Texas Transportation Institute

Pre-Feasibility Analysis for the Conversion of Landfill Gas to Liquefied Natural Gas to Fuel Refuse Trucks in India

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ABSTRACT
India's urban areas are characterized by high, dense populations that are continuing to grow, placing a significant burden on the urban infrastructure. Thus, the optimal management of municipal solid waste (MSW) in India's cities is an issue of critical importance. MSW management operations in India have two distinct yet related aspects that are of importance from an environmental and socio-economic perspective. One relates to the practices associated with disposal of waste at landfills; a majority of landfill sites in India are not engineered sanitary landfills, but rather open dumps. While measures have been taken recently to improve and retrofit existing landfills and engineer new landfill sites, this remains a major issue with respect to MSW management in India. Another issue relates to the major environmental impact of these landfills/disposal sites – the generation of landfill gas (LFG, primarily methane [CH_4]). This has implications from a global warming/GHG perspective, as well as local air quality impacts in urban India.

The goal of this project was to assess the feasibility of converting LFG to liquefied natural gas (LNG) or compressed natural gas (CNG) to be used as fuel for refuse trucks in India. While LNG and CNG only differ in terms of their physical state, the CNG option was deemed preferable in the Indian context. This process has the potential to significantly reduce landfill CH_4 emissions by capturing LFG, reducing refuse truck emissions by providing a cleaner burning fuel, and improving India's energy security by reducing reliance on conventional diesel. The process can also help boost economic growth by adding job opportunities at landfills. Three landfills were identified in the Mumbai area in Maharashtra, India for conducting the pre-feasibility analysis.

Mack Trucks Incorporated and Acrion Technologies, Inc. developed the carbon dioxide (CO_2) Wash Process that can clean LFG sufficiently to produce LNG/CNG and food grade CO_2. This process has been applied with success in the U.S. in Burlington, NJ, and was considered as a part of the analysis. Data were collected at each landfill regarding the size, age, depth, waste composition, gas quality, and refuse truck fleet. Models were used to estimate the potential LFG production, natural gas production, refuse truck emissions benefits, fuel consumption benefits, and economic feasibility of fueling refuse trucks with the natural gas produced at the landfills. It was found that this process may be economically feasible in certain cases and has the potential to reduce green house gas emissions, improve air quality, conserve energy, and assist with energy security in India. In addition to the option of converting LFG to natural gas for truck fuel, the feasibility of other options for the management of LFG generation were also considered in this study.

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TABLE OF CONTENTS

Abstract 2

Table of Contents 4

List of Figures 6

List of Tables 7

Executive Summary 8

- **Landfill Gas** 8
- **Issues Related to Landfills in India** 8
  - Additional Socio-Economic Issues 9
- **This Project** 9
- **Mumbai Landfill Case Studies** 10
- **MSW Management in Mumbai** 10
- **Pre-Feasibility Analysis for Sanitary Landfills and LFGTE Projects** 11
  - Estimation of LFG Generation 12
  - Evaluation of Costs and Benefits 13
  - Analysis Results 14
  - Alternative Analysis for LFGTE Options – Without Consideration of Capping Costs 14
- **Findings and Recommendations** 15

Introduction 17

- **Natural Gas and LFG – An Overview** 17
- **Need for LFG Collection Mechanisms** 17
- **Study Objectives** 18
- **Study Approach** 18
- **Report Overview** 19

Landfill Characteristics 20

- **Socio-Economic and Environmental Issues in Indian Cities** 20
- **Case Study Landfills** 21

Solid Waste Management Operations in Mumbai 24

- **Waste Characterization** 25
- **Collection and Transportation of Waste** 26
- **Vehicle Fleet Information** 26
- **Driving Characteristics of Refuse Fleet Vehicles** 27
  - Stationary Compactor 28
  - TATA Dumper Placer 30
  - Dumper 32

Concluding Remarks **34**

Methodology **35**

Identification of Analysis Scenarios for Pre-Feasibility Analysis **35**

Estimating Landfill Biogas Generation **37**

Estimating Natural Gas/ CH_4 Recovery 39
Natural Gas Generation for Mumbai's Landfills 40
Gas Generation Quantities 40

Estimation of Benefits for Pre-Feasibility Analysis **41**

Diesel and Natural Gas Savings 41
Earnings from Electricity Conversion 43
Carbon Credits 43
Using LFG as Transportation Fuel - Fleet Turnover Emissions Reduction 45
Other Benefits not Included in Calculations 49

Estimation of Costs for Pre-Feasibility Analysis **49**

Landfill Capping Costs 50
Cost of LFG-to-CNG Conversion System 51
Cost of Conversion of LFG to Pipeline Grade Natural Gas 51
Cost of Conversion of LFG to Electricity 52
Cost of Flaring LFG from Capped Landfill 53
Cost of Flaring LFG from an Active Landfill 53

Estimating the Net Return for Each Scenario **54**

Scenarios 1-3: Landfill Management Options 54
Scenarios 4-6: LFG to Energy Options 55
Alternative Analysis for LFGTE Options – Without Consideration of Capping Costs 55

Results **56**

Gorai Landfill **56**

Deonar Landfill **57**

Mulund Landfill **59**

Conclusions **61**

MSW Management and Landfills in Mumbai **61**

Pre-Feasibility Analysis of Options for Case Study Landfills **61**

Final Remarks **62**

Reference **64**

APPENDIX A- CO_2 Wash Process Details **66**

APPENDIX B – LFG Generation Quantities **67**

APPENDIX C – Details of Benefits Estimated Over Analysis Period **68**

APPENDIX D- Bus Service Earnings from LNG/CNG **73**

LIST OF FIGURES

Figure 1. Picture and Aerial View of Mulund Dumping Site......22
Figure 2. Picture and Aerial View of Deonar Dumping Site......23
Figure 3. Pictures of Gorai Dumping Site......23
Figure 4. Stationary Compactor......28
Figure 5. Route for Stationary Compactor......28
Figure 6. Speed Profile for Stationary Compactor......29
Figure 7. TATA Dumper Placer......30
Figure 8. Route for TATA Dumper Placer......30
Figure 9. Speed Profile for TATA Dumper Placer......31
Figure 10. Dumper......32
Figure 11. Route for TATA Dumper Placer......32
Figure 12. Speed Profile for Dumper......33
Figure 13. Recoverable Natural Gas Quantities Generated for Case Study Landfills......41

LIST OF TABLES

Table ES. 1. Basic Details of Case Study Landfills 10
Table ES. 2. Applicability of Costs and Benefits to Various Scenarios 13
Table ES. 3. Results of Pre-Feasibility Analysis with Capping Costs considered 14
Table ES. 4. Alternative Analysis for LFGTE Options 15
Table 1. Composition of Natural Gas 17
Table 2. Mumbai Landfill Site Details 24
Table 3. Waste Characteristics of Mumbai MSW 26
Table 4. Type of Vehicles Used by MCGM for Transportation of Waste 27
Table 5. Summary of Driving Pattern Parameters – Stationary Compactor 29
Table 6. Summary of Driving Pattern Parameters – TATA Dumper Placer 31
Table 7. Summary of Driving Pattern Parameters –Dumper 33
Table 8. Summary of Costs and Benefits Associated with Each Scenario 37
Table 9. Range and Suggested Values for L_o *and k* 38
Table 10. Recoverable Dry Gas for Entire Analysis Period 40
Table 11. Diesel Savings for Entire Analysis Period 42
Table 12. Earnings from Natural Gas for Entire Analysis Period 43
Table 13. Earnings from Electricity Conversion for Entire Analysis Period 43
Table 14. Earnings from Carbon Credits for Entire Analysis Period 45
Table 15. ARAI emission factors Diesel and CNG vehicles 46
Table 16. Emissions from Stationary Compactor 46
Table 17. Emissions from TATA Dumper Placer 47
Table 18. Emissions from Dumper 47
Table 19. Cost Savings Due to Emissions Reduction from LNG Vehicles 49
Table 20. Mumbai Landfill Capping Costs 50
Table 21. Base Cost of Landfills with Acrion System 51
Table 22. Cost of LFG to Pipeline Grade Natural Gas 52
Table 23. Cost of LFG to Electricity 53
Table 24. Cost of Flaring System from Capped Landfill 53
Table 25. Cost of Flaring System at an Active Landfill 54
Table 26. Cost of Emissions for Do-Nothing Scenario 54
Table 27. Results for Gorai Landfill 57
Table 28. Gorai Landfill – Additional Analysis for LFGTE Options 57
Table 29. Results for Deonar Landfill 58
Table 30. Deonar Landfill – Additional Analysis for LFGTE Options 59
Table 31. Results for Mulund Landfill 60
Table 32. Mulund Landfill – Additional Analysis for LFGTE Options 60

EXECUTIVE SUMMARY

Indian urban areas, faced with increasing populations and quantities of waste generated, have a need to optimally manage municipal solid waste (MSW). This includes exploring means of using MSW as an energy source, or considering other options for managing MSW to reduce environmental and socio-economic impacts.

Landfills, being the ultimate means of disposal for the municipal solid waste, are a prime target for implementing effective and environmentally sound MSW management practices. There are a variety of concerns relating to the environmental impacts of landfills – which not only take up vast areas of land, but can also affect water supply in nearby areas due to leachate seeping into the ground. In addition, the decomposition of waste at landfills releases gaseous byproducts collectively termed as landfill gas (LFG). Some components of LFG are noxious or odorous gases that affect air quality in local areas. However, it is greenhouse gases (GHG, primarily methane [CH_4]), that are a major constituent of LFG. Therefore, the proper management of landfills is an issue of significance for both the local environment and from a global perspective.

Landfill Gas

As previously mentioned, the gas generated by landfills is composed largely of methane, along with components such as Carbon Dioxide (CO_2). CH_4 is a GHG with a high global warming potential (GWP) – 21 times that of CO_2. CH_4 is also a major component of natural gas, a naturally-occurring energy source that is more energy-dense and cleaner-burning than other fossil fuel sources. Given the similarities in their composition, LFG can be a viable source of natural gas, after it is purified to remove certain undesirable components. This gas can then be used for a variety of applications, collectively termed as LFG-to-energy (LFGTE) projects. These include conversion to electricity, use as piped natural gas, or use as a transportation fuel. The use of natural gas as a diesel/gasoline alternative is either in the form of Compressed Natural Gas (CNG) or Liquefied Natural Gas (LNG).

Issues Related to Landfills in India

Historically, landfills in India differed from those in the U.S. in that they were not engineered sanitary landfills but rather open dumps. In recent times, the Indian government established regulations (specifically the Municipal Solid Waste Management and Handling and Rules, 2000) to ensure that new landfills are properly engineered, and that retroactive measures such as capping, lining, and gas collection are conducted to improve existing landfills.

The proper engineering of sanitary landfills can help in mitigating many of the impacts in local areas. The use of liners and proper construction of landfill cells can prevent soil and water quality impacts. Installing gas collection mechanisms can protect local air quality. The collection of LFG also provides the opportunity to use this gas (composed mostly of CH_4) as an energy source. The use of LFG as an energy source has a double benefit – reducing the GHG emissions from the landfill, as well reducing the dependence on other sources of energy.

Thus, when considering landfills in India, there are two separate issues that warrant attention:

1. While the waste disposal sites in India are termed as "landfills" this term is used rather loosely and does not represent the type of landfills currently operating in the U.S. and other developed nations. Rather, many landfills are open dumps. While recent regulatory measures have promoted sanitary landfill engineering practices, especially in urban India, it has to be noted that any LFGTE project or other means of landfill improvements must first consider the infrastructure or input required to bring the landfill to sanitary conditions.
2. The next issue, over and above the implementation of sanitary/landfill engineering practices is the management of the LFG generated. This is where the use of additional LFGTE projects are of relevance and can add to the benefits of creating sanitary landfill management practices.

Additional Socio-Economic Issues
Indian landfills also face other unique socio-economic issues due to the informal recycling trade that exists in and around landfills. Many people depend on the landfills as a source of income, by sorting through the dumped waste and collecting recyclable materials and selling them. People also choose to live on the landfills, as the methane gas generated helps maintain fires for cooking or for warmth. Areas near landfills also face many problems due to dust and odors as a result of open dumping. Urban air quality is also a concern in most of India, and landfills are viewed as contributors to this problem. Though sanitary landfill practices and LFGTE projects can result in societal benefits overall, certain segments of society, such as those in the informal recycling trade, may suffer. These issues need special consideration.

This Project
The goal of this project is to conduct a pre-feasibility analysis to assess various options of converting LFGTE sources in the state of Maharashtra, India. Of particular interest is the option of converting LFG to natural gas to be used as fuel for refuse trucks. This process has the potential to significantly reduce CH_4 emissions produced by the landfills, reduce refuse truck emissions by providing a cleaner burning fuel, and improve India's energy security. The process can also help boost economic growth by adding job opportunities at landfills. The terminology of a "pre-feasibility analysis" is used instead of "feasibility analysis" even though the analysis involves the monetization of costs and benefits. One reason for this is that the analysis accounts for costs of converting open-dump type landfills into sanitary landfills. This is a significant cost that may be covered through alternate funding sources (such as the World Bank or developmental agencies) because it is an issue of environmental importance in a developing

nation. Thus, these costs may not come into play when a feasibility analysis is conducted for a specific project. The purpose of this pre-feasibility analysis is to provide a general idea of the feasibility of further pursuing the LFG-natural gas fuel conversion or other LFGTE projects. The pre-feasibility analysis calculations also make certain assumptions and conservative estimates that may be revised with more project-specific information when conducting a detailed feasibility analysis.

Mumbai Landfill Case Studies

Three landfills in the city of Mumbai, Maharashtra were selected as case study landfills for conducting this research. Table ES.1 shows the Gorai, Mulund, and Deonar landfills, and a few selected details of each landfill. Of the three landfills, the Gorai landfill was closed for dumping in 2008, while the Deonar landfill is scheduled for partial closure in 2009. The landfills range in size from 19 Hectares to 132 Hectares, and are all currently open dumpsites, that have not been designed for a particular capacity. However, retrofit measures are being implemented at the landfills based on the regulations outlined in the MSW Management and Handling Rules.

Table ES. 1. Basic Details of Case Study Landfills

Data	**Site**		
	Deonar	**Mulund**	**Gorai**
Type of landfill	Open Dumpsite	Open Dumpsite	Open Dumpsite
Landfill size	132.1 Ha	25 Ha	19.6 Ha of which 17.7 Ha used for dumping
Waste in place (as of Jan 2006)	7.88 million metric tons	0.94 million metric tons	1.76 Million metric tons
Waste Depth	5 - 7 m	3.6 m	10.2 m (Nov 2005)
Year filling began	1927	1968	1972
Year landfill was closed or will close	Partial closure planned in 2008-09	Not yet planned	2008

MSW Management in Mumbai

According to the Municipal Corporation of Greater Mumbai (MCGM), currently Mumbai generates up to 8,500 metric tons of waste per day. This is comparable to the waste generation levels of major cities in the United States. MCGM is responsible for the management of waste in the city. In Mumbai, individual households and other waste generators are responsible for transporting waste to local "community bins" where it is collected by the municipal authorities and disposed of at landfills/dumping sites. MCGM employs over 35,000 people for the manual collection of waste and transportation to the various dumping sites and operates a fleet of 989 vehicles – both owned by the municipality and private contractors – for collection of waste.

Pre-Feasibility Analysis for Sanitary Landfills and LFGTE Projects

As discussed previously, there are two major aspects to consider in analyzing the feasibility of using LFG as an energy source:

1. The landfill processes conducted in India are not sanitary and satisfactory. There are costs and benefits associated with setting up a sanitary landfill system that would allow for the collection of LFG.
2. The next step beyond this would be to implement the various LFGTE projects, for example, using the LFG as a transportation fuel or converting it to electricity. These would have an additional set of costs and benefits.

Thus, in an ideal situation, the pre-feasibility analysis would be performed in two distinct steps, which can be seen as "first level" and "second level" applications:

- considering the costs and benefits of converting an open dump to a sanitary landfill; and
- considering the additional costs and benefits of then implementing an LFGTE project on the landfill.

However, conducting a separate analysis for the costs and benefits of converting the landfill into a sanitary landfill (through capping and installation of gas collection mechanisms) alone was not conducted. This is because the benefits associated with such a process are mostly socio-economic and cannot be readily quantified. It was only when further measures were conducted to do something with the captured LFG (such as flaring, or conversion to energy) that the benefits could be assessed, and these scenarios are included in the analysis. This research grouped the possible scenarios into two categories, termed as landfill management practices and LFGTE practices. A total of six analysis scenarios were selected and applied for the three case study landfills over a 20-year analysis period. These scenarios cover various options for collecting and disposing or using LFG, and are listed below:

Landfill Management Options;

1. Do Nothing;
2. Cap the landfill and flare the LFG; and
3. Flare the LFG from an active landfill.

LFGTE Options:

4. Convert the LFG to CNG to use as a transportation fuel;
5. Convert the LFG to pipeline grade natural gas; and
6. Convert the LFG to electricity.

Scenario 1 is the do-nothing option that represents the baseline conditions under which no LFG collection or conversion of the landfill to a sanitary landfill is conducted. Scenario 2 involves capping the landfill and installing a gas collection system before flaring the LFG (controlled combustion). Scenario 3 involves installing gas collection wells for flaring from an active landfill, and thus does not require the additional cost of capping. Flaring of LFG helps convert CH_4 into CO_2, which is a less harmful GHG. The three remaining scenarios are LFGTE options that involve the costs for capping and collection systems, along with the additional infrastructure costs. For Scenario 4, the conversion of LFG to CNG was considered (rather than conversion to LNG). While CNG and LNG are both forms of natural gas that only differ in the state of storage, the CNG option is preferred in India due to lower infrastructure costs. Also, CNG is currently used in India, mostly in bus fleets, which makes CNG more relevant in the Indian context.

Estimation of LFG Generation

The first step to conducting the pre-feasibility analysis is to quantify the gas generation potential at the landfill sites. For this, the U.S. Environmental Protection Agency's (EPA) modeling equation for closed landfills was applied for most scenarios. Equation ES-1 shows the equation. A slightly different version of this equation (for active landfills) was used for Scenarios 1 and 3 alone.

$$Q_t = 2 * L_0 * m_0 * \left(e^{k*t_a} - 1\right) * e^{-k*t} \qquad \textit{(ES-1)}$$

Where Q_t = expected gas generation rate in the t^{th} year, m^3/yr;

L_o = methane generation potential, m^3/yr;

m_o= constant or average annual solid waste acceptance rate, Mg/yr;

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

t = age of the landfill, yr; and

t_a = total years of active period of the landfill, yr.

Based on this equation, and the conversion of the LFG into natural gas quantities based on energy equivalencies, the recoverable dry natural gas over the 20-year analysis period was estimated for each landfill. It was calculated as approximately 1.06 million mcf (thousand cubic feet), 1.04 mcf, and 404,000 mcf for the Deonar, Mulund, and Gorai landfills respectively. It must be noted that this report uses the term "mcf" to represent a unit of one thousand cubic feet, and should not be confused with "Mcf" that is sometimes used to denote one million cubic feet. One aspect of LFG production in a closed landfill is that the LFG production rate is not consistent over a period of time, but rather decreases. While this factor has not been given explicit consideration in the pre-feasibility analysis, the quantity of LFG capable of being produced on a daily basis is something that should factor into decision-making while selecting options for the management of landfill gas.

Evaluation of Costs and Benefits
The various costs and benefits associated with the six analysis scenarios are then evaluated for the pre-feasibility analysis. The benefits to be quantified include:

- earnings from sale of carbon credits for any LFG collection or management practice that reduces GHG emissions;
- savings in diesel costs when LFG is converted to CNG for use as truck fuel;
- earnings from the sale of natural gas when LFG is converted to piped natural gas;
- earnings from the sale of electricity if LFG is used for electricity generation; and
- the monetized benefit of emissions reduction due to fleet turnover – replacement of diesel vehicles with CNG vehicles.

The costs considered include the cost of capping the landfill, the cost of operating LFG conversion facilities, as well as the cost of flaring. In the do-nothing scenario, the cost of emissions is considered (can be viewed as a "negative" benefit). Each of the costs and benefits discussed above are applicable only to certain specific scenarios. Table ES.2 indicates the applicability of the costs and benefits to the various scenarios.

Table ES. 2. Applicability of Costs and Benefits to Various Scenarios

Description	**Scenario**					
	1	**2**	**3**	**4**	**5**	**6**
Benefits						
Diesel or Natural Gas Savings				X	X	
Electricity Conversion						X
Carbon Credits		X	X	X	X	X
Fleet Turnover Emissions Reduction				X		
Costs						
Landfill Capping Costs		X		X	X	X
CNG Facility and Operation Cost				X		
Pipeline Natural Gas Facility and Operation Cost					X	
Electricity Plant and Operation Cost						X
Flaring System and Operation Costs		X	X			
Cost of Emissions	X					

Analysis Results

The pre-feasibility analysis was conducted as a benefit-cost analysis for the six scenarios for each case study landfill. Table ES.3 summarizes the results of this analysis.

Table ES. 3. Results of Pre-Feasibility Analysis with Capping Costs considered

Scenario	Gorai		Deonar		Mulund	
	Net Benefit ($)	Return (%)	Net Benefit ($)	Return (%)	Net Benefit ($)	Return (%)
Landfill Management Options						
Scenario 1: Do Nothing	$(17,015,502)	**N/A**	$ (44,693,492)	**N/A**	$(43,859,505)	**N/A**
Scenario 2: Cap the Landfill and Flare the LFG	$ (3,140,569)	**-31%**	$(7,870,880)	**-30%**	$5,252,208	**42%**
Scenario 3: Flare the LFG from an Active Landfill	$ (1,377,397)	**-16%**	$(18,025,538)	**-48%**	$8,389,332	**80%**
LFGTE Options						
Scenario 4: Convert LFG to CNG for Use as a Transportation Fuel	$ (7,375,991)	**-33%**	$ 465,457	**1%**	$ 13,208,186	**54%**
Scenario 5: Convert the LFG to Pipeline Grade Natural Gas	$ (9,374,035)	**-51%**	$ (11,718,243)	**-33%**	$ 1,332,408	**6%**
Scenario 6: Convert the LFG to Electricity	$ (3,719,716)	**-29%**	$ (15,788,418)	**-40%**	$ (1,965,718)	**-9%**

Alternative Analysis for LFGTE Options – Without Consideration of Capping Costs

The results shown in Table ES.3 represent the results of the pre-feasibility analysis that considered the costs of capping the landfill to bring it up to the standards of a sanitary landfill. However, as discussed previously, the conversion of a landfill to a sanitary landfill also has many other societal and environmental benefits. Additionally, funding for conducting this could also be obtained from other sources in due course, and may not necessarily need consideration while conducting a pre-feasibility analysis that examines LFGTE options. Thus, Table ES.4 summarizes the results from an additional analysis that was conducted for the LFGTE options alone. The costs of capping the landfill were not considered in this case. As the results show, this affects the feasibility of the LFGTE options to varying degrees for the different landfills.

Table ES. 4. Alternative Analysis for LFGTE Options

Scenario	Gorai		Deonar		Mulund	
	Net Benefit ($)	Return (%)	Net Benefit ($)	Return (%)	Net Benefit ($)	Return (%)
Scenario 4: Convert LFG to CNG for Use as a Transportation Fuel	$ (1,665,390)	**-10%**	$ 22,084,157	**135%**	$ 21,366,186	**130%**
Scenario 5: Convert the LFG to Pipeline Grade Natural Gas	$ (3,663,435)	**-29%**	$ 9,900,457	**70%**	$ 9,490,408	**67%**
Scenario 6: Convert the LFG to Electricity	$ 1,990,884	**28%**	$ 5,830,282	**33%**	$ 6,192,282	**46%**

Findings and Recommendations

This project studied the MSW management process in Mumbai, India, with a special emphasis on the unique problems faced in India. Three landfills in the Mumbai region were selected for further analysis, and researchers collected basic information about the landfills.

The results of the pre-feasibility analysis for the Gorai landfill indicate very low returns for the landfill management options, as well as for LFGTE projects, regardless of whether capping costs are considered. This is probably due to the relatively low LFG generation for this site. For the Deonar landfill, the initial pre-feasibility analysis shows very low returns for all options, with the returns for the LFG-to-CNG scenario being the highest at 1%. However, in the case of the LFGTE options without consideration of capping costs, the results show a very high return for the LFG-to-CNG option. This indicates that in the case of Deonar, there is the potential for setting up an LFG-to-CNG conversion process to generate transportation fuel, especially if the capping costs are recovered from other sources. For the Mulund landfill, multiple scenarios exhibited positive returns, including the LFG-to-CNG conversion option, which had the highest returns among the LFGTE scenarios. The returns further increased when the capping costs were not considered for the analysis, and the results indicate that for this particular landfill, the LFG-to-CNG conversion for transportation use is feasible regardless of whether capping costs are recovered from another source. However, as previously mentioned, the issue of LFG production volumes over the entire analysis period needs to be considered before making a decision on whether to implement a LFGTE project, especially for the LFG/Transportation fuel option, where a steady supply of CNG fuel is desirable.

Thus, the landfills in Mumbai represent an important source of LFG and methane that can be used for projects that can help reduce GHG emissions and provide alternative sources of energy. While the prefeasibility analysis indicates that flaring appears to be the best option when taking all costs into consideration, the LFG-to-CNG conversion also came up as a promising scenario.

A more detailed feasibility analysis of all the options is recommended, as certain estimations made in this analysis are highly conservative. Additional quantification of other benefits and more accurate knowledge of project-specific costs and potential LFG generation can also benefit the analysis. The knowledge of true incremental costs for implementing a sanitary landfill with or without a LFGTE project would also further benefit this research.

The results of this project indicated that there are many viable options that can be implemented for improving the overall management of Mumbai's landfills to promote public welfare. Most importantly however, measures such as LFG-to-CNG conversion can improve environmental quality by reducing the air quality impacts, GHG emissions and fuel consumption. Such LFGTE projects represent promising solutions that can improve India's energy security while also having a positive impact on the environment.

INTRODUCTION

The overall goal of this research project is to contribute to the optimal management of municipal solid waste in cities in India. Landfills, being the ultimate disposal mechanism for MSW, are a good target for the implementation of environmentally sound land filling practices, as well as a potential energy source through the generation of LFG.

This introductory section provides a general overview of LFG, its environmental impacts, potential use as an energy source and other options for landfill management. This section also describes the main research objectives, while the following sections of the report deal with India-specific landfill characteristics and the pre-feasibility analysis conducted for three case studies in the city of Mumbai in India.

Natural Gas and LFG – An Overview

Natural gas, in its pure form is colorless, odorless and highly combustible. It is clean burning and produces a great deal of energy, and lower levels of harmful byproducts when compared to other fossil fuel sources. Natural gas, which occurs in various natural sources, is composed primarily of Methane (CH_4). Its composition varies, and the typical components are listed in Table 1.[1]

Table 1. Composition of Natural Gas

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 sulphide	H_2S	0-5%
Rare gases	A, He, Ne, Xe	Trace

LFG is the gas that is emitted from landfills due to the decomposition of matter contained in it. LFG is also primarily composed of methane, along with other gases, mostly CO_2. While LFG and natural gas are not entirely synonymous, LFG, when purified and cleaned of toxins and CO_2 can be a source of natural gas.

Need for LFG 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. CH_4 is a GHG with a 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 and management are:

- do nothing – where the LFG is allowed to escape into the atmosphere;
- flaring – where the LFG is collected and burned in a controlled combustion process. This converts the methane into CO_2; or
- 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 GHGs with a high GWP. Flaring is a better option as it converts the methane into CO_2, which is less harmful that CH_4. 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 particularly concerned with the feasibility of converting LFG into natural gas for fueling refuse trucks or buses, the range of possible options for dealing with LFG are all presented in further detail in this report.

Study Objectives

This study was conducted as a part of the EPA's Methane to Markets Partnership. The specific objective of this research was to conduct a pre-feasibility analysis for the conversion of LFG into LNG to fuel refuse trucks or buses in India. CNG (which is another stored form of natural gas) was preferred over LNG for Indian conditions, and the analysis thus considers CNG instead. The research was conducted by the Texas Transportation Institute (TTI) partnering with India's National Environmental Engineering Research Institute (NEERI), Mack Trucks Incorporated (Mack) and Texas' State Energy Conservation Office (SECO). TTI and Mack Trucks Inc. provided expertise regarding the LFG-to-CNG conversion process, and conducted the pre-feasibility economic analysis. NEERI contributed their significant expertise on India's landfills, waste management operations, and data collection for all the case studies. SECO provided guidance based on their energy experience and an existing TTI project with SECO examining similar issues in Texas. The findings from this research are expected to contribute to the overall goal of improving and promoting efficient MSW management in India and other developing nations.

Study Approach

Three candidate landfills in the city of Mumbai (in the state of Maharashtra, India) were selected for the pre-feasibility analysis. The LFG-to-CNG conversion process that was considered was the CO_2 Wash Process™ developed by Mack in association with Acrion Technologies. Appendix A provides the details of the CO_2 Wash Process. In addition to this option of conversion to a transportation fuel, a variety of other scenarios, including the do-nothing option, flaring, and electricity generation were considered from a cost-benefit perspective for comparison. The benefits considered for the various scenarios (as applicable) included emissions benefits, carbon credits, and fuel/energy savings from the use of LFG.

Report Overview

The section of the report following the introductory section deals with the characteristics of Indian landfills and specific details of the three study landfills in Mumbai. The next section discusses solid waste management and waste characteristics in Mumbai, followed by a section on Mumbai’s refuse collection fleet, fleet operations, and driving cycles. Following this, the study methodology for conducting the pre-feasibility analysis is discussed, including the different scenarios evaluated and the costs and benefits associated with each. The results section presents the results from the six scenarios studied for the three landfills under consideration. The overall project findings are then discussed in the concluding section.

LANDFILL CHARACTERISTICS

Landfills in India differ vastly from those in the U.S. Most landfills in India can be considered controlled open dumps rather than engineered or lined landfills. A controlled open dump is a section of land that has been appropriated for the disposal of all waste. In the U.S., however, landfills are designed depending upon the waste that will be placed in there under the Resource Conservation and Recovery Act (RCRA). Various subtitles under the RCRA cover different types of waste, including municipal solid waste, hazardous waste, and construction debris.

In an attempt to improve the waste disposal process and promote the use of sanitary engineering for landfills, the Indian government enforced a set of regulations termed as the MSW Management and Handling Rules in 2000. Despite this, most Indian dumping sites and landfills also have many other challenges not present in the U.S. In addition to open dumping, the landfills are near areas that are inhabited by people who rely on the collection and sale of recyclables found in the landfill to make a living. Many homeless people end up as squatters at these sites. An informal recycling trade exists, in which persons, referred to as “rag pickers,” collect and sell recyclable materials found at these sites. Rag pickers sometimes set the waste on fire to recover metals from the waste with the help of magnets. Due to the CH_4 emissions from the landfills, the fires stay lit, or can even spread, causing safety hazards and issues with smoke and dust. The next segment of this report addresses socio-economic and environmental issues related with Indian landfills in further detail.

Socio-Economic and Environmental Issues in Indian Cities

The main socio-economic issue with respect to the impact of the landfills in Indian cities is related to the rag pickers who earn a livelihood from the landfills. The main environmental concerns relating to landfills in urban areas are problems caused with air quality.

Waste pickers or rag pickers are among the poorest workers in the urban economy of India. They earn their livelihood from the collection, segregation, and sale of scrap (recyclable waste) for recycling. Their work in separating recyclable material from the waste occurs both during the door-to-door collection of waste from households, and at the landfill sites themselves. There are about 20,000 rag pickers working in Mumbai’s landfill sites and collect approximately 1,050 metric tons of recyclable waste per year, which was sold for between $11 million-$15 million. However, rag pickers themselves face severe poverty, earning between $1.50 and $2 per day, and come from traditionally marginalized sections of society (85 percent are women, 5 percent are children; they generally belong to castes/classes of people who traditionally face discrimination). Most rag pickers are landless laborers who migrate to Mumbai from other drought-prone areas of Maharashtra.[2,3] There are various Non-Governmental Organizations (NGOs) that coordinate with rag pickers and try to improve their livelihood and quality of life. The agencies working in this sector in Mumbai include AKAR Mumbai, SMS, FORCE, Clean Mumbai Foundation, APNALAYA, Stree Mukti Sanghtana, and others. The NGOs train the rag pickers in identifying the recyclable and non-recyclable materials, and encourage the separation and collection of recyclable waste at the source (households) rather than at the landfills/dumpsites. There is strong support emerging for these NGOs, and they are being supported in many localities to help provide a place for sorting and selling the dry waste.

Air quality has been a major issue near all the landfill sites, where the local residents have protested against the smoke and dust generated due to illegal fires set at the landfills. In some areas, local residents in the Maharashtra High Court to seek relief from these problems have filed public interest litigations (PIL). Monitored air quality data also indicates poor air quality in the downwind areas of landfills within a distance of about 1-1.5 kilometers. Due to the litigation filed, and the increased attention given to this problem, attempts are being made at many landfill sites to improve the situation by providing stricter monitoring, fire hydrants, and other mechanisms to improve the air quality near landfills.

The provisions of the MSW Management and Handling Rules of 2000 did stipulate that existing landfills are brought to sanitary standards, with a compliance date of December 2002.[4] However, the compliance to this is very low, and conversations with sources in India indicated that there are very few cases of existing landfills being capped or brought to sanitary conditions, and that these were conducted only to comply with court orders brought on by public litigation. Thus, a majority of landfill sites in India still operate as open dumps, and special consideration is needed for the socio-economic and environmental aspects as discussed in this section.

Case Study Landfills

The city of Mumbai is located in the state of Maharastra in India. Three landfills in this city were selected as case studies for this project. In the greater Mumbai area, solid waste is dumped into open landfills at two different locations – the Deonar and Mulund dumping sites. Another location, the Gorai dumping site, was closed for solid waste dumping in 2008. Figures 1 through 3 contain aerial views and pictures from the three landfill sites.

Figure 1. Picture and Aerial View of Mulund Dumping Site

Figure 2. Picture and Aerial View of Deonar Dumping Site

Figure 3. Pictures of Gorai Dumping Site

Table 2 presents details of the three sites with regard to life, waste quantity, site area, and related information. As the table shows, the oldest and largest dumpsite is Deonar, which began operating in 1927. All these sites are located in low-lying areas close to marine water bodies and mangrove vegetation and have operated as open dumps without traditional sanitary landfill designs.

Due to the regulations in the MSW Management and Handling Rules, which were enacted in 2000, attempts have been made improve some of these open dump sites with proper engineering measures. For example, the Gorai site has been closed for operation and the waste in place (WIP) is being covered with geosynthetic liners with the goal of extracting methane gas to flare or to use for energy generation. Deonar is also planning to cover part of its WIP and develop the remainder of the site with environmentally sound sanitary landfill cells and processing facilities such as composting.

Table 2. Mumbai Landfill Site Details

Data	**Site**		
	Deonar	**Mulund**	**Gorai**
Type of landfill	Open Dumpsite	Open Dumpsite	Open Dumpsite
Landfill size	132.1 Ha	25 Ha	19.6 Ha of which 17.7 Ha used for dumping
Waste in place (as of Jan 2006)	7.88 million metric tons	0.94 million metric tons	1.76 Million metric tons
Designed landfill capacity	Not designed	Not designed	Not designed
Waste Depth	5 - 7 m	3.6 m	10.2 m (Nov 2005)
Year filling began	1927	1968	1972
Year landfill was closed or will close	Partial closure planned in 2008-09	Not yet planned	2008
Quantity of waste collected per day	5,000 metric tons with 1,000 metric tons of construction and demolition waste	400 metric tons with 100 metric tons of construction waste	2,000 metric tons (mixed waste)
Quantity of waste accepted annually at landfill	1,496,500 metric tons	2,266,000 metric tons	438,000 metric tons
Quantity of waste generated per capita	0.4 – 0.5 kg	0.4 - 0.5 kg	0.4 – 0.5 kg

SOLID WASTE MANAGEMENT OPERATIONS IN MUMBAI

It was estimated that the Greater Mumbai area generated approximately 5,320 metric tons of solid waste each day in 2001.[5] This increased to approximately 6,000 metric tons per day (TPD) of MSW at the rate of 0.475 kilograms per capita per day in 2006.[6] In addition, approximately 2,400 TPD of construction and demolition waste was also generated.[7] It was estimated that by 2008-2009, the total waste generated from Mumbai will aggregate about 9,000 metric TPD due to the increase in the city's population.[5] According to MCGM, currently Mumbai generates up to

8,500 metric tons of waste per day. This is comparable with a city like New York, where the sanitation department's collection levels were estimated at nearly 60,000 tons per week (8570 tons per day).[8]

MCGM is responsible for the management of waste in the city. The prevailing approach has been the collection from various locations, and transportation and disposal of waste in open dumps. Garbage is collected from community bins by the municipal authorities and disposed of at the two main dumping sites currently being used. Earlier, the Gorai landfill was also used for waste dumping, but it was recently closed to further dumping, having reached its full capacity.

Waste Characterization

The largest source of solid waste generation in Mumbai is domestic waste. Apart from this household waste, the following are also sources of considerable amounts of MSW in Mumbai:[6]

- commercial waste;
- hotel and restaurant waste;
- market waste;
- institutional wastes, i.e., schools, offices, hospitals, etc.;
- street sweepings;
- silt removed from drain cleaning; and
- construction wastes such as earth, stones, sand, etc.

In terms of the waste composition, the municipal solid waste of Mumbai can be classified as biodegradable waste, recyclable and non-recyclable waste, and silt or debris.[5] The biodegradable waste (wet waste) is comprised of vegetable and fruit remainders, leaves, spoiled food, eggshells, cotton, etc. Recyclable (dry waste) consists of newspapers, thermocol (polystyrene), plastic, battery cells, wires, iron sheets, glass, etc. Debris includes construction waste, renovation waste, demolition waste, etc. Silt is comprised of earth and clay from drains and road corners.

NEERI's analysis of Mumbai MSW composition indicated that the total compostable waste comprised approximately 55 percent of the total. The non-compostable matter consists of both recyclable materials (i.e., paper, plastics, glass, and metal) and inert materials (i.e., rubber, leather, rags, wooden matter, coconut shells, and bones). Table 3 shows the results from the analysis of Mumbai's MSW composition. The NEERI analysis also indicated that the MSW had a Carbon-to-Nitrogen Ratio (C/N Ratio) of 39.04, a Hydrocarbon Value (HCV) of 1786 Kcal/Kg and a moisture content of 54 percent.

Table 3. Waste Characteristics of Mumbai MSW

Waste Type	Detail	Quantity (%)	Total (%)
Total Compostable		55.25	**55.25**
Recyclables	Paper	8.85	**20.50**
	Plastic	10.30	
	Glass	0.92	
	Metal	0.44	
Other Including Inerts	Inerts	14.42	**24.25**
	Rubber& Leather	1.51	
	Rags	4.24	
	Wooden Matter	0.87	
	Coconut	3.30	
	Bones	0.20	
Total		**100**	**100**

Source: NEERI's analysis, 2007-2008.

Collection and Transportation of Waste

In Mumbai, individual households and other waste generators are responsible for transporting waste to local "community bins" where they are collected by MCGM. There are around 5,800 community bins in the city.[6] Garbage collectors are employed by housing societies (conglomerate of flats/residential communities) who collect the garbage manually and dump it into the community bins. After that, the MCGM's Solid Waste Management system takes over.

MCGM employs over 35,000 people for the manual collection of waste and transportation to the various dumping sites. It operates a fleet of 989 vehicles – both owned by the municipality and private contractors - for waste collection. MCGM spends about Rs.1.5-2.0 million ($30,000-40,000) per day collecting and transporting garbage and debris.[5] The MCGM's 2008-09 budget has allocated approximately Rs. 3.47 billion ($69 million) for MSW collection and transportation in Mumbai.[9] Continuing the comparison with US cities, while Mumbai's waste generation levels are found comparable to New York, MCGM's fleet size is much lower than the New York City Department of Sanitation's collection fleet of over 2000 vehicles[8]. This is probably compensated for by the high levels of manual labor used for collection in Mumbai.

Vehicle Fleet Information

MCGM uses both municipal and private contract vehicles for collecting and transporting waste. Waste is collected from the community bins and transported to the dumping sites at Deonar and Mulund. These vehicles used for transportation of the waste generated in Mumbai make 1,600 trips each day.[10] The number of municipal and private vehicles is 312 and 677, respectively. Table 4 provides additional details of the types of vehicles used.

Table 4. Type of Vehicles Used by MCGM for Transportation of Waste

Vehicle Type	Municipal	Outsourced	Total
Dumper (Big)	117	313	430
Dumper (Small)	-	258	258
Small Tipper (1 Ton)	-	106	106
Dumper Placers (Skip Vehicles)	89	-	89
Tippers (8 Ton)	90	-	90
Stationary Compactors	16	-	16
Total	312	677	989

Source: http://mumbainews.wordpress.com/2008/03/04/clean-up-mumbai/.

From an emissions and operational standpoint, a fleet of 793 vehicles (excluding the tipper trucks shown in Table 4) has been considered for the calculations. For the purpose of identifying emissions and driving characteristics, they have been classified as stationary compactors, TATA dumper placers (dumper placers or TDP), and dumpers. For the dumper category, both the 430 big dumpers and 258 small dumpers are considered. Similarly, 89 dumper placers and 16 stationary compactors have been considered for calculations in the report. The small tippers and tippers are not considered, as they are not used for the transportation of waste in the city. They mainly operate at the landfill site for management of waste within the landfill location itself.

Driving Characteristics of Refuse Fleet Vehicles

This section provides an overview of the driving routes of the three types of fleet vehicles as well as details for their driving patterns. To study the driving pattern of refuse fleet vehicles, they were followed by NEERI researchers and tracked using a Global Positioning System (GPS). GPS provided the information about the speed, stoppage time, and distance traveled.

This information on the driving patterns, i.e. speed and acceleration profiles are important when studying environmental effects of traffic. It is also used to estimate fuel consumption and emissions from the vehicles. The following parameters were assessed using the GPS data and other observations:

- total distance covered;
- speed of the vehicle;
- acceleration time;
- deceleration time; and
- idling time (for stoppage due to traffic signals, waste pickup, and disposal of solid waste at the landfill site).

The findings, including general route information and specific drive cycle details, are presented in this section for the three vehicle types.

Stationary Compactor

These are the large compactors that are located in residential and market areas where they collect waste for a 24-hour period. The waste from the stationary compactor is then disposed by the towing the compactor to the landfill site. A trailer carries an empty stationary compactor from the ward office and then replaces the filled stationary compactor with the empty one at the particular site where it is placed. The filled stationary compactor is then taken to the landfill site where it is emptied. Thereafter, the empty stationary compactor returns to the ward office location. These compactors have a capacity of about 1,500 metric tons, and Figure 4 shows a picture of this type of vehicle.

Figure 4. Stationary Compactor

This stationary compactor was followed from Worli Transfer Station through the collection point (where a full compactor is replaced by an empty one), disposal of waste at landfill site and back to the transfer station. Figure 5 shows the route followed by stationary compactors while Figure 6 shows the speed profile based on the collected GPS data.

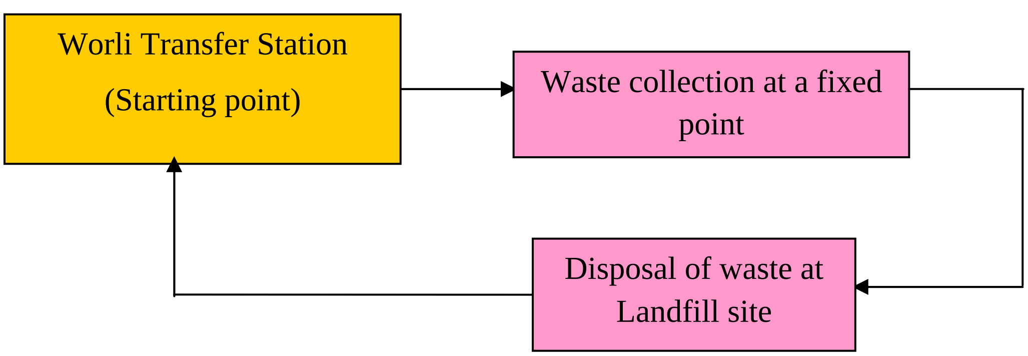


Figure 5. Route for Stationary Compactor

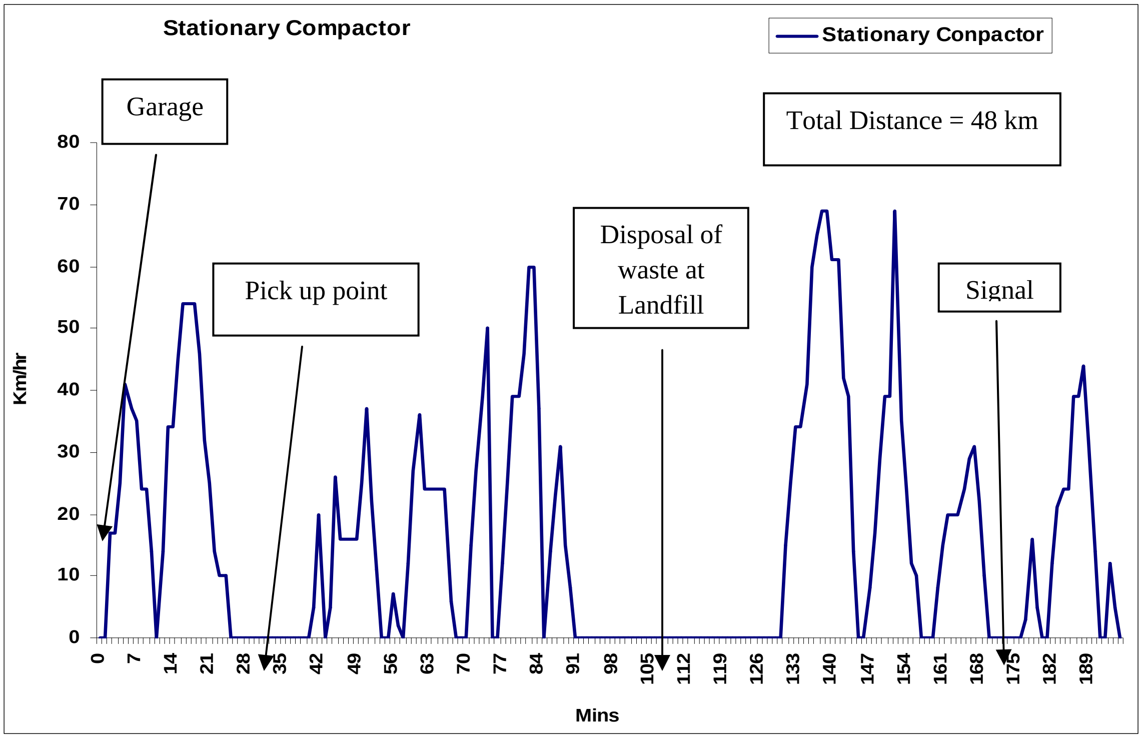


Figure 6. Speed Profile for Stationary Compactor

The data in Table 5 summarizes a complete cycle of a stationary compactor run. For one complete run, the maximum time required by the vehicle was 195 minutes and maximum distance covered was 48 km, as obtained from an original run and two sets of follow up runs. The vehicle had an average speed of 30 km/hr and a maximum speed reaching 69 km/hr. The driving pattern also indicates that about 40 percent of the time is spent idling. The idling time is due to collection of solid waste (15 minutes), disposal of waste at landfill site (40 minutes) and waiting in congested traffic and at signals.

Table 5. Summary of Driving Pattern Parameters – Stationary Compactor

Parameters	**Unit**	
Total time	min	195
Average Speed	km/hr	30
Distance covered	km	48
Max Speed	km/hr	69
Idling	% time	40.00
Acceleration	% time	26.67
Constant speed	% time	11.28
Deceleration	% time	22.05

TATA Dumper Placer

These vehicles are responsible for replacing filled community bins with empty bins at various locations around the city. These vehicles begin their journey for waste collection from their respective ward offices with an empty community bin. From the ward office, these vehicles travel to the bin location, where the filled bin is picked up and replaced with an empty one. This filled community bin is transported to the Worli Transfer Station, where the garbage is collected for later transportation to the landfill site. Figure 7 shows this type of vehicle.

Figure 7. TATA Dumper Placer

For studying the driving pattern of TDPs, these vehicles were followed from the ward office to the collection point and then to the disposal of waste at the Worli Transfer Station. Figure 8 shows the route followed by the TDP while Figure 9 shows the speed profile based on the collected GPS data.

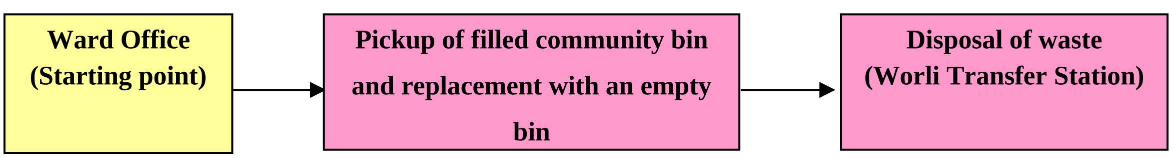


Figure 8. Route for TATA Dumper Placer

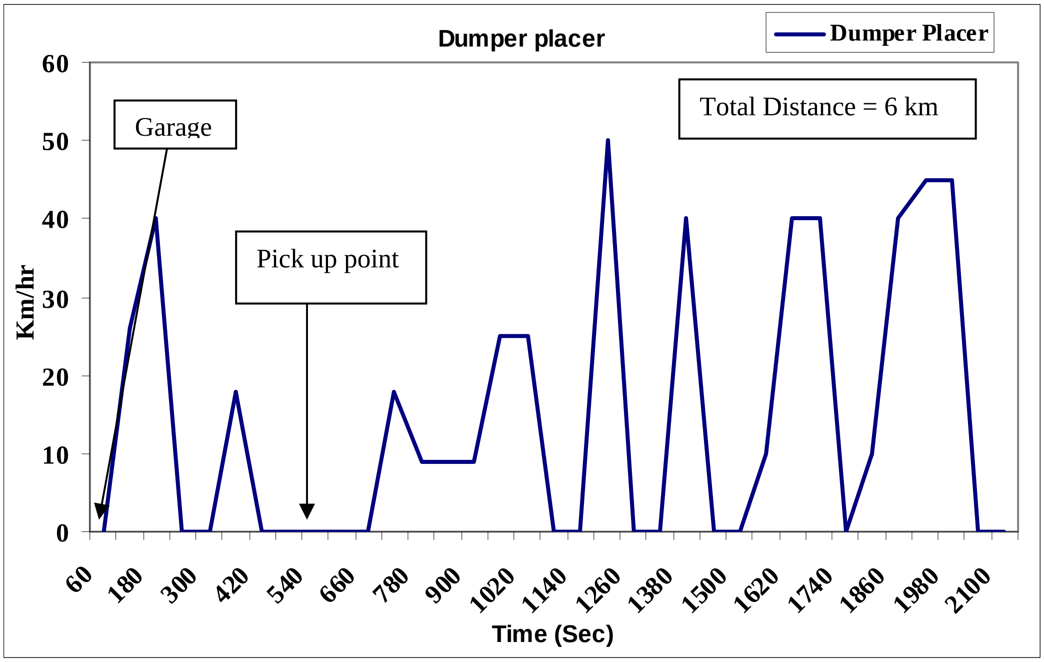


Figure 9. Speed Profile for TATA Dumper Placer

Table 6 presents the distance covered for solid waste collection along with other details. The distance covered by the TDP for a single run is quite short, as it only collects the waste from a community bin and disposes it at the transfer station. This is the end of the cycle for TDP, which can then make additional trips to other community bin locations. The larger filled bins in the transfer station are directly taken to landfill site where they are emptied (similar to the stationary compactors). A TDP covers a distance of about 6 km in a single trip. They operate in two shifts, one from 7 a.m. to 2 p.m. and another from 2 p.m. to 9 p.m. and complete six trips for waste collection and disposal in each shift. Thus, a total of 12 daily trips are made by a single TDP. The table also shows total time taken by a TDP for its single trip. It takes about 35 minutes for a trip with an average speed of around 23 km/hr. The idling percentage for the vehicle was about 42 percent, which included pick-up time and delay due to traffic congestion.

Table 6. Summary of Driving Pattern Parameters – TATA Dumper Placer

Parameters	**Unit**	
Total time	min	35
Average Speed	km/hr	23.66
Distance covered	km	6
Max Speed	km/hr	50
Idling	% time	42.86
Acceleration	% time	25.71
Constant speed	% time	8.57
Deceleration	% time	22.86

Dumper

The dumper collects waste from different community bins and then disposes of it at the landfill site. There are two types of dumpers, big and small dumpers. The capacity of big dumper is one metric ton. These dumpers collect waste from different community bins over a period of 24 hrs. The dumpers directly carry the waste to the landfill site for disposal. Figure 10 shows a typical dumper.

Figure 10. Dumper

To study the driving pattern of the dumper, the vehicles were followed from the G North Garage location, at the beginning point, through waste collection from different community bins (mainly in the vegetable market area), and disposal at the landfill site. Later, the dumper returns to the garage. Figure 11 shows the route followed by the dumper, while Figure 12 shows the speed profile as collected from GPS data.

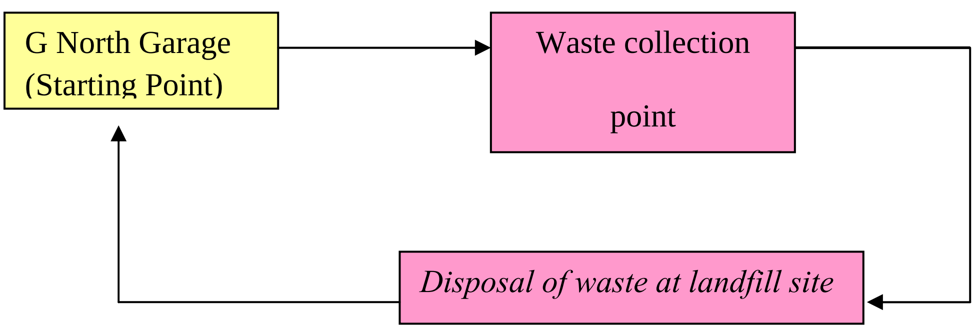


Figure 11. Route for TATA Dumper Placer

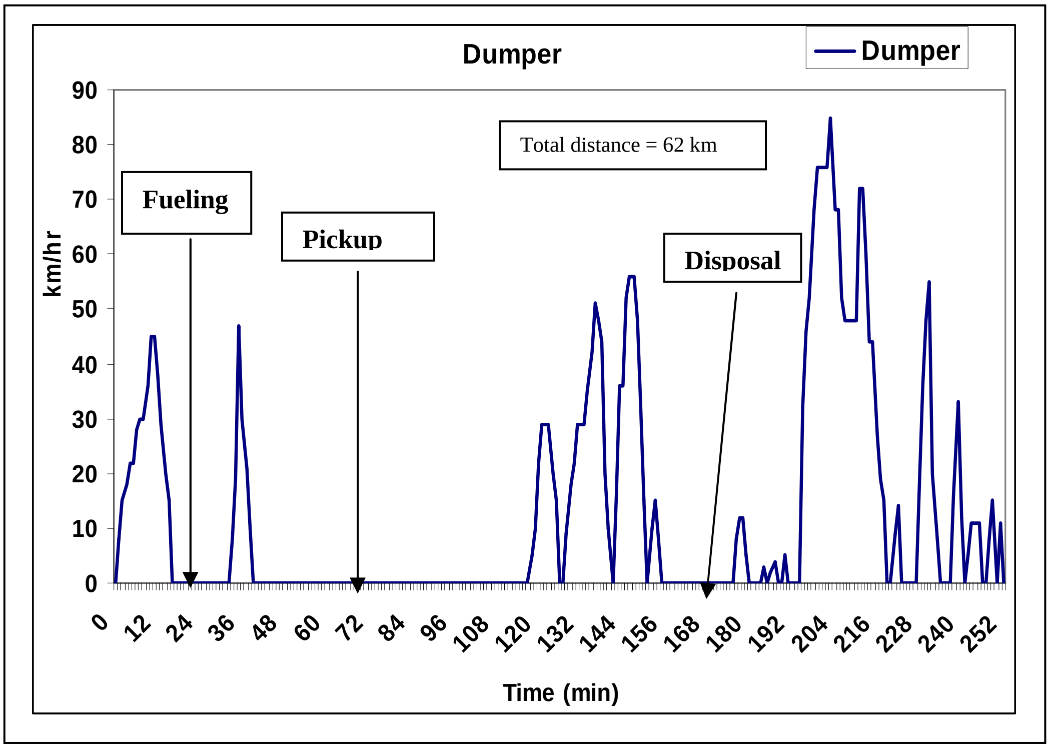


Figure 12. Speed Profile for Dumper

Table 7 presents the total distance covered for collection of solid waste and other details. It covers about 62 km in a single trip. The table also shows the total time taken by a dumper for the trip. It takes about 252 min for a cycle and during this period it travels at an average speed of 31 km/hr. The idling percentage was about 58 percent, which included diesel filling, pick-up time, disposal and traffic congestion.

Table 7. Summary of Driving Pattern Parameters –Dumper

Parameter	**Unit**	
Average Speed	km/hr	31
Total time	min	252
Distance covered	km	62
Max Speed	km/hr	85
Idling	% time	58.3
Acceleration	% time	21.4
Constant speed	% time	7.5
Deceleration	% time	12.7

Concluding Remarks

This section of the report provided an overview of the waste management operations in Mumbai. Details of the three landfills under study for the pre-feasibility analysis (Gorai, Deonar, and Mulund) and the waste composition details were provided. Vehicle fleet data, routes, and drive cycle details were also presented. The following sections of the report concern the analysis methodology, the benefits and costs associated with the LFG-to-CNG conversion process, and the results and findings from the pre-feasibility analysis.

METHODOLOGY

The introductory section of the report discussed in general terms the options for collecting and disposing or making use of LFG. For conducting a pre-feasibility analysis that involved examining costs and benefits, a total of six scenarios were chosen to examine which option is most financially viable, and to compare the LFG-to-CNG option with other possibilities.

Identification of Analysis Scenarios for Pre-Feasibility Analysis

The discussion in the introductory sections of this report indicated that there are two major aspects that need consideration in analyzing the feasibility of using LFG as an energy source for the Mumbai landfills:

- As with most landfills in India, the land filling practices at the three case study locations are not completely sanitary and satisfactory. There are costs as well as socio-economic and environmental benefits associated with setting up a sanitary landfill system at these landfills. Such sanitary landfills would also allow for collecting LFG for use in other applications.
- The next step beyond setting up a sanitary landfill and LFG collection mechanisms would be to implement the various LFGTE projects, for example, using the LFG as a transportation fuel or converting it to electricity. These would have an additional set of costs and benefits.

Thus, in an ideal situation, the pre-feasibility analysis would be performed in two distinct steps, one that considers the costs and benefits of converting an open dump to a sanitary landfill, and a second step that focuses on the costs and benefits of implementing an LFGTE project at the landfill. These can be viewed as two phases of projects, the first being setting up the landfill to enable collection of LFG, and the second phase that makes use of the collected gas.

However, conducting a separate analysis for the costs and benefits of converting the landfill into a sanitary landfill (through capping and installation of gas collection mechanisms) alone was not conducted in this analysis. This is because the benefits associated with such a process could not be readily isolated and quantified. It was only when further measures were considered such as doing something with the captured LFG (such as flaring, or conversion to energy) that the benefits could be readily assessed, and these scenarios are included in the analysis.

Another aspect to consider is the concept of incremental costs (also termed as differential costs). In the context of engineering economics and benefit-cost analyses, it refers to differences in cost for certain “with or without” situations.[11] For example, in this analysis, the infrastructure for an LFGTE project might cost less if it is implemented during the capping/installation of gas collection systems, rather than being implemented separately. These cost differences are not considered from the perspective of a pre-feasibility analysis, and can be considered when performing a more nuanced and case-specific feasibility analysis.

This research grouped the possible scenarios into two categories, termed as landfill management practices and LFGTE practices. A total of six analysis scenarios were selected and applied for the three case study landfills over a 20-year analysis period. These scenarios cover various options for collecting and disposing or using LFG, and are:

Landfill Management Options:

1. Do Nothing;
2. Cap the landfill and flare the LFG; or
3. Flare the LFG from an active landfill.

LFGTE Options:

4. Convert the LFG to CNG to use as a transportation fuel;
5. Convert the LFG to pipeline grade natural gas; or
6. Convert the LFG to electricity.

Scenario 1 is the do-nothing option that represents the baseline conditions under which no LFG collection or conversion of the landfill to a sanitary landfill is conducted. Scenario 2 involves capping the landfill and installing a gas collection system before flaring the LFG (controlled combustion). Scenario 3 involves installing gas collection wells for flaring from an active landfill, and thus does not require the additional cost of capping. Flaring LFG helps convert CH_4 into CO_2, which is a less harmful GHG. The three remaining scenarios are LFGTE options that involve the costs for capping and collection systems, along with additional infrastructure costs.

Numerous costs and benefits are associated with each option and some of them are common to more than one scenario. Table 8 summarizes the types of benefits and costs associated with each of the scenarios. As previously stated, the analysis period considered for all the scenarios was 20 years.

Table 8. Summary of Costs and Benefits Associated with Each Scenario

Description	**Scenario**					
	1	**2**	**3**	**4**	**5**	**6**
Benefits						
Diesel or Natural Gas Savings				X	X	
Electricity Conversion						X
Carbon Credits		X	X	X	X	X
Fleet Turnover Emissions Reduction*				X		
Costs						
Landfill Capping Costs		X		X	X	X
CNG Facility and Operation Cost				X		
Pipeline Natural Gas Facility and Operation Cost					X	
Electricity Plant and Operation Cost						X
Flaring System and Operation Costs		X	X			
Cost of Emissions	X					

** Instead of considering the refuse truck fleet, the bus fleet can be considered as an alternative scenario.*

The reasoning behind consideration of these costs and benefits, and the calculation methodology for these is provided under the "costs" and "benefits" sections in the following pages. Before considering individual costs and benefits, however, it is necessary to estimate the quantity of gas generation for each landfill, as this forms the basis for all the other calculations.

Estimating Landfill Biogas Generation

As stated previously, estimating the LFG production from open-dump landfills and furthermore the CH_4 potential from that LFG quantity is extremely difficult. Since a majority of the scenarios considered landfill closure, the methodology for acquiring an estimate of the LFG potential was developed using the EPA's 1997 modeling equation for closed landfills shown in Equation 1a. For Scenarios 1 and 3 alone, the equation for an active landfill (Equation 1b) was used.

$$Q_t = 2 * L_0 * m_0 * \left(e^{k*t_a} - 1\right) * e^{-k*t} \qquad (1a)$$

$$Q_t = 2 * L_0 * m_0 * \left(1 - e^{k*t}\right) \qquad (1b)$$

Where Q_t = expected gas generation rate in the t^{th} year, m^3/yr;

L_o = methane generation potential, m^3/yr;

m_o= constant or average annual solid waste acceptance rate, Mg/yr;

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

t = age of the landfill, yr; and

t_a = total years of active period of the landfill, yr.

The EPA conducted a pump test at the Deonar landfill in August of 2007. The pump test provided modeling inputs that were used in Equations 1a and 1b. The CH_4 generation potential, L_o, was found to be equal to 68 cubic meters per mega-gram or metric ton (m^3/Mg). The test report also stated that the CH_4 generation rate constant, k, for this region is 0.40 for organic waste (e.g. food), 0.08 for medium decay organic waste (e.g. paper), and 0.02 for slow decay organic waste (e.g. rubber).[12] Table 3 from the previous section provides the waste composition of the landfills in the greater Mumbai area. By taking the composition of each type of waste and multiplying it by its respective rate constant, a rate constant could be developed for the entire landfill. This is shown in Equations 2 through 5.

$$\text{Total Compostables} = 55.25\% * 0.40 \text{ for organic waste (OW)} = 0.221 \tag{2}$$

$$\text{Paper} = 8.85\% * 0.08 \text{ for medium decay OW} = 0.00708 \tag{3}$$

$$\text{Plastics and Inert Materials} = 35.9\% * 0.02 \text{ for slow decay OW} = 0.00718 \tag{4}$$

$$\text{Total for entire landfill, } k = 0.221 + 0.00708 + 0.00718 = 0.23526 \tag{5}$$

Therefore, the k value used for the Mumbai landfills was 0.235. This value is within the suggested range of proper k values for this region taken from published literature on this subject. Table 9 shows the ranges and suggested values.[13]

Table 9. Range and Suggested Values for L_o and k

Parameter	Range	Suggested Values
Lo (ft3/lb)	0 ~ 5	2.25 ~ 2.88
Lo (m3/Mg)	0 ~ 310	140 ~ 180
K (yr-1)	0.003 ~ 0.40	Wet Climate 0.10 ~ 0.35
		Medium Moisture Climate 0.05 ~ 0.15
		Dry Climate 0.02 ~ 0.10

** Source – Reference 11.*

The average acceptance rate per year, m_o, was calculated by taking the measured WIP and dividing by the number of years the landfill has been in existence. As an example, the Deonar landfill had a WIP in 2007 of 9.2 million Mg (metric tons). Including an additional 3.285 million Mg each for the years 2008 and 2009 produced an estimated total WIP when closure would occur. The 3.285 million Mg value was the suggested waste acceptance rate for the years 2008-2009 based on population growth and current per capita waste measurements. The total estimated WIP would equate to 15.77 million Mg. This value was divided by the number of years the landfill was open, producing an annual average acceptance rate of 192,317 Mg/yr. Similarly, the annual average acceptance rates were calculated for the other two landfills, Gorai and Mulund equaling 73,222 Mg/year and 188,732 Mg/yr respectively. This method was used due to the age of the landfills and the fact that data was not available for each year's waste acceptance value (which could provide a little more accuracy in the gas estimation procedures).

Based on all the components discussed above, the 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 LFG that will be generated from the site. In most instances, when a LFG collection system is installed, the collection system will not be 100 percent efficient in collecting the emitted LFG.

The efficiency assumed by the EPA for the Deonar Landfill was 47 percent in a recent study.[12] A 50 percent LFG collection efficiency was assumed in the calculations for this report. Taking the LFG generated each year and multiplying by the LFG collection efficiency results in the total amount of LFG that can be captured in a given year, as shown in Equation 6.

$$\text{Recoverable biogas} = \text{LFG per year}\left(\frac{m^3}{yr}\right) * \text{LFG efficiency (\%)} = Q_t * 0.5 \qquad (6)$$

Estimating Natural Gas/ CH_4 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 British Thermal Units (BTU) per cubic foot due to the consensus that LFG is comprised of 50 percent CH_4. Natural gas has a BTU value of 1,028 per cubic foot.[14] By equating the energy content of LFG and natural gas, and using simple unit conversions, an equivalent mcf (1,000 ft^3) of natural gas produced can be calculated (see Equation 7). It should be noted here that the calculations presented in this report use the unit "mcf" to represent on thousand cubic feet, as is standard notation. This is not to be confused with "Mcf", which is sometimes used to signify a quantity of one million cubic feet.

$$\text{mcf of Natural Gas Produced} =$$
$$\text{Recoverable Biogas}\left(\frac{m^3}{yr}\right) * \text{cubic feet per cubic meter (35.315)} \div 1{,}000\left(\frac{ft^3}{mcf}\right) * \left(\frac{500}{1028}\right) \qquad (7)$$

The LFG produced has been equated to natural gas in terms of BTU values. CH_4 comprises more than 80 percent the total composition of natural gas, which allows the use of both terms with relatively equal values and terminology in this study. Additionally, the natural gas provided in piped gas supply for residences and similar purposes is generally 100 percent CH_4. Thus, the pure CH_4, which is being produced, is considered equivalent to natural gas, and the sole comprising component in LNG and CNG.[1] By determining a cost for 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 8. This calculation for the value of natural gas produced will be considered while examining the benefits of the various scenarios in the pre-feasibility analysis.

$$\text{Annual mcf of Methane} * \text{Cost of 1 mcf of natural gas} = \text{Annual value (\$)} \qquad (8)$$

Natural Gas Generation for Mumbai's Landfills

Based on the methodology previously presented, the quantity of CH_4 or dry natural gas that can be extracted from the three landfills – Deonar, Mulund, and Gorai – was calculated over 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, with corrections made for Gorai which was closed in 2008). The table in Appendix B provides the details of the calculated LFG generation, recoverable LFG and the CH_4 equivalent. Table 10 summarizes the main results. These values can be equated with monetary values to determine feasibility for the various LFGTE projects. For example, if the LNG is used as a transportation or truck fuel source, the first benefit received would be the cost savings from no longer needing to purchase diesel fuel over the next 20 years.

Table 10. Recoverable Dry Gas for Entire Analysis Period

Landfill	**Recoverable dry gas over 20 year analysis period (mcf)**
Deonar	1,063,846
Mulund	1,043,927
Gorai	404,960

Gas Generation Quantities

One aspect of LFG production in a closed landfill is that LFG production rate is not consistent over a period of time, but rather decreases. Figure 13 shows the projected gas generation quantities for the three case study landfills post-closure. It can be seen that gas generation quantities for Mulund and Deonar are similar, and much higher than for the Gorai landfill. Another aspect is that the generated quantities must be large enough to justify the investment in infrastructure for LFGTE projects. While these factors have not been given explicit consideration in the pre-feasibility analysis, the quantity of LFG capable of being produced on a daily basis over a reasonable lifetime period is something that should factor into decision-making. This is especially true for the LFG to Transportation fuel option, where a steady supply of fuel is desirable to operate the trucks. For example, previous research has indicated that 1-2 million cubic feet of landfill gas generation per day (resulting in LNG/CNG production of 5000-10000 gallons) is desirable for long-term viability. [15,16] None of the three Mumbai landfills, however, are estimated to produce gas quantities in this range for an extended period of time. For example, the Deonar landfill, for which the highest gas generation quantities are projected, is shown to produce over 6000 gallons per day in the first year of analysis, but due to decreasing gas generation quantities will only average approximately 1430 gallons per day over the 20 year period.

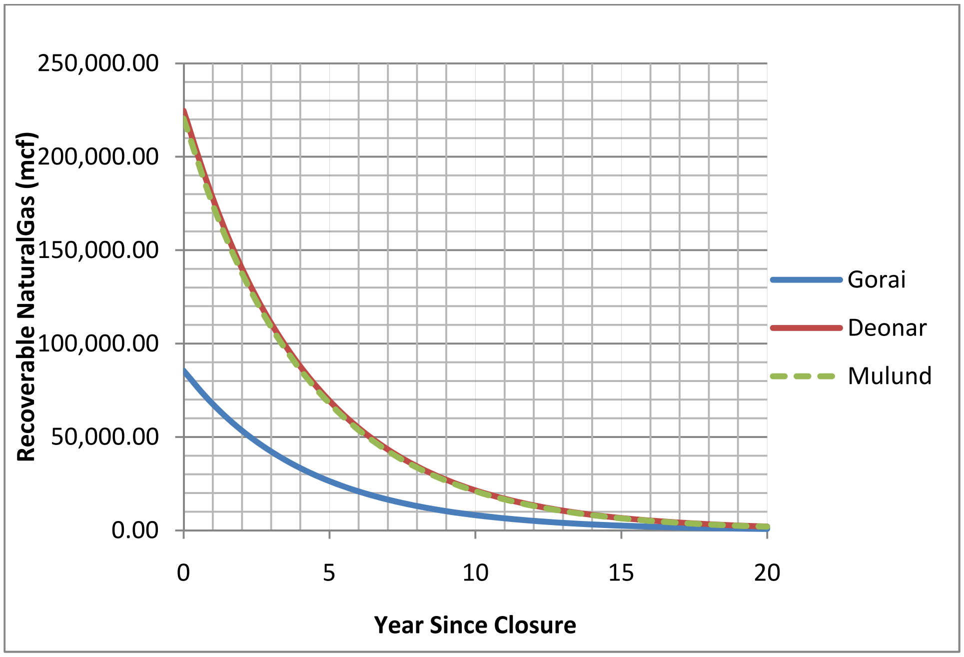


Figure 13. Recoverable Natural Gas Quantities Generated for Case Study Landfills

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, earnings from fuel savings or 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.

Diesel and Natural Gas Savings

When the natural gas recovered from LFG is used either as a transportation fuel or sold as piped natural gas (Scenarios 1 and 2), the savings due to either not purchasing diesel, or though the sale of natural gas, can be estimated as benefits. Since future energy prices are hard to predict, the price associated with each mcf of gas and each gallon of diesel should be estimated based on the cost of that commodity over the next 20 years. Based on historical market prices for natural gas and diesel, the prices selected were $4.57/mcf of gas and $2.60 per gallon of diesel.[17] The natural gas price was chosen because it is the average global market price for an mcf of natural gas since 1994.[18] Similarly, $2.60 has been the average market price of all types of diesel over the past five years. Market conditions in India are different in that the sale of diesel and petroleum products are highly regulated and heavily taxed. However, the costs assumed are considered to be reasonable assumptions for this analysis.

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[14] (see Equation 9). This produces a conservative estimate of the value of energy savings, due to the consideration of true energy equivalents, as well as considering lower collection efficiency for the Indian scenario.

$$1{,}028{,}000 \text{ BTU (NG)} \div 139{,}000 \left(\frac{Diesel}{gal}\right) = 7.3957 \text{ gallons equivalent} \qquad (9)$$

The cost savings from not purchasing diesel fuel over the next 20 years was calculated by estimating the diesel gallons equivalent to the natural gas produced, and computing the NPV of these savings. Appendix C contains detailed results for these cost savings. Table 11 summarizes the NPV of the savings for the three landfills over the entire analysis period.

Table 11. Diesel Savings for Entire Analysis Period

Landfill	**NPV of Savings in Diesel Costs over 20 year analysis period ($)**
Deonar	18,493,762
Mulund	18,147,497
Gorai	7,039,782

For the alternative of selling natural gas, as stated above, the value associated with one mcf of natural gas was $4.57. This value was used to calculate earnings from an LFGTE project in which the LFG was sold as natural gas. This is also presented in a detailed table in Appendix C. Table 12 summarizes the NPV of the earnings for the three landfills over the entire analysis period. It should be noted here that for both the diesel and natural gas sales 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 percent inflation rate. Since 2002, the U.S. Bureau of Labor Statistics has estimated an average inflation rate of 2.5 percent , thus considering 3 percent inflation is a conservative estimate.[19]

Table 12. Earnings from Natural Gas for Entire Analysis Period

Landfill	NPV of Earnings from Natural Gas over 20 year analysis period ($)
Deonar	4,395,313
Mulund	4,313,018
Gorai	1,673,107

Earnings from Electricity Conversion

Conversion of LFG 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 one BTU was equated to 0.000293 Kilowatt-Hours (kWh) of electricity. By assuming a price of $0.1 per kWh of electricity, the value of the electricity generated was calculated. Due to the decreasing gas generation quantities over a period of time (as shown in Figure 13 and discussed previously), the analysis assumes an electricity plant capacity based on the average gas generation quantities over the first ten years of the analysis, rather than for the maximum gas generation that would occur immediately after closure. This implies that in earlier years of the analysis, the gas generation will exceed the electricity plant's capacity, and the remaining landfill gas will need to be flared (burned off) from the plant. The flared portion of the natural gas will earn carbon credits, which are explained in more detail in the next section. The carbon credits are also included in the earnings considered in the analysis. Again, these calculations were performed for a 20-year period and the NPVs calculated for each landfill. Appendix C shows the results for each analysis year. Table 13 summarizes the NPV values of the earnings over the entire analysis period, computed for each of the three landfills.

Table 13. Earnings from Electricity Conversion for Entire Analysis Period

Landfill	NPV of Earnings from Electricity Conversion over 20 year analysis period ($)
Deonar	23,151,700
Mulund	18,061,623
Gorai	9,232,430

Carbon Credits

Due to emerging political and societal requests for a reduction in global GHG emissions, carbon credit trading has emerged as a potential solution to this global issue. Thousands of tons of various emissions, most notably CO_2, CH_4, and oxides of nitrogen (NOx) are emitted from landfills each year. Some countries have passed cap-and-trade legislation, which 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 with its emissions or purchase offset emissions credits for the number of tons that you expect to exceed your imposed regulations. 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 grow fewer. The ability to cap a landfill and sell its carbon credits creates a huge economic return for landfill owners wishing to curb their GHG emissions and immeasurable societal benefits to the local communities.

In this analysis, the baseline is considered to be the “do nothing” scenario. By reducing GHG emissions below these baseline levels through LFGTE projects, carbon credits are considered to be earned. For use in the pre-feasibility analysis, a cost value needs to be assigned to these carbon credits. In India, there is currently a commodity exchange market known as the Multi-Commodity Exchange (MCX). The MCX currently only trades carbon credits based on carbon equivalents. A 1-carbon emissions reduction (CER) credit is equivalent to 1 metric ton of CO_2. Therefore, contaminants that are much more detrimental to the environment such as CH_4 would trade at their GWP.[20] GWP is considered to be the standard for converting other pollutants such as CH_4 into a carbon equivalent. CH_4’s GWP is 21, meaning that it is 21 times more harmful than CO_2. MCX is currently trading futures for May 2009 at a cost of $13.51 ($1 =50 Rs; 1 CER=691 Rs.). The same CER credits were trading for $15.15 in March of 2009.[20] A value of $13.82 was used 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. A more in depth analysis is required to develop more accurate estimates, but these values provide a conservative estimate of the earnings that would be produced from an LFGTE project.

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 atm @ 25°C) are 1.977 and 0.717 kg/m^3 respectively. Equations 10 through 12 provide examples of the calculation.

$$\text{Molecular Weight of } CO_2 = 44.01 \left(\frac{g}{mol}\right) \tag{10}$$

$$\text{Volume at Standard Temperature and Pressure} = 24.4658 \text{ L} \tag{11}$$

$$\rho = \frac{MW}{V} = \frac{44.01}{24.4658} = 1.799\left(\frac{g}{l}\right) = 1.799\left(\frac{kg}{m^3}\right) \quad (12)$$

Splitting the volume of CO_2 and methane into two equal parts (since it was assumed that the composition was 50 percent CH_4 and 50 percent CO_2) enables the LFG generated (m^3/yr) to be multiplied by the densities of CO_2 and CH_4 and then divided by 1,000 to provide the Mg of emissions per year (Equation 13).

$$1.799\left(\frac{kg}{m^3}\right) * \text{LFG generated}\left(\frac{m^3}{yr}\right) * 50\%\ CO_2 \div 1{,}000\left(\frac{kg}{Mg}\right) = \left(\frac{Mg}{yr}\right), \text{(metric tons)} \quad (13)$$

Based on the methodology outlined here, the earnings from carbon credits over a 20-year period, and the NPV of this were calculated for the three landfills as shown in Table 14. The earnings shown here are for the capture of all the GHGs that are generated. In the case of certain scenarios that involve flaring (which releases some level of GHGs), the earnings from carbon credits are reduced accordingly before consideration. Appendix C shows the detailed results.

Table 14. Earnings from Carbon Credits for Entire Analysis Period

Landfill	**NPV of Earnings from Carbon Credits over 20 year analysis period ($)**
Deonar	20,897,475
Mulund	20,506,557
Gorai	7,954,773

Using LFG as Transportation Fuel - Fleet Turnover Emissions Reduction

In the scenario where the LFG is captured and converted to natural gas for use as transportation fuel, there would also be emissions benefits from the replacement of older, higher emitting vehicles with more efficient (and lesser emitting) LNG or CNG vehicles. The two options for possible consideration are fueling refuse trucks or fueling public transportation (Mumbai's BEST Buses). For this analysis, the option of using LFG for fueling refuse trucks and replacing older diesel trucks with more efficient CNG trucks was considered, and are discussed below. Appendix D provides the emissions details for Mumbai's buses and may be used when an alternative analysis is desired.

To estimate the emissions benefit due to the fleet turnover from older trucks to new CNG trucks, a baseline emissions estimate is needed for the existing refuse truck fleet, as well as an estimate of emissions from CNG trucks. NEERI conducted an analysis of the emissions load for the three types of vehicles in the refuse truck fleet. The Automotive Research Association of India (ARAI) provided emissions factors for diesel and CNG vehicles that were also used for this analysis, as Table 15 shows.

Table 15. ARAI emission factors Diesel and CNG vehicles

Parameters	ARAI Estimated Emission Factors (g/km)	
	For Diesel Vehicles	For CNG Vehicles
Carbon Monoxide (CO)	6	3.72
Hydrocarbons (HC)	0.37	3.75
NOx	9.3	6.21
Particulate Matter (PM)	1.24	Not Applicable

The emission load, E, is defined as the product of the number of vehicles, average distance traveled, and the emissions factor for the vehicle and pollutant of concern. This is shown in Equation 14.

$$E = \text{Total Number of vehicles} \times \text{Distance traveled per day (km)}^{*} \times \text{Emission factor} \qquad (14)$$

*Average of distance traveled by all vehicles is taken into consideration while calculating the emission load.

Estimation of Emissions Load for Stationary Compactors: There are approximately 16 stationary compactors operating in Mumbai city. Each stationary compactor makes a single trip in each day. The driving pattern study indicates the maximum distance covered by a single stationary compactor is about 48 km, while on an average, the total distance covered by 16 compactors is 720 km in a day. Table 16 shows the calculated emissions load from a stationary compactor.

Table 16. Emissions from Stationary Compactor

Parameters	g/day	Metric tons/year
CO	4320	1.6
HC	296	0.1
NOx	4966	1.8
PM	893	0.3

Estimation of Emissions Load for TATA Dumper Placers: There are about 89 TATA dumper placers operating in Mumbai city. They operate in two shifts, carrying out 12 trips for waste collection and disposal every day. The driving pattern study showed that the distance covered by a single TDP is about 6 km. On an average, the total distance covered by the 89 TDP is 534 km/day. Table 17 shows the calculated emissions load from TDPs.

Table 17. Emissions from TATA Dumper Placer

Parameters	g/day	Metric tons/Year
CO	3204	1.2
HC	198	0.1
NOx	4966	1.8
PM	662	0.2

Estimation of Emissions Load for Dumpers: There are about 688 dumpers operating in Mumbai city. They operate in single shift for waste collection and disposal during the day. The driving pattern studies indicated the maximum distance covered by a single Dumper is about 62 km for the Mulund dumping site. However, sometimes these dumpers also travel to the Deonar dumping site for waste disposal. Therefore, the average distance of 55 km has been considered, and the distance covered by the 688 dumpers is approximately 37,840 km. Table 18 shows the calculated emissions load from the dumpers.

Table 18. Emissions from Dumper

Parameters	g/day	Metric tons/Year
CO	227040	82.9
HC	14001	5.1
NOx	351912	128.4
PM	46922	16.8

With the emissions data for each of the refuse trucks being used for collection, the total annual emissions from refuse trucks for the Mumbai area were generated, and a cost value assigned based on CER values. For this analysis, CO was given the same GWP as CO_2 because it is not a GHG but does hinder the breakdown of CH_4 in the atmosphere. Through natural courses, it will eventually turn into CO_2. NOx is a generic term given to all pollutants that are solely comprised of nitrogen and oxygen. NOx emissions were equated with a global warming potential of 310 in this study as designated by numerous environmental regulatory agencies for the compound N_2O.[21] Although not all of the NOx that will be formed is N_2O, the GWP of N_2O was paired with those pollutants. HCs and PM 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. The NPV of the annual cost of emissions over 20 years was then calculated. Over the course of 20 years the total cost of emissions from these vehicles will reach a NPV of nearly $9 million (U.S. dollars).

To estimate the cost savings from emissions using CNG trucks instead of diesel-powered trucks, the emissions rates were scaled using the ARAI data for estimated emissions from heavy-duty vehicles (Table 15). The emissions rates for each type of vehicle (dumper, TATA dumper, etc.) were developed by extrapolating the CNG emissions data with the estimated diesel vehicle emissions. Another assumption is that the diesel and CNG trucks operate for the same number of days in a year. Equations 15 and 16 show an example for the first estimation of CO for stationary compactors.

Ratio of CNG emissions to diesel emissions as per Table 15,

$$\frac{CNG\ Emissions}{Diesel\ Emissions} = \frac{3.72\ g/km}{6\ g/km} = 0.62 \qquad (15)$$

Stationary compactor emissions (Table 16) = 1.6 metric tons/year. Therefore,

$$\text{Emissions for LNG vehicles} = 1.6\ \text{metric tons/yr} * 0.62 = 0.99\ \text{metric tons/yr} \qquad (16)$$

This methodology was used for each vehicle type and pollutant. The cost savings from using an LNG vehicle versus a diesel vehicle were then calculated. The cost savings from switching from diesel to LNG vehicles appears to reach an NPV of approximately $1.57 million over the course of 20 years. Table 19 summarizes the cost savings from emissions reductions. Appendix C provides a more detailed table.

Table 19. Cost Savings Due to Emissions Reduction from LNG Vehicles

Vehicle Type	For Diesel Vehicles: Emissions (metric tons/yr)		For Diesel Vehicles: Cost of Emissions/ Year ($/yr)	For LNG Vehicles: Emissions (metric tons/yr)	For LNG Vehicles: Cost of Emissions/ Year ($/yr)	Cost Savings in Emissions/ Year ($/yr)
Stationary Compactor	CO	1.6	$ 7,734	1.0	$ 843	$6,891
	HC	0.1		1.0		
	NOx	1.8		0.2		
	PM	0.3		N/A		
TATA Dumper Placer (TDP)	CO	1.2	$ 7,728	0.7	$ 40,882	$ (33,153)
	HC	0.1		1.0		
	NOx	1.8		9.5		
	PM	0.2		N/A		
Dumper	CO	82.9	$ 551,237	51.4	$ 426,205	$ 125,032
	HC	5.1		51.7		
	NOx	128.4		85.7		
	PM	16.8		N/A		
Total			**$ 566,699**		**$ 467,929**	**$ 98,770**

Other Benefits not Included in Calculations

There are other benefits applicable to some of the scenarios considered that were not considered for the pre-feasibility analysis calculations. These included possible earnings from the sale of food-grade CO_2 obtained from the CO_2 wash process. Another benefit that was not monetized in the analysis was the social benefit obtained from emissions reduction. Urban areas in India face significant air quality problems, and the benefits of emissions reduction to the general public are also important. Since both these benefits have not been considered in this analysis due to lack of data to make assumptions, the pre-feasibility analysis provides a more conservative estimate than if these benefits were considered.

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 8. Each of these costs is described in this section. A majority of costs (such as capping, investment in LNG, CNG or 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. For recurring annual costs, their NPVs (in current dollar values) have been directly considered.

Landfill Capping Costs

A majority of the six analysis scenarios considered involve capping the landfill. Capping of a landfill is a necessity in the U.S. 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 emissions of harmful gases. The capping process involves covering the entire landfill with geo-synthetic liners, membranes, and topsoil. Throughout this covering or capping process, contractors may also drill gas extraction wells directly into the face of the landfill to extract the LFGs 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 CH_4 or any other gas builds up underneath the landfill cap, the cap could eventually tear, rip, or burst, defeating the purposes 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 LNG, electricity, or natural gas. Data were obtained from NEERI that estimates landfill capping costs and collection system installation for the three landfills, as shown in Table 20. For this analysis, the base cost estimates (excluding ancillary work, environmental maintenance, and unforeseen costs) were considered.

Table 20. Mumbai Landfill Capping Costs

No.	**Item Description**	**Cost ($ Million)**		
		Gorai	**Deonar**	**Mulund**
		Area -7.5Ha	Area- 132.5 Ha	Area - 25 Ha
1	Receiving, leveling and reformation work	1.88	14.25	2.69
2	Cover layers	3.49	26.42	4.99
3	Gas and leachate collection wells and collection system with gas flaring station	0.34	2.57	0.48
	Total (Base Cost Estimate)	**5.71**	**43.24***	**8.16**

**This preliminary estimated cost is reduced by 50% for pre-feasibility calculation purposes.*

Assumption of Reduced Capping Costs for Deonar Landfill: Table 20 shows that the capping costs for the Deonar landfill are much higher when compared to the other two locations, due to the large area covered by the landfill. One method to reduce the capping costs for this landfill, as proposed by NEERI researchers, is to reduce the area that requires capping by about 50 percent, and increasing the height of the waste dump. Thus, the same amount of LFG can be captured from the waste, but with lesser capping costs. Thus, for the Deonar landfill alone, the base costs of capping have been considered as 50 percent of the amount shown in Table 20. This is considered to be a reasonable estimate for purposes of this pre-feasibility analysis.

Cost of LFG-to-CNG Conversion System

An LFG conversion system can be used to filter the LFG to produce natural gas and food grade CO_2. The harmful pollutants from the LFG are disposed or recycled back into the landfill and the CH_4 from the LFG ultimately produces a transportation fuel. The Acrion Technologies, Inc. CO_2 WASH™ (described in Appendix A) has been chosen as the technology for cleaning LFG and ultimately converting it to natural gas. A pilot project in Burlington, NJ, proved the technology's reliability and functionality. The study took LFG from the Burlington County landfill and converted it into LNG, which then fueled refuse trucks.[22] As discussed previously, there is currently technology available to fuel vehicles on CNG, and it is preferable to LNG in the Indian context. Generally, LNG is considered to be more convenient than CNG as it requires less storage capacity than CNG (approximately one-fourth the volume[23]) for the same energy output. However, both LNG and CNG are just different forms of natural gas and are very similar in terms of overall fuel efficiency and emissions.

The costs associated with the installation of an LFG-to-CNG conversion system include the capping costs and LFG collection system costs (from Table 21) and the cost of the Acrion CO_2 WASH™ technology. An additional cost to be considered is the purchasing of CNG vehicles in phases over time. The Acrion system is estimated to cost roughly $18 million for conversion to LNG, and $12 million for producing CNG, for all three landfills. The CNG conversion option is selected here. Table 21 shows the total costs of capping the landfill and installing the CNG conversion system for each landfill. This does not include the cost of phasing in new LNG trucks, which is estimated separately.

Table 21. Base Cost of Landfills with Acrion System

Landfill	**Gorai**	**Deonar**	**Mulund**
Capping and Collection System Costs ($ million)	5.71	43.24	8.16
Acrion System Cost ($ million)	12	12	12
Total ($ million)	**17.71**	**55.24**	**20.16**

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-CNG conversion. The CO_2 WASH™ process must be used to truly rid the LFG of all contaminants to sell the LFG to a natural gas provider. Adding a lower grade of natural gas such as direct LFG, at 50 percent CH_4, would not only devalue the price of the natural gas, but would 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™ process was chosen as the filtering process to convert LFG into pipeline grade natural gas. Pure CH_4 would be produced from the CO_2 WASH™ process, and since CH_4 comprises 80 percent the composition of natural gas, the value of the gas would be nearly identical to that of the fair market value. Typically, natural gas produced in the petroleum engineering fields is more valuable than the market value because it contains trace amounts of the additional gases: ethane, propane, butane, pentane, as well as precipitates that can be refined for uses in other products. Therefore, the market price for the natural gas from the Mumbai landfills meets the 1 million BTU criterion, which is the measure for which 1 mcf of natural gas is priced.

The cost to convert LFG to pipeline grade natural gas will include the $12 million CO_2 WASH™ process as well as capping costs of the landfill. There is also an operational cost of $2 per mcf associated with the treatment process as well, causing this scenario to total the amounts seen in Table 22 for each of the landfills.[24]

Table 22. Cost of LFG to Pipeline Grade Natural Gas

Landfill	**Gorai**	**Deonar**	**Mulund**
Capping, Collection and Acrion System Cost ($ million)	17.71	55.24	20.16
Operational Costs over Analysis Period ($ million)	0.71	2.13	2.09
Total Cost over Analysis Period ($ million)	**18.52**	**57.37**	**22.25**

Cost of Conversion of LFG to Electricity

The costs associated with converting LFG to electricity include the cost of the cap, the cost of the facility, and the operational costs. The cost of the facility was determined first by the size of facility required to accommodate a desirable level of electricity production. To estimate electricity production capability from the LFG, the BTU equivalent of the LFG produced was converted to kWh using the conversion factor of 1 BTU= 0.000293 kWh. The energy in kilowatt-hours divided by the conversion factor of 8,928,000 results in the megawatts (MW) of electricity that could be produced at a given time, which can be used to determine the electricity plant size to the nearest 0.5MW. The plant size was determined to accommodate the average LFG production over the first ten years, rather than for the maximum LFG output. It is assumed that in the initial years, any excess LFG will be flared at the plant.

This provides estimations of the electricity generation needed based on the MW output. For this study, $1.5 million was used per MW to determine the cost of the electric generation facility. An operational cost of 5¢ per kWh was used.[24] Based on these assumptions, Table 23 shows the cost at each of the landfills for an electricity generation facility.

Table 23. Cost of LFG to Electricity

Landfill	Gorai	Deonar	Mulund
Facility Cost ($ million)	2.25	5.25	4.5
Total Cost Over Analysis Period($ million)*	**12.92**	**39.18**	**21.66**

**includes facility costs, operational costs and landfill capping costs*

Cost of Flaring LFG from Capped Landfill

The cheapest option of the capped landfill scenarios is a flaring system. With this scenario, the landfill will still be capped, extraction wells will be installed, and the LFG will be collected and flared. This action allows many of the more pollutant emissions such as CH_4 to be burned off as CO_2 and heat instead of being emitted into the atmosphere with 21 times the GWP as CO_2.[25] The equipment needed for this mitigation strategy is very simple. A flaring system will collect the LFG from the LFG collection system and flare the gas. Table 24 shows the flaring system and operational costs for this scenario.

Table 24. Cost of Flaring System from Capped Landfill

Landfill	Gorai	Deonar	Mulund
Flaring System Cost ($)	2,500,000		
Operational Costs over Analysis Period ($)	1,800,000		
Total Costs over Analysis Period ($)	**4,300,000**		

The costs are unchanged for each landfill because there is no difference in total or operational costs. The total cost assumes the same size flare is adequate for each landfill and the operational costs are equal because the time of operation on an equal size flare will also be equal.

Cost of Flaring LFG from an Active Landfill

Flaring from an active landfill yields similar results as the capped landfill flaring system except the additional step of capping the landfill is not necessary. A smaller LFG collection system with wells is still needed for this scenario instead of the capping costs. These costs are calculated by multiplying the number of hectares at each landfill by the cost to install wells and a collection system per hectare which was assumed to be $250,000.[26] The cost of the flaring system and operational costs are the same as for the capped landfill (Table 25). Table 25 shows the total estimated costs for flaring from an active landfill.

Table 25. Cost of Flaring System at an Active Landfill

Landfill	Gorai	Deonar	Mulund
Extraction Well System Cost ($ million)	4.43	33.03	6.25
Flaring System Cost ($ million)	2.5		
Operational Costs Over Analysis Period ($ million)	1.8		
Total Cost over Analysis Period ($ million)	**8.73**	**37.33**	**10.55**

Cost of Emissions

The cost of emissions comes into play in the "do-nothing" scenario. These are the costs associated with taking no action based on current landfill practices, and represent the economic and social implications via the cost of pollutants being emitted. CER equivalents are considered for this scenario, and Table 26 presents the values for each landfill.

Table 26. Cost of Emissions for Do-Nothing Scenario

Landfill	Gorai	Donar	Mulund
CO_2 Equivalent Tons	1,584,469	4,227,183	4,197,523
Emissions Value Based on CERs (million $)	17.01	44.69	43.86

Estimating the Net Return 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 8, 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 net return for each of the scenarios is evaluated as shown in Equation 17.

$$\text{Return (\%)} = \frac{Total\ NPV\ of\ Benefits - Total\ NPV\ of\ Costs}{Total\ NPV\ of\ Costs} \qquad (17)$$

Scenarios 1-3: Landfill Management Options

The following details the costs and benefits considered for each of the landfill management scenarios.

Scenario 1- Do Nothing: For this scenario, the costs and benefits are not explicitly considered, as they relate to just maintaining the landfill as it is without taking any actions. Thus, the return on investment is not calculated for this scenario. The net costs (which are a "negative" benefit), however, can be considered as the costs of the emissions based on the CER values as shown in Table 26.

Scenario 2- Flaring of Capped Landfill: The costs of this scenario include the capping costs from Table 21 and the costs for installing and operating the flaring system (shown in Table 24). The only benefit for this scenario comes from the NPV of carbon credit earnings, for which 95 percent efficiency is assumed.

Scenario 3- Flaring of an Active Landfill: The costs and benefits considered for this scenario are very similar to Scenario 2. The only difference is that the capping costs are not included, and the cost of extraction wells and the flaring system are as taken from Table 25.

Scenarios 4-6: LFG to Energy Options
The following details the costs and benefits considered for each of the LFGTE scenarios.

Scenario 4- Conversion of LFG to CNG for Use as a Transportation Fuel: In this scenario, the costs incurred for each landfill include the capping cost and the cost of the Acrion system as shown in Table 21. In addition, the operational cost of the CNG facility, as well as the NPV of the cost of investing in new trucks are also considered. In terms of the benefits, these include the NPV of savings due to not purchasing diesel, carbon credits (assuming 95 percent conversion efficiency), and the emissions benefits from the use of CNG trucks instead of diesel.

Scenario 5-Conversion of LFG to Pipeline Grade Natural Gas: The costs for this scenario include the entire capping and facility costs and operational costs as listed in Table 22. The benefits considered include the NPV of earnings from the natural gas sales and carbon credits, assuming 95 percent conversion efficiency.

Scenario 6- Conversion of LFG to Electricity: The costs for this scenario include the capping, the electricity plant, and operational costs (as shown in Table 23). The benefits considered for this scenario include the NPV of benefits from the sale of electricity and the carbon credits.

Alternative Analysis for LFGTE Options – Without Consideration of Capping Costs
As previously discussed in this report, the conversion of a landfill to a sanitary landfill alone has many societal and environmental benefits, some of which are not quantified in this research. While it appears that there are difficulties in securing financing for such landfill capping/retrofit measures in India, it is possible that funds from Indian government agencies or external funding agencies may be used, especially in specific landfills where it is necessitated by public interest/local concerns. In such cases, the implementation of an LFGTE project need not consider the capping/gas collection installation costs, as these represent costs that would be expended on the landfill in any case. Thus, an alternative analysis, which did not include the landfill capping

costs, was performed for the three LFGTE scenarios. This analysis provided an indication of the feasibility of implementing an LFGTE project when the initial capping costs are recovered from other sources, and thereby not considered.

RESULTS

When combining all potential costs and benefits previously discussed, the net cost and final returns provide indicators of feasibility for each scenario and each prospective landfill.

Gorai Landfill

Table 27 presents the results from the Gorai landfill. While all scenarios show negative returns, flaring the active landfill has the lowest negative return. Earnings from carbon credits provide the only income from this scenario. If CER credit prices fall, or are not purchased, the feasibility of this project could be severely impacted. The accuracy of the carbon credits that can be earned from flaring at an active landfill are also highly debatable. The EPA LFG modeling equation for an open landfill was used. But very little research has been conducted to determine the exact quantity of LFG that is captured from an active landfill and destroyed by flaring. Little is also known as to whether or not this action disrupts the production of additional emissions, such as CH_4 and CO_2. This value appears to be the best option in this scenario, but must be examined with greater scrutiny to select this option for final feasibility. LFG to CNG proves to provide the greatest return of the three options that produce a useable product, yet still receives a less than desirable return of negative 33 percent. The additional analysis results shown in Table 28 indicate that the LFGTE options still perform poorly, despite the exclusion of landfill capping costs. However, the LFG-to-electricity option exhibits a positive return of 28 percent in this case, while the return for the LFG-to-CNG option improves to a negative10 percent.

Table 27. Results for Gorai Landfill

Scenarios	NPV of Costs ($)	NPV of Benefits: Diesel/ Natural Gas/ Electricity ($)	NPV of Benefits: Carbon Credits ($)	Net ($)	Return (%)
Landfill Management Options					
Scenario 1: Do Nothing	0	0	0	$ (17,015,502)	**N/A**
Scenario 2: Cap the Landfill and Flare the LFG	$10,010,600	N/A	$6,870,031	$ (3,140,569)	**-31%**
Scenario 3: Flare the LFG from an Active Landfill	$ 8,725,000	N/A	$7,347,603	$ (1,377,397)	**-16%**
LFGTE Options					
Scenario 4: Convert LFG to CNG for Use as a Transportation Fuel	$ 22,092,221	$7,039,782	$7,676,449	$ (7,375,991)	**-33%**
Scenario 5: Convert the LFG to Pipeline Grade Natural Gas	$ 18,520,521	$1,589,452	$7,557,034	$ (9,374,035)	**-51%**
Scenario 6: Convert the LFG to Electricity	$ 12,920,473	$8,770,809	$ 429,949	$ (3,719,716)	**-29%**

Table 28. Gorai Landfill – Additional Analysis for LFGTE Options

Scenarios	NPV of Costs ($)	NPV of Benefits: Diesel/ Natural Gas/ Electricity ($)	NPV of Benefits: Carbon Credits ($)	Net ($)	Return (%)
LFGTE Options					
Scenario 4: Convert LFG to CNG for Use as a Transportation Fuel	$ 16,381,621	$7,039,782	$7,676,449	$ (1,665,390)	**-10%**
Scenario 5: Convert the LFG to Pipeline Grade Natural Gas	$ 12,809,921	$1,589,452	$7,557,034	$ (3,663,435)	**-29%**
Scenario 6: Convert the LFG to Electricity	$ 7,209,873	$8,770,809	$429,949	$ 1,990,884	**28%**

Deonar Landfill

Table 29 summarizes the results for the Deonar landfill. The LFG-to-CNG conversion appears to yield the highest return of all options, but still only yields a slight positive return of 1 percent. Deonar also must be examined closely due to the age and design of the landfill. Literature and research pertaining to LFG generation is relatively new, since the 1970s, and inhabitants have burned some CH_4 at open dump landfils in existance prior to and after the 1970s. Thus, the CH_4

that is still available for capture after closure cannot be estimated with much accuracy. The capital costs associated with all mitigating options are extremely high and additional pump test data is needed to recommend the best scenario.

A main contributor to the high costs at the Deonar landfill is the inital outlay for capping costs. Thus, when the capping costs were excluded from the analysis (Table 30), the LFG-to-CNG scenario resulted in high returns (135 percent), while the pipeline natural gas conversion option and the electricity conversion option also demonstrated positive returns of 70 percent and 33 percent respectively.

Table 29. Results for Deonar Landfill

Scenarios	NPV of Costs ($)	NPV of Benefits: Diesel/ Natural Gas/ Electricity ($)	NPV of Benefits: Carbon Credits ($)	Net ($)	Return (%)
Landfill Management Options					
Scenario 1: Do Nothing	0	0	0	$ (44,693,492)	**N/A**
Scenario 2: Cap the Landfill and Flare the LFG	$25,918,700	N/A	$18,047,820	$(7,870,880)	**-30%**
Scenario 3: Flare the LFG from an Active Landfill	$37,325,000	N/A	$19,299,462	$(18,025,538)	**-48%**
LFGTE Options					
Scenario 4: Convert LFG to CNG for Use as a Transportation Fuel	$ 38,000,321	$18,493,762	$19,972,016	$ 465,457	**1%**
Scenario 5: Convert the LFG to Pipeline Grade Natural Gas	$ 35,746,392	$4,175,547	$19,852,602	$ (11,718,243)	**-33%**
Scenario 6: Convert the LFG to Electricity	$ 39,182,359	$21,994,115	$1,399,826	$ (15,788,418)	**-40%**

Table 30. Deonar Landfill – Additional Analysis for LFGTE Options

Scenarios	NPV of Costs ($)	NPV of Benefits: Diesel/ Natural Gas/ Electricity ($)	NPV of Benefits: Carbon Credits ($)	Net ($)	Return (%)
LFGTE Options					
Scenario 4: Convert LFG to CNG for Use as a Transportation Fuel	$ 16,381,621	$18,493,762	$19,972,016	$ 22,084,157	**135%**
Scenario 5: Convert the LFG to Pipeline Grade Natural Gas	$ 14,127,692	$4,175,547	$19,852,602	$ 9,900,457	**70%**
Scenario 6: Convert the LFG to Electricity	$ 17,563,659	$21,994,115	$1,399,826	$ 5,830,282	**33%**

Mulund Landfill

The results found from the Mulund landfill yield the most promising results, as Table 31 shows. The equations for LFG generation are very accurate at this landfill as well as Gorai due to their relatively young age. The gas generation rates that were present at this landfill prove results that were expected from previous analyses. The highest returns are present from the flaring of an active landfill, and the LFG-to-CNG scenarios. The concerns of the applicability of flaring from an active landfill as discussed previously also apply to in this case. Flaring at a closed landfill yields a fairly high return at 42 percent. This scenario was hypothesized to be a feasible option for Indian landfills and proved to be true at this landfill. Earnings again solely come from carbon credit sales, and risks associated with their sale and price must still be considered. The LFG-to-CNG conversion yields an extremely promising return of 54 percent from earnings resulting from diesel savings as well as carbon credits. The LFG-to-CNG conversion produces the greatest reduction in GHG emissions and should be assessed in more detail in a comprehensive feasibility analysis. The overall goal of the project is to lower GHG emissions, and the LFG-to-CNG conversion at this particular landfill accomplishes those goals. Additionally, when the landfill capping costs are not included in the analysis, the LFG-to-CNG option provides higher returns of around 130 percent (Table 32).

Table 31. Results for Mulund Landfill

Scenarios	NPV of Costs ($)	NPV of Benefits		Net ($)	Return (%)
		Diesel/ Natural Gas/ Electricity ($)	Carbon Credits ($)		
Landfill Management Options					
Scenario 1: Do Nothing	0	0	0	$(43,859,505)	**N/A**
Scenario 2: Cap the Landfill and Flare the LFG	$12,458,000	N/A	$17,710,208	$5,252,208	**42%**
Scenario 3: Flare the LFG from an Active Landfill	$10,550,000	N/A	$18,939,332	$8,389,332	**80%**
LFGTE Options					
Scenario 4: Convert LFG to CNG for Use as a Transportation Fuel	$ 24,539,621	$18,147,497	$19,600,310	$ 13,208,186	**54%**
Scenario 5: Convert the LFG to Pipeline Grade Natural Gas	$ 22,245,854	$4,097,367	$19,480,895	$ 1,332,408	**6%**
Scenario 6: Convert the LFG to Electricity	$21,660,740	$17,158,542	$2,536,480	$ (1,965,718)	**-9%**

Table 32. Mulund Landfill – Additional Analysis for LFGTE Options

Scenarios	NPV of Costs ($)	NPV of Benefits		Net ($)	Return (%)
		Diesel/ Natural Gas/ Electricity ($)	Carbon Credits ($)		
LFGTE Options					
Scenario 4: Convert LFG to CNG for Use as a Transportation Fuel	$ 16,381,621	$18,147,497	$19,600,310	$ 21,366,186	**130%**
Scenario 5: Convert the LFG to Pipeline Grade Natural Gas	$ 14,087,854	$4,097,367	$19,480,895	$ 9,490,408	**67%**
Scenario 6: Convert the LFG to Electricity	$ 13,502,740	$17,158,542	$2,536,480	$ 6,192,282	**46%**

CONCLUSIONS

This research sought to promote the overall goal of optimal management of MSW. The specific objectives of this research were to study MSW management characteristics in Mumbai, India, and perform a pre-feasibility analysis for three case study landfills to assess various LFGTE options, including the conversion of LFG to LNG for use as a refuse truck fuel. This section discusses the findings specific to MSW management in Mumbai, the findings from the pre-feasibility analysis, and presents concluding remarks including the study limitations and scope for further research.

MSW Management and Landfills in Mumbai

The quantity of refuse collected in Mumbai is about 8500 metric TPD, and will possibly increase in coming years considering the expected growth in population. A majority of this waste ends up at Mumbai's landfill sites, which currently operate more as open dumps than as sanitary landfills. These landfills are also the site of an informal recycling trade carried out by rag pickers, who often live at the landfill sites.

There are many social, economic and environmental benefits to improving landfill management practices in India, though special consideration is needed for the local context, including funding availability issues. The landfills in Mumbai also represent an important source of LFG and CH_4 that can be used for LFGTE or other projects that can help reduce GHG emissions and provide alternative sources of energy. Capturing and flaring LFG is also another means of reducing the carbon footprint of the landfills by converting CH_4 to CO_2, which has a lower GWP.

Pre-Feasibility Analysis of Options for Case Study Landfills

Three Mumbai landfills were analyzed as a part of the pre-feasibility study. The current refuse quantities available at the landfill sites can generate enough CH_4 for fueling refuse vehicles or city buses, leading to significant reduction in overall vehicle emissions, as well as capturing harmful LFGs. Other LFGTE projects, as well as options of just capturing LFG and flaring the gas were also analyzed.

For the Gorai landfill, the results of the pre-feasibility analysis did not show positive returns for any of the scenarios. For the Mulund and Deonar landfills however, multiple scenarios, including LFG-to-CNG conversion and flaring options showed potential for high returns. The Mulund landfill has proven to be the best option for the LFG-to-CNG conversion process. This option will not only dramatically reduce GHG emissions but will serve as a source of vehicle fuel. Other options such as capping the landfill and flaring the gas can also help in reducing the GWP, help reduce the air pollution and odors, and benefit general public health and well-being.

One aspect to note, that was not explicitly considered in the pre-feasibility analysis is the overall LFG/methane generation rates. As discussed in the section on LFG generation, the three study landfills produce relatively lesser quantities of gas over a 20-year period, mostly due to landfill age. While there are still significant quantities of gas generated (sufficient for economic feasibility), it might be worthwhile to consider newer landfills that have a greater potential for gas generation in a more detailed feasibility analysis.

It should also be noted that this pre-feasibility analysis does not consider many intangible benefits, and also makes conservative assumptions for costs and most other analysis inputs. Thus, more detailed, case-specific feasibility analyses are recommended, with concrete information on costs, funding, availability of grants, incremental costs, etc. Overall, the findings indicate that Mumbai's landfills are good candidates for LFGTE projects to help with the goals of reducing GHG emissions, protecting the environment, and promoting public well-being. Thus, no single scenario or option for any landfill should be ruled out from consideration at this stage.

Final Remarks

The results of this project indicated that there are many viable options that can be implemented for improving the overall management of Mumbai's landfills to promote public welfare. Most importantly however, measures such as LFG-to-CNG conversion can help reduce air quality impacts, GHG emissions, and fuel consumption. The following remarks summarize the project findings, and discuss the limitations and scope for further research.

- Note that the analyses presented are the pre-feasibility analyses that make use of conservative estimates, and do not assign monetary value to many benefits, including public health, local environmental quality, and job creation.
- The landfills studied here as a part of the pre-feasibility analysis are older landfills that need to be retrofitted with LFG collection mechanisms before undertaking the various landfill management/LFGTE projects. Due to concerns over the quantities of LFG that can be generated on a sustained basis, newer landfills that are constructed as sanitary landfills might be more viable for implementation of these projects.
- In the Indian context, another significant benefit for landfill management or LFGTE projects is the benefit to the poor, especially the rag pickers, who can benefit from conducting the sorting/recycling activity at other locations instead of the landfills. Formalizing this trade can enable rag pickers to work in a cleaner environment and earn more.
- It is expected that more refined feasibility analyses conducted for proposed projects at Mumbai's landfills would result in higher returns than indicated by the pre-feasibility analyses, and would benefit from the consideration of other landfill locations as well. Thus, the pursuit of LFGTE projects is significant and important, and further research is needed on this subject.
- It is also worth noting that for projects such as these that have a significant public welfare and environmental benefit, the benefit-cost analysis or return on investment alone

should not be the driving force for project selection. However, preliminary findings indicate that there is also an economic benefit to conducting these projects in the context of Mumbai's landfills.

- Another issue is the availability of funding, which is required to cap landfills, set up gas collection systems, as well as for the infrastructure for LFGTE projects. Possible funding sources include various government agencies, and grants from international entities.
- However, funding will not necessarily be available for all landfill projects that have prospects of being socially/environmentally beneficial as well as economically viable. Thus, capital rationing becomes an issue to consider, and further research is needed to identify how investments can be prioritized when faced with such choices.
- Also, per Clean Development Mechanism processes, the funding gap for certain LFGTE projects can be eliminated by fulfilling an additional clause – indicating that the project should be financed in the interest of reducing GHG, leading to lower GWP of the site. This is also a potential means of funding landfill management/LFGTE processes.

This research is a good beginning point for the consideration of economic benefits for LFGTE projects. The research findings also provide an overview of MSW management in India, the preliminary assessment of costs and benefits, and can form the basis for future research and more detailed feasibility analyses.

REFERENCE

1. Natural Gas Background 2004. www.naturalgas.org, accessed 11/12/2008.

2. Salvi, P., K. Mehta, and D. Sankarreddy. *Integrated Solid Waste Management Programme – A sustained and Perennial Solution*. Save Bombay Committee, India, 2005. http://www.savebombaycommittee.org/database/reports/ISWMP.pdf.

3. *Assessment of Status of Municipal Solid Waste Management in Metro Cities, State Capitals, Class I Cities and Class II Towns of India*, NEERI Report, 2005

4. Zhu, D., P.U. Asnani, and C. Zurbrugg. *Improving Municipal Solid Waste Management in India: A Sourcebook for Policy Makers and Practitioners*. World Bank Institute Development Studies, November 2007.

5. *Waste Generation and Composition*. Prepared by Central Pollution Control Board, India, 2005.

6. *Solid Waste Management of Mumbai*. Prepared by Bombay Community Public Trust (BPCT), 2007.

7. *Report on Selection of Waste Processing Technology and Scientific Management of Landfills*. Prepared by IL&FS, 2007.

8 . New Yock City Department of Sanitation, 2008 Annual Report http://www.nyc.gov/html/dsny/downloads/pdf/pubinfo/annual/ar2008.pdf

9. Municipal Corporation of Greater Mumbai, http://www.mcgm.gov.in/irj/portal/, accessed January 2, 2009.

10. Clean Up Mumbai. http://mumbainews.wordpress.com/2008/03/04/clean-up-mumbai/, accessed January 10, 2009.

11. Grant,E.L., W.G. Ireson, and R.S. Leavenworth. *Principles of Engineering Economy*. Wiley Publications, 1982.

12. U.S.EPA. *Preliminary Assessment for Landfill Biogas Project Opportunities: Deonar Landfill*. 2006.

13. Qian, X., R.M. Koerner, and D.H. Gray. *Geotechnical Aspects of Landfill Design and Construction*. Prentice Hall, Upper Saddle River, NJ. p. 352-374, 2002.

14. U.S. Energy Information Administration. Energy Conversion Calculators, 2008. http://www.eia.doe.gov/kids/energyfacts/science/energy_calculator.html, accessed November 1, 2008.

15. Zietsman, J., Gokhale, B., Lord, D., Farzaneh, M., Jacobs, T., *Application of Natural Gas as a Liquefied Natural Gas Fuel for Refuse Trucks in Texas*. Draft Report for State

Energy Conservation Office, Texas Transportation Institute, Texas A&M University System, College Station, Texas.

16. Zietsman, J., et al. Feasibility of Landfill Gas as a Liquefied Natural Gas Fuel Source for Refuse Trucks. *Journal of the Air and Waste Management Association, Volume 58, May 2008.*

17. U.S. Energy Information Administration. Diesel Fuel Components History, 2009. http://tonto.eia.doe.gov/oog/info/gdu/dieselpump.html, accessed March 12, 2009.

18. U.S. Energy Information Administration. Natural Gas Futures, 2009. http://tonto.eia.doe.gov/dnav/ng/hist/rngc1A.htm, accessed March 12, 2009.

19. U.S. Bureau of Labor Statistics. Consumer Price Index Summary, 2009. http://www.bls.gov/news.release/cpi.nr0.htm, accessed April 20, 2009.

20. Multi Commodity Exchange India. Carbon Credits. www.mcxindia.com, accessed February 12, 2009.

21. United Nations Framework Convention on Climate Change. Global Warming Potential, 1995. http://unfccc.int/ghg_data/items/3825.php, accessed April 2, 2009.

22. Cook, W. J, et al. *Production of Liquid Methane Truck Fuel from Landfill Gas*. 2005.

23. Tusianai, M., and G. Shearer. *LNG: A Nontechnical Guide*. PennWell Corporation, pp. 22-24, 2007

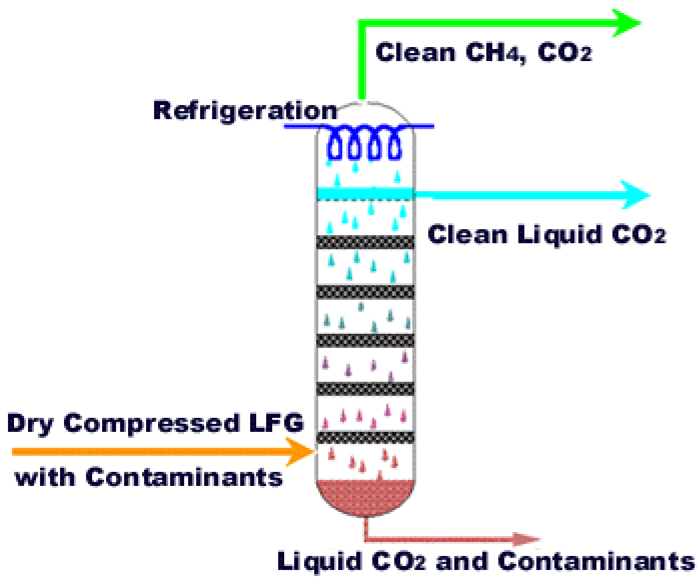
24. State of California Energy Commission. *Economic and Financial Aspects of Landfill Gas to Energy Project Development in California*. 2002.

25. U.S. EPA. *Methane*. www.epa.gov/methane, accessed September 25, 2008.

26. John Zink Co. *Specifying a Cost Effective Landfill Flare System*. Presented at SWANA's 28th Annual Landfill Symposium 2005. http://www.johnzink.com/products/flares/pdfs/tp_cost_effective_landfill_rev.pdf, accessed April 2, 2009.

APPENDIX A- CO_2 WASH PROCESS DETAILS

The CO_2 wash process developed by Acrion Technologies is used to clean contaminants from LFG to produce clean CH_4 as well as food-grade CO_2. The wash process has been used with success to produce cleaned gas that can be used for various purposes. Further details about this process are available at: http://www.acrion.com/. The following schematic diagram shows the CO_2 wash process.



Source: http://www.acrion.com/

APPENDIX B – LFG GENERATION QUANTITIES

Recoverable Dry Natural Gas Quantities

Time Since Closure (Years)	Deonar			Mulund			Gorai*		
	LFG Generated Postclosure (m^3/yr)	**Recoverable LFG (m^3/yr)**	**CH_4 Generated (mcf/yr)**	**LFG Generated Postclosure (m^3/yr)**	**Recoverable LFG (m^3/yr)**	**CH_4 Generated (mcf/yr)**	**LFG Generated Postclosure (m^3/yr)**	**Recoverable LFG (m^3/yr)**	**CH_4 Generated (mcf/yr)**
0	26,155,122	13,077,561	224,625	25,665,411	12,832,705	220,420	9,956,133	4,978,066	85,505
1	20,672,101	10,336,051	177,536	20,285,051	10,142,525	174,212	7,868,982	3,934,491	67,580
2	16,338,512	8,169,256	140,318	16,032,601	8,016,300	137,691	6,219,371	3,109,685	53,413
3	12,913,394	6,456,697	110,903	12,671,612	6,335,806	108,826	4,915,575	2,457,788	42,216
4	10,206,299	5,103,149	87,654	10,015,203	5,007,601	86,013	3,885,100	1,942,550	33,366
5	8,066,705	4,033,352	69,278	7,915,669	3,957,834	67,981	3,070,648	1,535,324	26,371
6	6,375,644	3,187,822	54,755	6,256,270	3,128,135	53,730	2,426,934	1,213,467	20,843
7	5,039,088	2,519,544	43,277	4,944,739	2,472,370	42,466	1,918,165	959,082	16,474
8	3,982,720	1,991,360	34,204	3,908,150	1,954,075	33,564	1,516,051	758,025	13,020
9	3,147,804	1,573,902	27,034	3,088,867	1,544,433	26,528	1,198,234	599,117	10,291
10	2,487,915	1,243,958	21,367	2,441,333	1,220,667	20,967	947,043	473,521	8,133
11	1,966,362	983,181	16,888	1,929,545	964,772	16,571	748,510	374,255	6,428
12	1,554,144	777,072	13,347	1,525,045	762,523	13,097	591,596	295,798	5,081
13	1,228,342	614,171	10,549	1,205,343	602,672	10,352	467,577	233,788	4,016
14	970,839	485,419	8,338	952,661	476,331	8,182	369,557	184,778	3,174
15	767,317	383,659	6,590	752,950	376,475	6,466	292,085	146,042	2,508
16	606,461	303,230	5,208	595,106	297,553	5,111	230,854	115,427	1,983
17	479,326	239,663	4,117	470,351	235,176	4,039	182,459	91,229	1,567
18	378,842	189,421	3,254	371,749	185,875	3,193	144,209	72,105	1,238
19	299,424	149,712	2,572	293,818	146,909	2,523	113,978	56,989	979
20	236,654	118,327	2,032	232,223	116,112	1,994	90,084	45,042	774
Total	123,873,013	61,936,507	**1,063,846**	121,553,698	60,776,849	1,043,927	47,153,143	23,576,571	**404,960**

**Gorai has been closed since 2008. This has been accounted for in all calculations.*

APPENDIX C – DETAILS OF BENEFITS ESTIMATED OVER ANALYSIS PERIOD

Earnings from Diesel Savings

Time Since Closure (Years)	Deonar			Mulund			Gorai*		
	Diesel Equivalent per Year (Gallons)	Cost of Diesel at Market Prices ($)	Net Present Value ($)	Diesel Equivalent per Year (Gallons)	Cost of Diesel at Market Prices ($)	Net Present Value ($)	Diesel Equivalent per Year (Gallons)	Cost of Diesel at Market Prices ($)	Net Present Value ($)
0	1,661,258	4,319,271	4,319,271	1,630,154	4,238,400	4,238,400	632,370	1,644,161	1,644,161
1	1,313,001	3,413,802	3,314,371	1,288,417	3,349,884	3,252,315	499,803	1,299,488	1,261,639
2	1,037,750	2,698,151	2,543,266	1,018,320	2,647,632	2,495,647	395,027	1,027,070	968,112
3	820,202	2,132,525	1,951,562	804,845	2,092,597	1,915,022	312,216	811,761	742,876
4	648,259	1,685,474	1,497,521	636,121	1,653,916	1,469,483	246,764	641,587	570,042
5	512,361	1,332,140	1,149,116	502,768	1,307,198	1,127,600	195,034	507,089	437,419
6	404,953	1,052,877	881,768	397,371	1,033,164	865,258	154,148	400,785	335,651
7	320,061	832,158	676,620	314,068	816,577	663,952	121,833	316,767	257,560
8	252,965	657,709	519,201	248,228	645,394	509,480	96,293	250,361	197,638
9	199,935	519,830	398,406	196,191	510,097	390,947	76,107	197,877	151,656
10	158,021	410,856	305,715	155,063	403,163	299,991	60,152	156,395	116,373
11	124,895	324,726	234,589	122,556	318,646	230,197	47,542	123,609	89,298
12	98,712	256,652	180,011	96,864	251,847	176,640	37,576	97,696	68,522
13	78,019	202,849	138,130	76,558	199,051	135,544	29,698	77,216	52,580
14	61,663	160,325	105,994	60,509	157,323	104,009	23,473	61,029	40,347
15	48,737	126,715	81,334	47,824	124,343	79,811	18,552	48,235	30,960
16	38,520	100,151	62,411	37,799	98,276	61,242	14,663	38,123	23,757
17	30,445	79,156	47,891	29,875	77,674	46,994	11,589	30,131	18,230
18	24,062	62,562	36,749	23,612	61,391	36,061	9,160	23,815	13,989
19	19,018	49,447	28,199	18,662	48,521	27,671	7,239	18,822	10,734
20	15,031	39,081	21,638	14,750	38,349	21,233	5,722	14,877	8,237
Total	7,867,867	20,456,455	**18,493,762**	7,720,555	20,073,442	**18,147,497**	2,994,960	7,786,895	**7,039,782**

**Gorai has been closed since 2008. This has been accounted for in all calculations.*

Earnings from Sale of Natural Gas

Time Since Closure (Years)	Deonar			Mulund			Gorai*		
	CH_4 Generated (mcf/yr)	Earnings ($/year)	Net Present Value ($)	CH_4 Generated (mcf/yr)	Earnings ($/year)	Net Present Value ($)	CH_4 Generated (mcf/yr)	Earnings ($/year)	Net Present Value ($)
0	224,625	1,026,538	1,026,538	220,423	1,007,335	1,007,317.63	85,505	390,759	390,759
1	177,536	811,340	787,709	174,215	796,163	772,960.13	67,580	308,842	299,847
2	140,318	641,255	604,444	137,694	629,259	593,127.07	53,413	244,098	230,086
3	110,903	506,826	463,817	108,828	497,345	455,133.08	42,216	192,927	176,555
4	87,654	400,577	355,908	86,014	393,084	349,244.08	33,366	152,483	135,479
5	69,278	316,603	273,104	67,982	310,680	267,990.69	26,371	120,517	103,959
6	54,755	250,232	209,565	53,731	245,551	205,641.31	20,843	95,252	79,772
7	43,277	197,774	160,809	42,467	194,075	157,797.83	16,474	75,284	61,213
8	34,204	156,314	123,396	33,565	153,390	121,085.37	13,020	59,502	46,971
9	27,034	123,545	94,687	26,528	121,234	92,914.25	10,291	47,028	36,043
10	21,367	97,646	72,658	20,967	95,819	71,297.28	8,133	37,170	27,658
11	16,888	77,176	55,754	16,572	75,732	54,709.61	6,428	29,378	21,223
12	13,347	60,997	42,782	13,098	59,856	41,981.15	5,081	23,219	16,285
13	10,549	48,210	32,829	10,352	47,308	32,214.02	4,016	18,351	12,496
14	8,338	38,104	25,191	8,182	37,391	24,719.27	3,174	14,504	9,589
15	6,590	30,116	19,330	6,467	29,552	18,968.21	2,508	11,464	7,358
16	5,208	23,802	14,833	5,111	23,357	14,555.16	1,983	9,061	5,646
17	4,117	18,813	11,382	4,040	18,461	11,168.83	1,567	7,161	4,333
18	3,254	14,869	8,734	3,193	14,591	8,570.34	1,238	5,660	3,325
19	2,572	11,752	6,702	2,523	11,532	6,576.41	979	4,473	2,551
20	2,032	9,288	5,143	1,994	9,114	5,046.38	774	3,536	1,958
Total	1,063,846	4,861,776	**4,395,313**	1,043,945	4,770,829	**4,313,018**	404,960	1,850,669	**1,673,107**

**Gorai has been closed since 2008. This has been accounted for in all calculations.*

Earnings from Electricity Generation

Time Since Closure (Years)	Deonar			Mulund			Gorai*		
	Energy Content Present (BTU)	Electricity Output (kWh)	Net Present Value **($)	Energy Content Present (BTU)	Electricity Output (kWh)	Net Present Value **($)	Energy Content Present (BTU)	Electricity Output (kWh)	Net Present Value**($)
0	230,914,852,584	30,660,000	$3,801,108	226,595,246,576	17,520,000	$2,723,015	87,899,379,592	13,140,000	$1,564,636
1	182,507,093,186	30,660,000	$3,416,795	179,093,026,367	17,520,000	$2,375,226	69,472,621,976	13,140,000	$1,414,916
2	144,247,278,555	30,660,000	$3,107,331	141,548,918,514	17,520,000	$2,100,029	54,908,751,650	13,140,000	$1,293,787
3	114,008,047,618	30,660,000	$2,855,724	111,875,357,399	17,520,000	$1,880,778	43,397,973,504	12,715,606	$1,163,658
4	90,108,007,942	26,401,646	$2,345,752	88,422,403,537	17,520,000	$1,704,692	34,300,253,560	10,049,974	$892,927
5	71,218,245,246	20,866,946	$1,800,001	69,886,001,968	17,520,000	$1,561,958	27,109,731,153	7,943,151	$685,183
6	56,288,431,758	16,492,510	$1,381,222	55,235,472,863	16,183,716	$1,355,361	21,426,591,553	6,277,991	$525,772
7	44,488,424,825	13,035,108	$1,059,874	43,656,202,622	12,791,048	$1,040,029	16,934,835,059	4,961,907	$403,448
8	35,162,108,476	10,302,498	$813,289	34,504,348,902	10,109,601	$798,061	13,384,706,465	3,921,719	$309,584
9	27,790,911,396	8,142,737	$624,073	27,271,041,035	7,990,278	$612,388	10,578,807,914	3,099,591	$237,558
10	21,964,972,799	6,435,737	$478,879	21,554,085,290	6,315,239	$469,913	8,361,122,986	2,449,809	$182,289
11	17,360,352,929	5,086,583	$367,466	17,035,601,689	4,991,346	$360,585	6,608,341,711	1,936,244	$139,878
12	13,721,021,036	4,020,259	$281,973	13,464,348,915	3,944,987	$276,693	5,223,004,163	1,530,340	$107,335
13	10,844,619,290	3,177,473	$216,370	10,641,754,546	3,117,981	$212,319	4,128,081,398	1,209,528	$82,363
14	8,571,211,082	2,511,365	$166,031	8,410,873,821	2,464,344	$162,922	3,262,692,408	955,969	$63,201
15	6,774,388,057	1,984,896	$127,403	6,647,663,046	1,947,732	$125,017	2,578,718,955	755,565	$48,497
16	5,354,241,438	1,568,793	$97,762	5,254,082,383	1,539,420	$95,932	2,038,130,053	597,172	$37,214
17	4,231,806,790	1,239,919	$75,017	4,152,644,546	1,216,704	$73,613	1,610,867,327	471,984	$28,556
18	3,344,673,362	979,989	$57,564	3,282,106,268	961,641	$56,486	1,273,173,683	373,040	$21,912
19	2,643,513,858	774,550	$44,171	2,594,062,997	760,047	$43,344	1,006,272,336	294,838	$16,814
20	2,089,341,697	612,177	$33,895	2,050,257,451	600,715	$33,260	795,322,765	233,030	$12,902
Total	1,093,633,543,924	246,273,188	**$23,151,700**	1,073,175,500,733	180,054,796	**$18,061,623**	416,299,380,210	99,197,458	**$9,232,430**

**Gorai has been closed since 2008. This has been accounted for in all calculations.*

*** NPV includes electricity sales plus carbon credits (including carbon credits for flaring excess gas)*

Earnings from Carbon Credits

Time Since Closure (Years)	Deonar			Mulund			Gorai*		
	Total Potential LFG Emissions (metric tons/year)	CO_2 Equivalent (metric tons)	Net Present Value of Carbon Credits ($)	Total Potential LFG Emissions (metric tons/year)	CO_2 Equivalent (metric tons)	Net Present Value of Carbon Credits ($)	Total Potential LFG Emissions (metric tons/year)	CO_2 Equivalent (metric tons)	Net Present Value of Carbon Credits ($)
0	32,105	353,160	4,880,665	31,504	346,547	4,789,282	12,221	134,433	1,857,860
1	25,375	279,125	3,745,154	24,900	273,899	3,675,032	9,659	106,251	1,425,619
2	20,056	220,611	2,873,825	19,680	216,480	2,820,017	7,634	83,977	1,093,942
3	15,851	174,363	2,205,215	15,554	171,098	2,163,926	6,034	66,373	839,431
4	12,528	137,811	1,692,161	12,294	135,230	1,660,478	4,769	52,459	644,133
5	9,902	108,921	1,298,471	9,716	106,881	1,274,159	3,769	41,461	494,272
6	7,826	86,087	996,375	7,680	84,475	977,720	2,979	32,770	379,277
7	6,185	68,040	764,564	6,070	66,766	750,248	2,355	25,900	291,037
8	4,889	53,777	586,684	4,797	52,770	575,699	1,861	20,470	223,325
9	3,864	42,503	450,189	3,792	41,707	441,760	1,471	16,179	171,368
10	3,054	33,593	345,450	2,997	32,964	338,982	1,162	12,787	131,498
11	2,414	26,551	265,080	2,369	26,054	260,116	919	10,107	100,904
12	1,908	20,985	203,407	1,872	20,592	199,599	726	7,988	77,428
13	1,508	16,586	156,084	1,480	16,275	153,161	574	6,313	59,414
14	1,192	13,109	119,770	1,169	12,863	117,528	454	4,990	45,591
15	942	10,361	91,905	924	10,167	90,184	359	3,944	34,984
16	744	8,189	70,523	730	8,035	69,202	283	3,117	26,845
17	588	6,472	54,115	577	6,351	53,102	224	2,464	20,599
18	465	5,115	41,525	456	5,020	40,748	177	1,947	15,807
19	368	4,043	31,864	361	3,967	31,267	140	1,539	12,129
20	290	3,195	24,451	285	3,136	23,993	111	1,216	9,307
Total	152,054	1,672,595	**20,897,475**	149,207	1,641,279	**20,506,205**	57,880	636,685	**7,954,773**

**Gorai has been closed since 2008. This has been accounted for in all calculations.*

Savings Due to Fleet Turnover Emissions Reduction

			Current Practice – Diesel Trucks				Use of New LNG Trucks			
Vehicle Type	**Total Number of Vehicles**	**Total Distance Traveled in a Day (km)**	**Pollutant**	**Diesel Emissions (metric tons/year)**	**Total CER Equivalent**	**Cost of Emissions/ Year ($/yr)**	**Emissions (metric tons/yr)**	**Total CER Equivalent**	**Cost of Emissions / Year ($/yr)**	**Cost Savings in Emissions/ Year ($/yr)**
Stationary Compactor	16	768	CO	1.6	1.6	$7,734	1.0	1.0	$843	$6,891
			HC	0.1	0		1.0	0.0		
			NOx	1.8	558		0.2	60.0		
			PM	0.3	0		N/A	N/A		
TATA Dumper Placer (TDP)	89	37,840	CO	1.2	1.2	$7,728	0.7	0.7	$40,882	$(33,153)
			HC	0.1	0		1.0	0.0		
			NOx	1.8	27,590		9.5	27,590		
			PM	0.2	0		N/A	N/A		
Dumper	688	89	CO	82.9	82.9	$551,237	51.4	4,260.9	$426,205	$125,032
			HC	5.1	0		51.7	0.0		
			NOx	128.4	39,804		85.7	26,579		
			PM	16.8	0		N/A	N/A		
Total	**793**	**38,697**				**$566,699**			**$467,929**	**$98,770**

APPENDIX D- BUS SERVICE EARNINGS FROM LNG/CNG

An alternative option to considering the use of LNG/CNG for the refuse trucks operating around the landfills is to consider their use for Mumbai's public transportation system buses. The pre-feasibility analysis was not performed for this, but some details of the bus fleet and emissions have been provided in this section as supplemental information. The buses primarily run on diesel, though around 18 percent of the buses currently operate on CNG and provide extremely dramatic emissions benefits in comparison to the diesel buses in the fleet. The bus fleet also has a fairly high turnover rate.

The Brihanmumbai Electric Supply and Transportation Undertaking (BEST) operates the public transport services in Mumbai. BEST took control of the bus services in 1947. BEST's bus operation is divided into 25 depots that operate buses all over Mumbai. The transport wing of BEST operates buses within the Municipal limits of Greater Mumbai and currently extends service to Belapur in Navi Mumbai in the northeast as well as to Bhayander and Teen hath naka at Thane (Source: http://www.bestundertaking.com/trans_engg.asp). On an average, the buses run approximately 203 km per day and are mainly operated within the urban areas. The following table show the number and categories of the buses.

Bus Fleet Details

Bus category		**Manufacturer**	**Total Number**
1	Single Decker Diesel Buses	Ashok Leyland	2,054
2	Single Decker Midi buses	Ashok Leyland	63
3	CNG Buses	Ashok Leyland	188
		TATA	289
4	AC buses	Ashok Leyland	51
5	MUTP	Ashok Leyland	644
6	Double Decker	Ashok Leyland	163
7	Midi CNG buses	Ashok Leyland	100
8	King Long AC buses	JCBL	19
Total			**3,571**

Of the 3,571 buses, BEST has 577 buses operating on CNG and the remaining 2,994 buses are powered by diesel fuel (about 83 percent). The average retirement age of the buses is about 15 years. The number of buses retired and new buses added in recent years are shown in the following table. The table shows that about 1,786 buses were retired in past five years, while 1,976 new buses were added during the same period.

Fleet Turnover Details

Year	Number of Buses Retired	Number of Buses Added
2003-04	260	266
2004-05	217	222
2005-06	924	924
2006-07	307	319
2007-08	78	245
Total	**1,786**	**1,976**

Using the ARAI's emission factors for heavy-duty vehicles and the information regarding fleet size and travel distance, the emissions loads from all the buses have been computed. The following table shows the annual emissions load for the BEST bus fleet.

Emission Loads from BEST Buses

Parameters	Metric tons/Day	Metric tons/Year
CO	4.3	1569.5
HC	0.26	94.9
NOx	6.7	2445.5
PM	0.89	324.9