raw LFG is composed of methane. A sophisticated process such as the CO\(_2\) WASH™ process can convert approximately 80% of this methane to LNG. Approximately 10,000 gallons of LNG can, therefore, be produced per day for every 2 million cubic feet of LFG.\(^9\)

Fleet Conversion

The typical price of a new diesel-fueled refuse truck is more than $100,000 and LNG-fueled refuse trucks cost approximately $30,000 more. However, with the help of a tax credit the difference is reduced. It is still not conceivable that a landfill will replace all their existing diesel-fueled trucks with LNG-fueled trucks at one time. Instead, it will follow some replacement scheme over time. In addition, the average retirement age of refuse trucks is seven years resulting in another opportunity for replacements of existing diesel-fueled trucks with LNG-fueled trucks. The analysis tool developed under this project makes it possible for the landfill owner to evaluate the feasibility of various replacement schemes.


**Fleet Operations**

Refuse trucks have unique operating characteristics because they have to start and stop at very short distances for collecting waste from several disposal bins. This results in numerous accelerations, decelerations, and idling at short intervals. The refuse trucks also have to travel on the highway system to and from the landfill, which involves high-speed cruising. Other important characteristics typical of refuse truck operations are the varying loads carried by such trucks and hydraulic compactions performed by some types.

The operating characteristics of refuse trucks are best described with drive cycles, which are speed profiles used to replicate the driving pattern of a vehicle. It is normally developed as the speed of a vehicle as a function of time or distance and includes operating characteristics such as acceleration, deceleration, idling, creep idling, and cruising. One purpose of developing a drive cycle is to replicate the driving conditions during emissions and fuel consumption testing and modeling.

Refuse trucks operating at the Clint Landfill in El Paso were equipped with Global Positioning System (GPS) units to collect their second-by-second position data. The GPS units consist of a GPS receiver/antenna and a GPS data logger. The GPS data was then used to develop drive cycles for each of the four modes of operation – urban driving, trash collection, freeway driving, and landfill operations. Figure 3 shows sample speed profiles for the four operational modes. A detailed description of the drive cycles and their development can be found elsewhere.¹⁰

**Economic Feasibility**

The economic feasibility model considers the feasibility of the three options – do nothing (flare the LFG), electricity generation, and converting LFG to LNG to fuel refuse trucks. The net present worth (NPV) technique was used for this purpose to facilitate the decision-making. The following factors were included in the economic analysis model:

- capital cost of conversion equipment (electricity generation or vehicle fuel);
- maintenance and operational cost of conversion equipment (electricity generation or vehicle fuel);
- capital cost of truck fleet conversion (diesel and/or LNG);
• maintenance and operational cost of truck fleet (diesel and/or LNG);
• emissions benefits;
• tax credits; and
• sale of products – electricity, food grade CO₂, and surplus LNG.

Values for the capital, maintenance, and operational costs of the conversion equipment were obtained from existing owners and operators of these facilities. Similarly, values for the capital, maintenance, and operational costs of refuse trucks were obtained from landfill operators. The difference in costs between LNG and conventional diesel-fueled trucks were obtained from various literature sources. Similarly, tax credits for the production of electricity from landfills and the production of LNG from landfills as well as sale prices for products such as electricity, food grade CO₂, and surplus LNG were obtained from the literature.

Developing values for emissions and associated emissions benefits involved a comprehensive process. The Texas Transportation Institute used portable emissions measurement system (PEMS) equipment to measure the emissions and fuel consumption of three diesel-fueled refuse trucks during actual operating conditions at the El Paso landfill. Rates from the MOBILE6 emissions model were used to augment the measured rates to make them cover a broad range of model years and refuse truck types. Emissions and fuel consumption differences between diesel-fueled and LNG-fueled refuse trucks were obtained from previous studies. The emissions and fuel consumption could then be determined for each trip based on the rates for that truck type (diesel or LNG fueled), model year, and distance traveled in each component of the drive cycle (urban driving, trash collection, freeway driving, and landfill operations). Costs are then associated with the different pollutants – NOx ($13,000/ton), HC ($10,700/ton), CO ($15,600/ton), CO₂ ($42/ton), and PM ($26,000/ton).11, 12, 13

Decision Making

All the aspects and equations associated with the economic feasibility analysis were coded into a user-friendly analysis tool. A landfill owner or city using the tool will be prompted to enter the required input data and the tool will then perform all the required calculations. All the costs and benefits associated with these options are calculated over a 20-year analysis period and brought
to current year dollars using the NPV method allowing comparison of the various options. Each
round of analysis can lead to a decision or a repeat of the process while changing parameters as
part of sensitivity analyses.

TExAS CaSE StUdy

Inventory of Landfills in Texas

The first step was to develop an inventory of Texas landfills that includes information on the
landfill name, location, ownership, amount and classification of waste in place (WIP), size and
depth, presence of LFG collection system, and amount of LFG collected. It also includes details
about the operational status of energy recovery projects at the landfill and the amount of LFG
consumed by such projects. EPA’s Landfill Methane Outreach Program (LMOP) database
contains information on 2,456 landfills nationwide with 96 being in Texas. This database
provided good information and was supplemented by interviews of key people at individual
landfills. The 96 landfills in Texas were short-listed using the evaluation criteria based on those
developed by the EPA with regards to WIP, waste acceptance, depth, and gas generation rate.

It was found that 17 landfills in Texas have the potential for energy recovery projects including
the production of LNG to fuel their refuse trucks. Figure 4 shows a map of the eight-hour ozone
nonattainment and near nonattainment areas in Texas as well as the locations of the 17 short-
listed landfill sites. The figure shows that nine landfills are located in nonattainment areas and
seven landfills are located in near nonattainment areas for ozone. Emissions saved due to
conversion of LFG to LNG could therefore, improve the attainment status of these areas.

Inventory of Refuse Trucks in Texas

Typically, there are two types of collection operations associated with refuse trucks —
residential and commercial. However, large cities may have a third type of collection operation
involving Citizen Collection Stations (CCS). The CCSs are selected sites where voluntary
disposal of waste is permitted. These sites are suitable for large commercial or bulk residential
disposal. The different types of collection operations require different types of refuse trucks.
These trucks have slightly different operational characteristics and include side loaders, front
loaders, rear loaders, and roll off compactors.
The inventory of refuse trucks at the major landfills in Texas was assembled through a survey. The survey was designed to collect information on truck fleet details and operational characteristics. The survey was sent to the major refuse truck companies operating on the short-listed landfills in Texas. Information collected included the make and model year of the trucks and the type and size of the engines. It also included information on the operational characteristics of refuse trucks such as the type of collection operation, average round-trip length to the landfill and number of trips to the landfill or transfer station. This information provided the basis for modeling fleet and operational characteristics.

Example Application

The Clint Landfill located in El Paso was used as case study for this research. It is a large landfill (one of the 17 short-listed landfills in Texas) with WIP of approximately 5 million tons and annual WAR of 390,000 tons. The landfill is considered fairly typical and El Paso is considered a medium-size Texas city.15

Table 3 shows the input data for the example application. The table shows that with a modest amount of input data the full analysis can be performed. In addition to the input data listed in this table, the user also has the ability to change the values of several other parameters such as the cost of diesel, selling price of LNG, and the cost of emissions to reflect more current information or to be able to perform sensitivity analyses.

Figure 5 shows the findings from the analysis by comparing the NPV of the three options – do nothing (flare the LFG), establish a plant to generate electricity, and establish a plant to convert the LFG to fuel refuse trucks. It should be noted that the NPV values are negative because it costs money to own and operate a landfill and the values are therefore shown in the form of net present costs (NPC) with the lowest NPC value indicating the most economically feasible option.

Figure 5 shows that the option of converting LFG to LNG is the most economically feasible option (40% improvement over status quo) followed by converting LFG to electricity (18% improvement over status quo). Note that the analysis performed is an economic evaluation and
not a pure financial analysis. In the case of a financial analysis the benefits due to emission
reductions would not be included because it is then based on pure cash flow. Additionally note
that the analysis is for illustration purposes and, based on other assumptions, the results would be
different.

Sensitivity analyses were performed by changing aspects such as the fleet growth rate, length of
the analysis period, cost of diesel, and selling price of LNG. The sensitivity analyses indicate the
variations in the NPV due to changes in the above factors and assist in developing better
decisions. For illustration purposes, Figure 6 shows the variation in NPC with regard to the cost
of diesel. The figure shows that, for all the cases, the NPCs increase linearly with increased price
of diesel. In addition, because the LFG-to-LNG option has a growing portion of the fleet
operating on LNG instead of diesel, the rate of increase in the cost for this option is less than that
of the other two options. This reduced impact due to diesel price increases makes the LFG-to-
LNG option even more attractive.

This figure only assumes a variation in one of the factors and is for illustration purposes only.
More complex analyses, varying multiple factors in combination with one another, will improve
the final decision. The analysis tool provides for this flexibility and ease of use.
CONCLUSIONS

The following could be concluded from this research project.

- There are several applications of LFG such as up-gradation to pipeline quality gas, generation of electricity, use in fuel cells, and vehicular fuel. This study focused on the conversion of LFG to vehicular fuel and compared it to the generation of electricity and purely flaring the gas.

- The utilization of LFG for vehicular fuel applications is more recent than other applications. Several tests have been performed by Mack Trucks, Inc. and Acrion Technologies, Inc. to evaluate the feasibility of using LNG obtained from the LFG to fuel refuse trucks and the results have been very promising.

- The application of LFG depends upon its quantity, composition, and quality. Researchers identified 17 landfills in Texas that could potentially benefit from a LFG-to-LNG conversion project to produce fuel for its refuse trucks.

- A methodology was developed that is based on the modeling of several components – LFG generation, energy recovery processes, fleet operations, economic feasibility, and decision-making. This methodology was coded into a user-friendly analysis tool and applied to a pilot landfill in El Paso, TX.

- The preliminary results indicate that the methodology could easily be applied to landfills and that the conversion of LFG to LNG proved to be the most economically feasible option for the case study. It should be noted, however, that the analysis was for illustration purposes and, depending on the values of several assumptions, the results could be different.
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The opinions expressed in this paper reflect the views of the authors only and do not necessarily reflect the points of view of any other sponsoring or contributing individual or agency.

REFERENCES


ABOUT THE AUTHORS

Dr. Josias Zietsman is the Director of the Center for Air Quality Studies of the Texas Transportation Institute (TTI). TTI is part of the Texas A&M University System. Bhushan Gokhale is an employee of the Jacobs Engineer Group in Dallas, Texas. Dr. Dominique Lord is an Assistant Professor at Texas A&M University. Mr. Ehsanul Bari is a Graduate Research Assistant in the Center for Air Quality Studies at TTI and Mr. Aaron Rand is a Research Associate in the Center for Air Quality Studies at TTI.
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Table 1. Typical Composition of Landfill Gas.

<table>
<thead>
<tr>
<th>Component</th>
<th>Percent (dry volume basis)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methane</td>
<td>47.5</td>
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<tr>
<td>Carbon dioxide</td>
<td>47.0</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>3.7</td>
</tr>
<tr>
<td>Oxygen</td>
<td>0.8</td>
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<tr>
<td>Paraffin hydrocarbons</td>
<td>0.1</td>
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<tr>
<td>Aromatic and cyclic hydrocarbons</td>
<td>0.2</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>0.1</td>
</tr>
<tr>
<td>Hydrogen Sulfide</td>
<td>0.01</td>
</tr>
<tr>
<td>Carbon monoxide</td>
<td>0.1</td>
</tr>
<tr>
<td>Trace compounds</td>
<td>0.5</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>100</strong></td>
</tr>
</tbody>
</table>

Table 2. Inputs for El Paso Landfill.

<table>
<thead>
<tr>
<th>LANDFILL INPUTS</th>
<th>TRUCK FLEET INPUTS*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current WIP (tons)</td>
<td>5 million</td>
</tr>
<tr>
<td>Waste Acceptance Rate (tons)</td>
<td>390,000</td>
</tr>
<tr>
<td>Bioreactor Landfill</td>
<td>No</td>
</tr>
<tr>
<td>Amount of Rainfall (inches/month)</td>
<td>0.77</td>
</tr>
<tr>
<td>Organic Content (percentage)</td>
<td>32</td>
</tr>
<tr>
<td>Collection Efficiency (percentage)</td>
<td>N/A</td>
</tr>
<tr>
<td>Raw LFG Consumption by other applications (percentage)</td>
<td>N/A</td>
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<tr>
<td>Current Number of Trucks (per model year bin)</td>
<td>110</td>
</tr>
<tr>
<td>Average Number of Stops</td>
<td>400</td>
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<tr>
<td>Distance per trip Urban, Freeway, Collection, Landfill (miles)</td>
<td>4, 30, 5, 2</td>
</tr>
<tr>
<td>Number of Trips to Landfill per Day</td>
<td>2</td>
</tr>
<tr>
<td>Collection Days per Week</td>
<td>4</td>
</tr>
<tr>
<td>Annual Replacements and Retirements</td>
<td>12 and 3</td>
</tr>
</tbody>
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